PneUI: Pneumatically Actuated Soft Composite Materials for Shape Changing Interfaces

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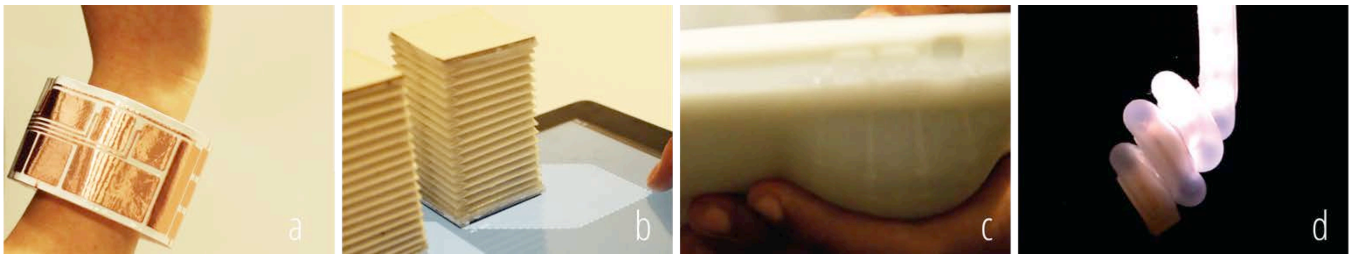

Figure 1: Application demonstrations. (a) A shape changing mobile. (b) Height changing tangible phicons. (c) A transformable tablet case. (d) A shape-shifting lamp.

ABSTRACT
This paper presents PneUI, an enabling technology to build shape-changing interfaces through pneumatically-actuated soft composite materials. The composite materials integrate the capabilities of both input sensing and active shape output. This is enabled by the composites' multi-layer structures with different mechanical or electrical properties. The shape changing states are computationally controllable through pneumatics and pre-defined structure. We explore the design space of PneUI through four applications: height changing tangible phicons, a shape changing mobile, a transformable tablet case and a shape shifting lamp.

Author Keywords
Soft Composite Material; Pneumatic System; Soft Actuator; Soft Robotics; Human-Material Interaction; Shape Changing Interface; Radical Atoms; Organic User Interface

ACM Classification Keywords
H.5.2. User Interfaces: Haptic I/O; Prototype

INTRODUCTION
Hard bodies with construction of rigid structural and electronic elements have limited the form, function and interaction of shape changing interfaces in HCI [37]. Thus a range of technologies in HCI have been developed to enable soft and organic interfaces, including flexible sensing techniques [28], dynamic stiffness [3], texture and buttons on malleable surfaces [6, 7], soft deformable surface output [1, 13], and 2.5D shape display with elastic covers [18]. In contrast, inspired by marine organisms that sense and accomplish drastic body deformation and locomotion by soft actuators [28], we take a holistic view of the material itself and envision a composite material that integrates input sensing and active shape output. Materials with different mechanical properties can be combined to form separate structural layers for the soft composites, which can be utilized to create shape changing interfaces without rigid mechanical elements. This research is driven by the vision of Radical Atoms [11], which proposes a group of physical materials as a dynamic manifestation of digital information.

While the study of soft motion and mechanisms is a growing topic in robotics, approaches and techniques in soft robotics have not been fully explored in HCI. In this paper, we presented PneUI, pneumatically actuated soft composite materials, that follow three principles: 1) the shape output is computationally controllable through pneumatics and pre-defined structure; 2) the material should enable either isotropic (uniform in all orientations) or anisotropic (directionally dependent) deformation determined by the intrinsic properties of the composite; 3) the material should integrate both input sensing and active shape output. Examples of utilizing shape changing primitives for HCI applications are illustrated in Figure 1.

In this paper, we first describe the design considerations of applying our soft composite materials for HCI. We then talk about the layered structures of soft composite materials and explain the composites' active shape output and input

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sensing capabilities in separate chapters. Finally, we describe pneumatic control systems and applications.

We present the following main contributions:

- Creation of pneumatically actuated soft composite materials, which integrates both input sensing and active shape output.
- Development of a framework for creation and testing of selected materials, structures, soft fabrication processes, and pneumatic control systems to construct soft composite materials.
- Primitives of soft shape changing at both macro and micro scales, including curvature change of surfaces, unidirectional volume change of solid geometries, and dynamic texture change.
- Development of two techniques that embed sensing into composite material and interfaces: 1) conductive pads composited on structural layers for sensing shape output and gestural input using capacitive and electric field sensing; 2) liquid metal embedded in elastomeric air channels for sensing deformation of soft surfaces.

RELATED WORK

Soft Robotics

Soft robotics is an emerging domain that is dedicated to robots comprised of soft components including soft actuators, flexible sensor/circuits, and soft bodies [10]. In contrast to other techniques for shape change, such as spatial arrangement of actuated modules [20], self-foldable chains [9], self-foldable surfaces [8, 15], soft robotics often focuses on pneumatic actuation of elastomeric channels and bladders. Pneumatic actuation is chosen because air is a lightweight, compressible and environmentally benign energy source [32].

While a primary focus of soft robotics is the improvement of the robot's performance and the exploration of the bio-inspired mechanism itself, there is a large space to introduce soft robotic technology in constructing shape changing interfaces. One design space is to explore not only isotropic, but also anisotropic deformation with soft composite materials: an elastomer by itself deforms uniformly under stress; however, by compositing different structural layers with various mechanical properties, the orientation of deformation can be pre-defined [19]. We build on this work by exploring other topologies, integrating sensing, and applying these concepts to HCI.

Shape Changing User Interfaces

The exploration of Shape Changing User Interfaces in HCI is still in its infancy, as techniques for shape change, flexible sensing and interaction techniques are being developed [2, 37]. Shape-Changing Mobiles [9] are actuated by RC servo motors to provide tapering of the back of the mobile phone. Densely arranged linear actuator arrays have demonstrated successful results in presenting complex 2.5D relief forms [18]. Those rigid mechanisms can achieve controllable transformations, yet not compliant, making it hard for these systems to conform to intricate shapes and limiting the amount of possible shape change states. Shape memory alloy (SMA) based actuators have been used to bend surfaces [1]. It has been integrated into mobile devices [27, 5] allowing for edges to be bent. SMA is lightweight and strong for its weight, but often slow.

In the field of HCI, pneumatic inflation has also been explored as an approach for shape change. Volflex [12] is a volumetric display consisting of independently controlled balloons. Deformable convex or concave hemispherical membranes with rims can be used for an inflatable multi-touch display [35]. Inflatable Mouse [13] is a shape-shifting mouse that can change the volume by using an air balloon and a built-in pump. Closely related to our work, Harrison explored dynamically changeable physical buttons on a display, with a variety of different materials for creating soft and ridged buttons, and integrated multi-touch sensing on the surface through diffuse illumination, pressure sensing for input [7]. Granular jamming [3], which can also be controlled pneumatically, can provide malleable surface with adjustable stiffness, and allows for passive shape change. In contrast to jamming, this work focuses on pneumatic actuation – allowing for active shape change.

The types of shape change in HCI have been categorized as: orientation, form, volume, texture, viscosity, spatiality, adding/subtracting and permeability [26]. We chose to focus on curvature, volume and texture as shape change primitives because we believe those encompass a large space of shape change in mobile and tangible applications, as demonstrated by past work [9, 6, 27].

Flexible Sensing Techniques

A range of sensing techniques on soft surfaces has been explored in HCI, optical sensing [3] and flexible capacitive sensing [3, 31] are among common approaches. “Sensing through structure” has been introduced to sense the deformation of flexible surfaces and structures [33, 8].

In Soft Robotics, sensing through the deformation of the surface itself is a unique approach afforded by the elastic nature of soft materials. A range of stretchy sensors, bend sensors and pressure sensors have been built [1, 22,16, 17].

Soft Fabrication

We choose fabrication processes that are feasible in common fabrication laboratories. One notable case is Soft Lithography [25], which is used to generate 3D structures within elastic polymers. Soft roboticists adapted the process for fabricating elastomer, especially silicon rubber, with integrated air bladders and channels. This process requires high precision equipment and fabrication processes, such as high resolution molds, spin coaters, and precise deposition process.

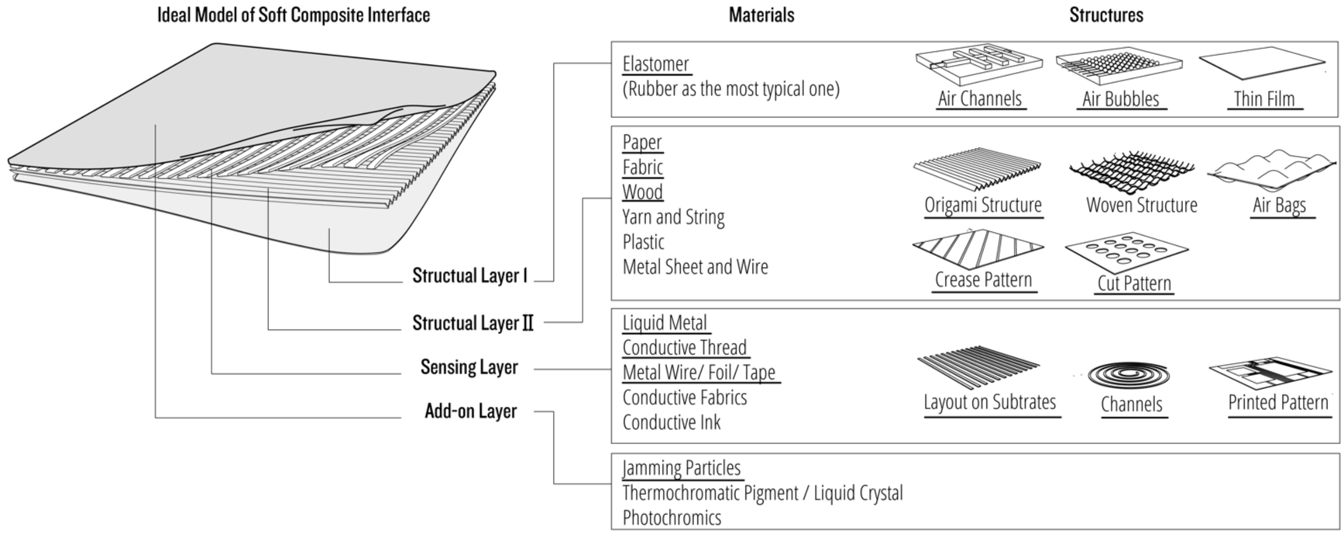

Figure 2: Diagram of composite structure. Structure Layer I responds isotropically to stress; Structure Layer II enables anisotropic deformation in response to air pressure; Sensing Layer enables the sensing of both hand input and shape output; Add-on Layer manipulates other material properties rather than the shape change, either haptically or visually. The underlined materials and structures are the ones that have been tested out.

SOFT COMPOSITE INTERFACE FOR HCI

Pneumatic soft composites provide many opportunities for designing significant and novel applications for HCI, primarily as an enabling technology for shape changing user interfaces. Shape change can be used to convey information to the user about computational state and provide dynamic affordances. By combining a sensing layer in the soft composite interface, PneUI interface can sense a range of inputs and outputs.

Information Representation

Shape change, both at the macro and micro level, can be used to convey computational states to users as a type of display. For example, smaller scale shape change, which we call texture change, has previously been shown to enable a separate haptic channel for representing or communicating information [6]. Pneumatic soft composites provide dynamically controllable texture patterns that can vary density, frequency and sequence. A shape changing iPad case is introduced in the paper as an example of dynamic textures.

Dynamic Affordances and Ergonomics

Shape change can also provide new ways for users to interact with devices on demand. In addition to dynamic physical affordances, adaptable shapes can increase economic performance for specific tasks. We develop a prototype of mobile phone that can change shape and motion for different use cases.

Sensing Modalities

We categorize the achievable sensing modalities into: 1) sensing gestures on the surface, 2) gestures hovering over the surface, 3) gestures that deform the surface, and 4) air deforming the surface. The first three are input modalities, and the last one is shape output. Further, the innate characteristics of soft interface could afford a wider variety of manipulations to deform the surface, such as pushing, stretching, bending, embracing, stroking and squeezing. A system of shape changing tangible phicons is developed to demonstrate different gesture sensing modalities.

STRUCTURE OF THE SOFT COMPOSITE MATERIAL

Layered Structure

Our pneumatically-actuated soft composite material is designed to enable both isotropic and anisotropic deformation in response to air pressure. The composite material is fabricated with three main layers, including two structural layers and one sensing layer (Figure 2). One structural layer utilizes an elastomeric polymer (or elastomer) as the main material to enable isotropic shape deformation. To go beyond isotropic deformation, an additional structural layer includes a range of materials with different elasticity to create constrained anisotropic deformation in response to air pressure. Moreover, conductive materials, either solid or liquid, such as conductive thread and liquid metal, are composited as the sensing layer to sense both input and output. Finally an add-on layer can be composited to control other material properties other than active shape output. For example, Jamming particles can control surface stiffness to give haptic affordances or lock shapes in a certain state [3]; and thermochromic liquid crystals can be injected into air channels of elastomer to change the color of surfaces.

Materials Choices

Each layer of the composite includes one or more materials with extrinsically designed structures. These structures can enhance or modify the deformations caused by pneumatic inflation. For example, copy paper itself has relatively low elasticity, however, origami structure enables increased flexibility in a specific directions. Further, composited conductive layers can form a sensing network. For example, placing electrodes onto 3D substrates enables sensing the 3D shape output through changes in capacitance.

Selecting different materials from Figure 2, and layering them in different orders allow the construction of multiple soft composite materials. The choice of materials is driven both by the type of shape change we want to achieve and also materials that we think other researchers would have ready access to, so as to make our work more accessible. The underlined materials from Figure 2 are the ones that have been verified during our exploratory experiments. We constructed the table assuming that air is the main actuation method. By introducing a greater variety of energy sources, we could composite additional ranges of active materials, such as heat-driven shape memory alloys and thermoplastics.

SHAPE CHANGING PRIMITIVES

We choose curvature, volume and texture to explore how soft pneumatic composite materials provide a range of deformation behaviors and thus enable or enhance shape changing interfaces on both the macro and micro level (Figure 3).

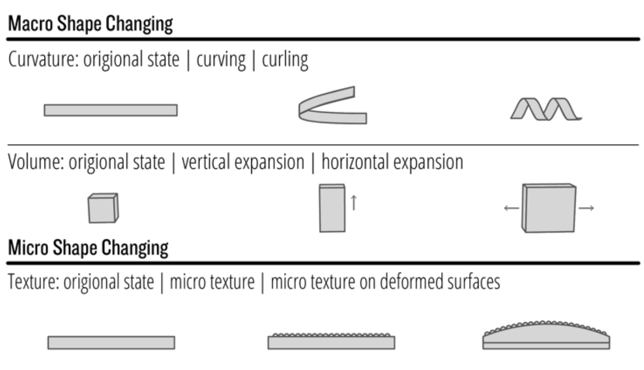

Figure 3: Shape changing primitives: curvature, volume and texture.

Curvature Change on Surfaces - Bending and Curling

The soft mechanical alphabet [2] describes the combination of compression and elongation to generate curvatures at given points of a surface. This is the basis to create physical forms under the constraints of preserved topological equivalents. We introduce two types of composite materials to generate such surface curvatures, utilizing compression and elongation behaviors with inflatable airbags (Figure 4). For both cases, crease patterns on the paper layer or the location of airbags define the position of the deformation. Air pressure determines the degree of curvature.

Elongation with Elastic Airbags for Bending and Curling

This composite material includes three layers, a silicon layer with embedded airbags connected with air channels, a paper layer with crease patterns, and a thin silicon layer at the bottom to bond and protect the paper layer (Figure 5).

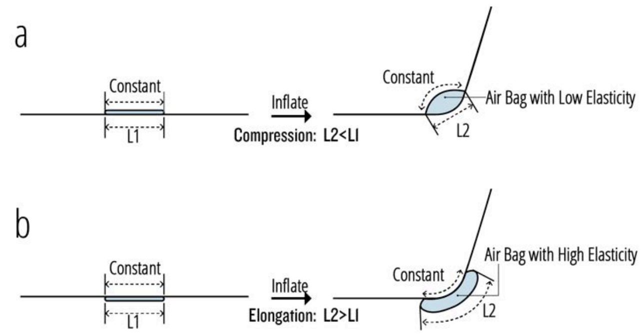

Figure 4. Surface curvature can be determined by the compression of airbags with low elasticity (a), or the elongation of airbags with high elasticity (b).

While soft actuators have been introduced before [19], our work focuses on introducing paper composite with various crease patterns to control the bending behavior. When inflated, the inner airbags function as actuators to generate elongation and force the surface to bend towards the opposite direction.

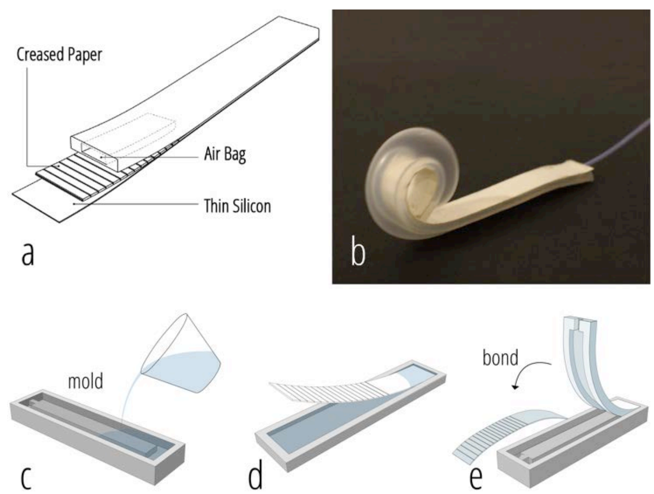

Figure 5: (a, b) Structure of the composite. (c, d, e) Fabrication process. (c) Pre-mixture of silicon (EcoFlex 00-30, Smooth-on, Inc) is poured into a 3D printed mold designed to form a shape with air channels. (d) Creased paper is soaked into the same silicon mixture. (e) Silicon and paper layer are peeled off molds separately once thermally cured. Two layers are then bonded with uncured silicon.

In this case, dynamic control of the curvature is determined by two factors: air pressure and crease pattern. First, air pressure can control the degree of curvature. Our experiments show how pumping additional air will make a single bending (Figure 6d) turn into a curling with continuous bending (Figure 6e). Secondly, the design of paper crease patterns will affect the deformation. We vary three factors of crease patterns in our experiments: density, location and angle. Figure 6a and 6b indicate how density affects the sharpness of bending. Low density creases enable sharper bends and by varying the location of crease, we can control the bending location on the surface (Figure 6c and 6d). Laying out the crease lines diagonally (Figure

6f) generates helical shapes instead of curling on a single plane (Figure 6e). Finally, through Figure 6g and 6h we demonstrate a variation of on-surface pattern cuts on thin pieces of wood instead of paper. It shows similar bending and curling behaviors.

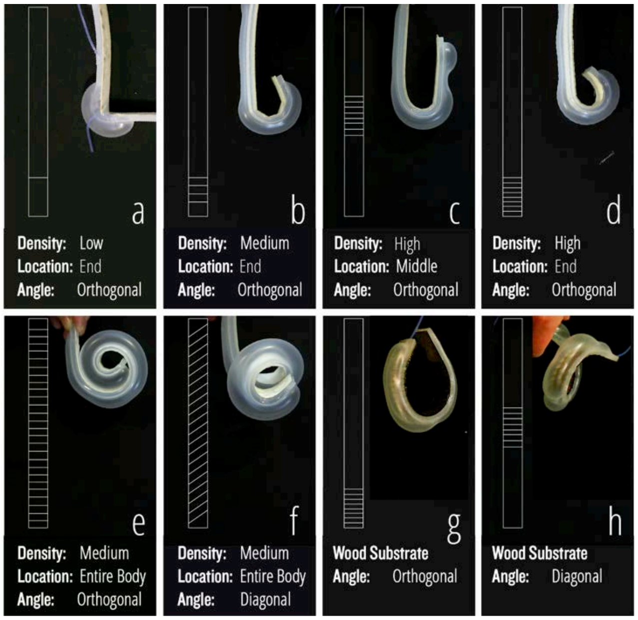

Figure 6: (a, b) Crease patterns with varied density; (b, c) Crease patterns at varied location; (d, e) (e, f) Crease patterns with varied angles; (g, h) Crease patterns on thin wood.

To apply the aforementioned approaches of dynamic control of shape changing states, we test how specifically designed crease patterns and respective control of airbags can make a flat circular shape morph into different spatial structures with three stands (Figure 7a). We also show a progressive transformation from a line to a square (Figure 7b).

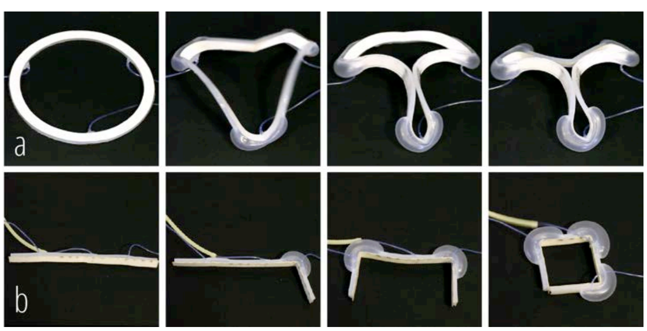

Figure 7: Specifically designed crease patterns and respective control of airbags enabling dynamic transformation of shapes.

Compression with Nonelastic Airbags

This composite material includes two layers: a plain paper layer and plastic airbags with low elasticity (Figure 8a). Airbags are fabricated using plastic welding and glued with the paper layer. While inflated, the airbags behave like the biceps (the muscle to pull the arm up), and compresses itself to cause the surface to bend. The inflation of nonelastic airbags happens on the same side as the surface bends towards (Figure 8). Experiments indicate that muscle like nonelastic airbags have stronger bending force than aforementioned elastic airbags, and can bend thicker paper or surfaces made from thin wood or plastic.

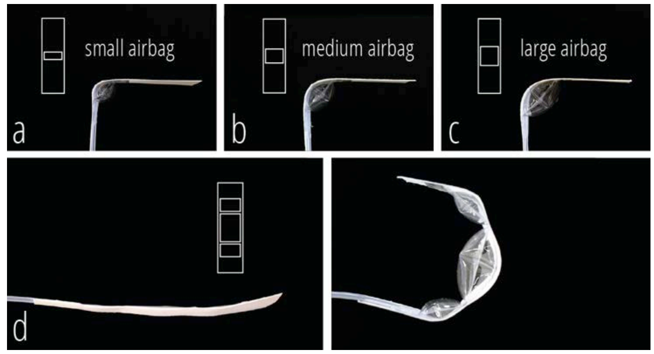

Figure 8: (a, b, c) Curvature control by size of the airbag. (d) Combination of the two different airbag sizes.

Unidirectional Volume Change of Solid Geometries

Origami is adapted through engineering methods to create 3D structures out of paper folds [36]. Inspired by the work in soft robotics that combines origami with elastomers to build soft actuators [19], we explore the orientational volume changing behaviors. We do this through compositing a range of origami structures with elastomers. The origami structures are spin coated and sealed with silicon (EcoFlex 00-30, Smooth-on, Inc), allowing the volume change to be actuated with air transported into the hollow space (Figure 9). Direct manipulation can also deform the shape.

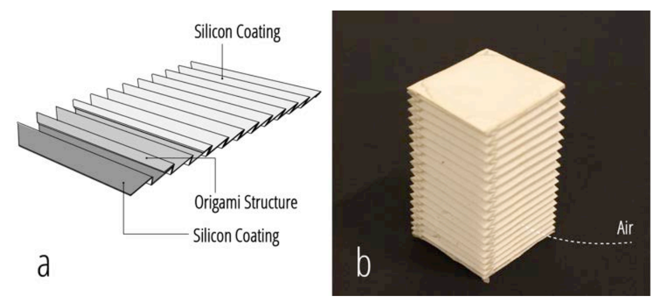

Figure 9: (a) Structure of the composite surface that forming the volume. (b) Air is pumped into the hollow space for actuation.

Three orientational volume changing behaviors are explored: 1) linear elongation, 2) angular expansion and 3) rotatory elongation. Accordion structure folded from V-pleats [24] enables linear elongation (Figure 10a). Utilizing the same pleating pattern and bonding one side of the folds with silicon, we are able to achieve angular expansion (Figure 10b). Lastly, rotatory elongation can be achieved with cylindrical structures folded with triangular pleats (Figure 10c) [29]. In this case silicon serves three functions: sealing the origami structure for air actuation, coating the paper surface for enhancing material durability, and constraining elasticity of origami structure within a specific range.

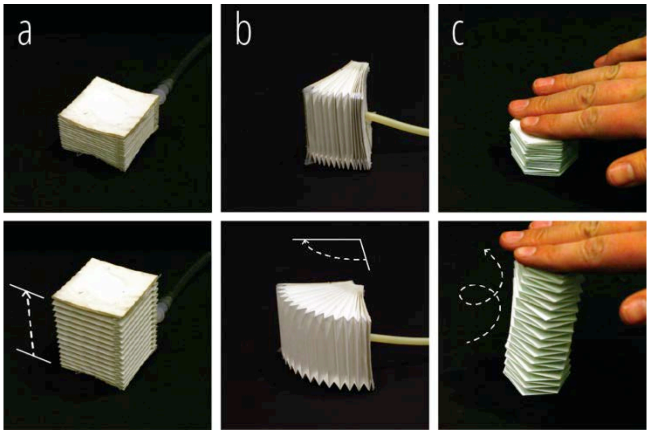

Figure 10: (a) Linear elongation. (b) Angular elongation. (c) Rotatory elongation.

Dynamic Texture Change

We perceive the change of texture as a local and micro level shape changing behavior occurring on the surface. Two approaches are examined to generate textures on soft surfaces: fabricating air bubbles inside elastomer and compositing fabric with cut patterns. Conductive threads, such as plated silver type threads, can be embedded in the composite material for human touch and gesture sensing.

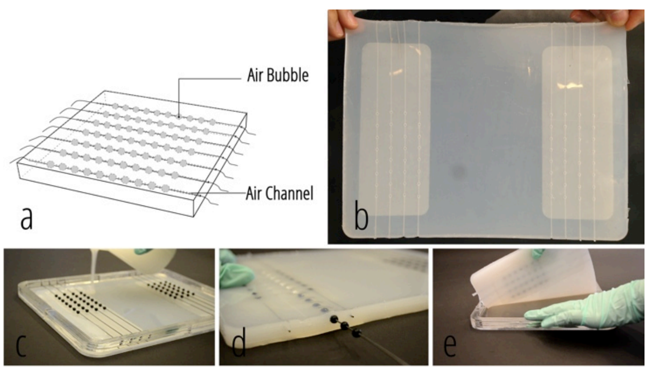

Figure 11: (a, b) Structure of the composite material. (c, d, e) Fabrication process. (c) Pouring pre-mixture of silicon into a mold with threads of beads suspended in the mid-air. (d) Thermally curing the silicon and peeling it off the mold. (e) Pulling the beads out of the silicon for the final sample.

Fabricating Air Bubbles inside Elastomer

In the sample from Figure 11, each column of air bubbles can be inflated separately. We can vary the density, frequency and sequence of texture by pumping and vacuuming air in separate columns at different times. The combination of the three factors is capable of communicating different types of information, such as directional signals and speed. Also, by compositing a second silicon layer with bigger airbags, we can combine deformation on both macro and micro level, to create texture patterns on a deformable, 3D surface.

Compositing Fabric with Cut Patterns

Another approach to generate texture on soft surfaces is to composite flexible material with cut patterns (Figure 12). Elastic fabric (Spandex) was chosen due to its compliance under stress when composited with silicon.

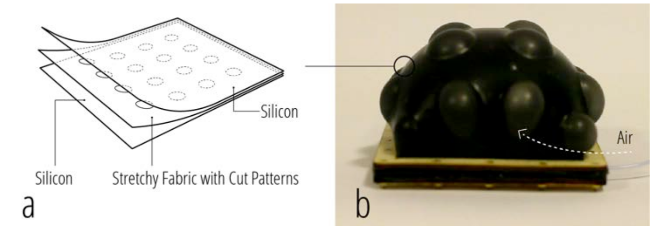

Figure 12: (a) Structure of composite material. (b) Fabric constraints of deformation in local areas of surface.

The difference in the elastic modulus of fabric compared with silicon creates multi-state deformation. We demonstrate that the same surface will deform from macro to micro level as air pressure is increased (Figure 13).

Figure 13: As the increase of air pressure, the surface deform from global to local region.

One advantage of a fabric-elastomer composite is the ease of designing and fabricating different patterns. Rather than making customized molds for textures, patterns can be quickly designed and cut with digital fabrication methods, such as laser cutting. Figure 14 shows a variety of texture patterns we have explored.

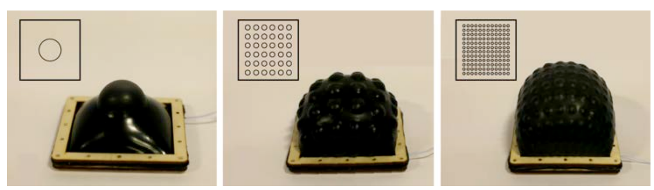

Figure 14: Different textures are generated due to different cut patterns on the fabric composite layer.

COMPOSITE SENSING LAYER

To sense input and output, we have explored different sensing techniques, including compositing electrodes to sense global structural change, and embedding fluid conductors to sense local surface deformation with high sensitivities. The cause of shape deformation can be air or human gestures.

Composite Thin and Flexible Circuitry

Flexible circuitry, which is cut out of copper tape or printed by an inkjet printer with conductive ink, can be composited as a sensing layer in the soft composite material. We designed customizable electrode patterns to sense direct touch and near range proximity by measuring the capacitance between human fingers and the electrode network. A coating of silicon layer on top of the sensing pads enables insulation. Multilayer circuitry can be composited with silicon layers in between. Further, through the application of shape shifting lamp, we have also demonstrated the possibility of compositing rigid electrical components, such as surface mounted LEDs, within soft bodies.

Composite Sensors on Folding Structures

In the case of using origami as a supporting and constraining structure, electrodes made from copper tape can be composited with paper folds to sense structural deformations. These deformations can be caused by either pneumatic actuation or direct manipulation. The separation distance between folds correlates to the capacitance between the electrodes as shown in Figure 15. For a linear accordion, four electrode pairs on both sides of the structure were sufficient to measure the height of each side. Other electrode placements can be extended to sense additional geometrical folding structures.

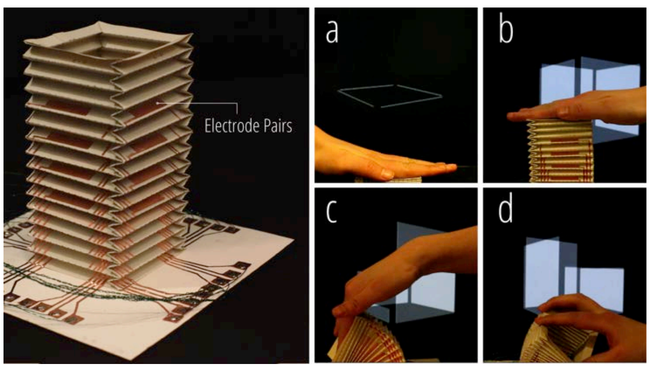

Figure 15: Four pairs of electrodes on adjacent faces of the folds are used to sense geometrical deformation. (a, b) Sensing the height. (c) Sensing side bending. (d) Sensing diagonal bending.

Measurements are taken by stimulating one electrode with a square wave and then reading the induced voltage on the adjacent electrodes. Readings are taken at time T after the rising and falling edges of the square wave, and the difference between these measurements is averaged for 23 cycles (Figure 16). Because the time constant of an RC circuit is dependent on C, as C changes, the voltage at time T changes, allowing for relative changes in capacitance to be measured. Sensor data for each side is averaged and then passed through a windowed time average in order to eliminate noise. The value for each side is then unity-normalized to determine the relative height of each side.

Composite Liquid Metal in Elastomeric Channels

Soft robotic engineers have shown how to construct elastic sensing surfaces by injecting conductive liquid metal (eGaIn) into inner channels of elastomer [1]. The resistance of liquid metal changes in response to the deformation of the channels.

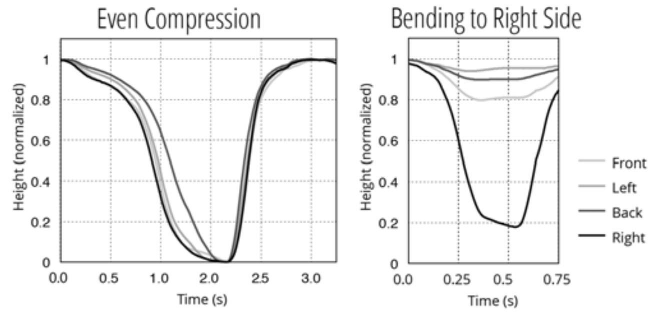

Figure 16: Relative side heights for various deformations of a linear accordion

We adapt this sensing technique to fabricate the top layer of the composite material. It can sense surface deformation through both direct manipulation and air actuation (Figure 17). These conductive channels can also be used for capacitive sensing.

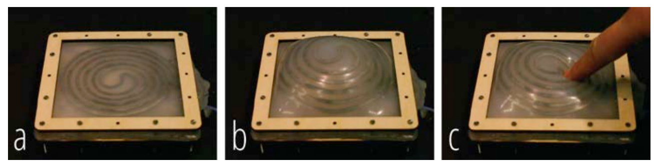

Figure 17: The resistance of liquid metal sensor changes in response to the deformation of the elastomeric channels through either air actuation (b) or direct manipulation (c).

PNEUMATIC CONTROL SYSTEMS

The pneumatic control system energizes the soft composite material. Air can be either injected into air channels inside elastomer, or introduced into the space wrapped around by the composite material.

There are three modes to control the airflow in and out of the soft composite material: supply, exhaust, and close. The supply/exhaust is the mode to inflate/deflate an air bag. The close mode stops the airflow to air inside the composite. Figure 18 shows a pneumatic control circuit consisting of two 3-port solenoid valves, an air compressor, and a vacuum pump for a single air bag.

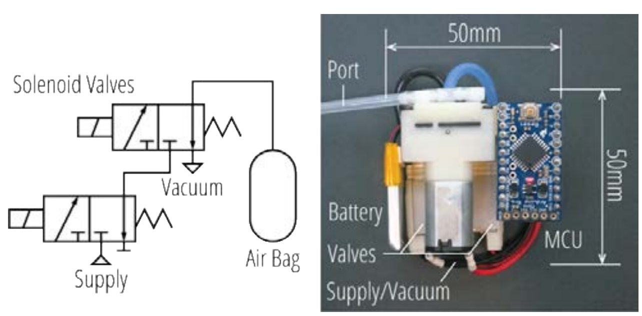

Figure 18: (Left) Basic pneumatic circuit for single air bag; (Right) self-contained pneumatic system

We use a large-sized stationary air compressor (Silent Aire Tech., Super Silent compressor 50) and a vacuum pump (Rocker Scientific, Oil-Free Pump 300) for experiments. However, typical tethered pneumatic systems with a stationary air compressor limits use in portable applications. Therefore, we developed a miniature pneumatic control system with small solenoid valves (SMC, Series S070), a pump used as both supply and vacuum (Koge Electronics, Series KPV), and lithium polymer battery (3.7V, 110mAh). The system indicates feasibility of a further mobile application. The noise levels of the systems are 40dB and 72dB for the stationary air compressor and the miniature pump used in the portable system, respectively (catalog value).

APPLICATIONS

We build four prototypes to explore the potential of shape changing interfaces enabled by the soft composite material. Different soft fabrication processes that combine structural layers with sensing layers are described in brief.

Shape Changing Mobile: Fabricating Multi-state Bending Surfaces

The shape changing mobile is a flexible body that enables multiple bending states, to give users dynamic affordances for various use cases. The surface will animate between flat and bending state when a call comes in. It can morph from a bar shape to a curved phone shape if a user answers the phone call; when placed over the user's arm, it turns into a wearable wristband (Figure 19).

The fabrication of the shape changing mobile is based on one type of the aforementioned primitives: curvature change on surfaces. Touch sensing pads are composited on both upper and bottom side to detect direct touch.

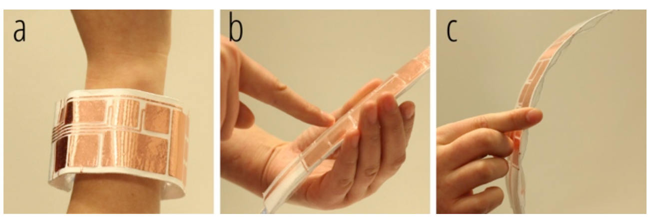

Figure 19: (a) Wrist band mode (b) Bar mode (c) Phone mode

Height Changing Tangible Phicons: Origami Composite with Sensing

This application demonstrates the controllability and connectivity of multiple height-changing objects mediated by graphics (Figure 20). The system casts computationally generated digital shadows on a graphic touch screen corresponding to the height of the box and imaginary time. Users can change the height of the box by push/pull and release the top. In addition, a user can change the height of the box by editing the digital shadow with drag gesture. This application is intended for computer-aided urban planning in which total capacity of the buildings is one of the conditions. By making bridge between boxes, users can also examine the height of the boxes without changing total volume of the multiple boxes.

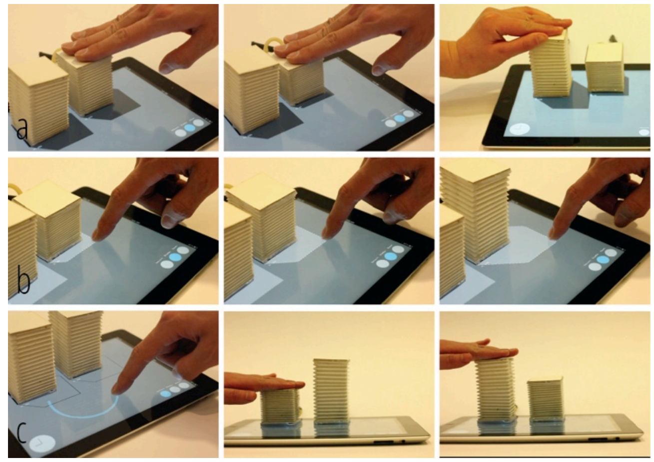

Figure 20: (a) Direct push/pull height-changing of the box with shadow simulation (b) Height-changing by editing digital shadow (c) Connecting two boxes with bridge and setting total volume constraint

The construction is based on linear elongation of shape changing primitives. The composite sensing techniques of the folding structure is adapted to sense the height change of the buildings. The main fabrication process includes pasting electrodes on paper, folding origami structures, dip coating and spin coating with silicon.

Transformable Tablet Cases: Fabricating Multilayer Airbags

For this prototype, while bigger airbags are inflated as grippers for a car racing game controller, columns of smaller air bubbles on top can be inflated sequentially to directions through haptics (Figure 21).

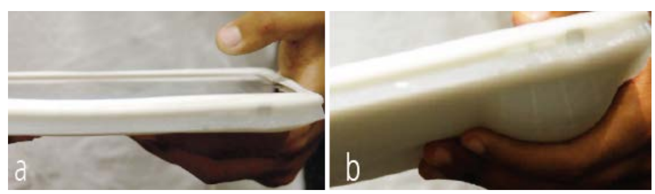

Figure 21: (a) Flat tablet cover in initial state. (b) Macro volume change for forming grips and micro volume change for haptic sensation.

This prototype demonstrates the hybrid of macro and micro level shape change, based on the isotropic deformation behavior exhibited by homogeneous elastomer. Flexible texture layer is molded on top of the bigger airbags. The fabrication involves multi-stage molding and casting. To keep the prototype thin and light, we embed two flat Mylar pieces during the casting process, to create two flat yet inflatable airbags below finer texture bubbles.

Shape-shifting Lamp: Soft Lithography with Embedded Sensing and Light

This lamp supports large deformation from a straight strip shape to a rounded bulb shape. Users can pull the strip like pulling the chain of a conventional lamp. The strip is the illuminating light itself and it starts to curl and light up.

This demonstrates Shape-changing combined with optical properties (Figure 22).

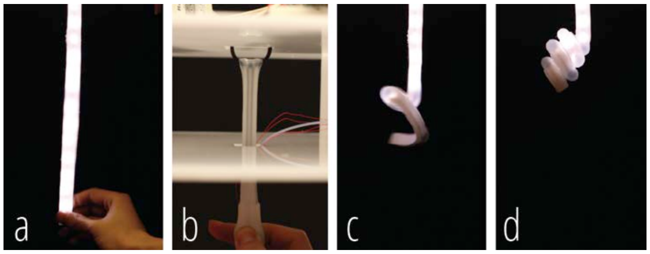

Figure 22: (a, b) Lamp in straight state capable of user input by pulling the entire body. (b) Silicon with embedded liquid metal as pulling sensor. (c, d) Lamp in bulb state by curling

The construction of the lamp is inspired by one type of shape changing primitives: the curling behavior under curvature change on surfaces. Silicon with embedded liquid metal is fabricated as pulling sensor, which is attached to the top of the lamp stip. Soft lithography is adapted for fabricating the shape-shifting lamp. Before the casting process, surface mounted LEDs are soldered on top of flexible copper strips. We then bond the copper strips with a paper substrate with angular cut patterns. The two layers, paper layer and air channel layer, are bonded together with half cured silicon.

LIMITATION AND FUTURE WORK

While the current soft composite materials have unique limitations in both design and fabrication processes, it opens up exciting directions to explore in the future.

Compositing Active Material

The current fabrication process allows the interfaces to morph between two shapes, by designing certain structure layers that composite with airbags. It is still desired that the interface can have multiple shape-changing states that can be dynamically controlled in real-time. This could be achieved by introducing other active stimulus and compositing a wider range of active materials. For example, by embedding memory alloy or heat reactive polymers, and combining two actuation sources (air and heat respectively), we might be able to achieve more flexible control of shape changing states. This is a step closer towards programmable, dynamically controllable, shape changing interfaces.

Variations of Source for Actuation

Current stationary system has limited mobility. We have shown an untethered mobile pneumatic system in the previous section. However the pumping and vacuuming speed drops significantly in the mobile system. Another issue of the pneumatic system is the continuous noise of the pump. The noise can be reduced with an insulation enclosure.

Future work is required to explore new approaches to enable smaller, faster and more integrated pneumatic control systems. Exploring other types of fluid rather than air to actuate and deform the soft composites is also an exciting direction, and it may enable new interaction behaviors. For example, Helium, or hot air can let inflated surfaces float in air or water. Using chemical reactions to generate gas sources may help eliminate hard pneumatic control systems.

Extension of Shape Changing Behaviors

Other types of shape changing behaviors are yet to be explored systematically. A broader and systematic exploration of shape changing primitives could increase use cases in the design of shape changing interfaces. For example, topological change, including creating holes on surfaces, can give interesting affordances for interaction. Locomotion as a bio-inspired mechanism can be achieved with programmable constraints in the material structure [32]. Shape locking is currently implemented with solenoid switches. However, stiffness changing materials, such as Jamming particles, can be adapted to lock shapes or introduce dynamic constraints.

3D Printing as a Promising Fabrication Approach

Soft fabrication requires handwork and time-consuming cast molding processes. This issue could be improved by using enhanced 3D printing technology. While current commercially available 3D printers are not able to print material with high elasticity, we envision printing elastic polymer will be feasible in the near future. It is helpful for constructing complex air channels, combining soft and hard materials, and additional automatic fabrication process.

CONCLUSION

We have presented various types of shape-changing interface enabled by pneumatic soft composite materials. By introducing constraints through materials with pre-programmed structures, we can design and control the direction, location and angle of deformation. We demonstrated shape-changing primitives, and present a framework and test results of the selection of materials, structures, soft fabrication processes, and pneumatic control systems to construct soft composite materials. The soft composite material is a fusion of sensing and actuation on the single-piece of malleable material. This approach creates new opportunities to employ shape-changing interfaces by using responsive materials.

CONCLUSION

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