aeroMorph - Heat-sealing Inflatable Shape-change Materials for Interaction Design

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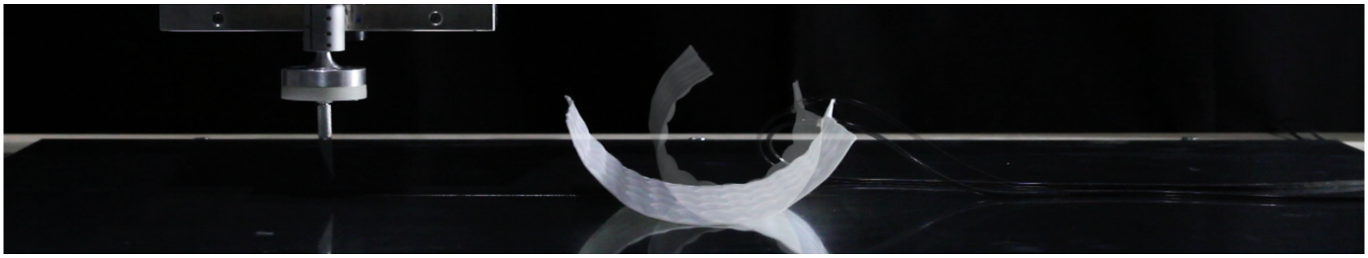

Figure 1. Heat-sealed rayon challis fabric changes its shape upon inflation

ABSTRACT

This paper presents a design, simulation, and fabrication pipeline for making transforming inflatables with various materials. We introduce a bending mechanism that creates multiple, programmable shape-changing behaviors with inextensible materials, including paper, plastics and fabrics. We developed a software tool that generates this bending mechanism for a given geometry, simulates its transformation, and exports the compound geometry as digital fabrication files. We show a range of fabrication methods from manual sealing to heat pressing with custom stencils and a custom heat-sealing head that can be mounted on usual 3-axis CNC machines to precisely fabricate the designed transforming material. Finally, we present three applications to show how this technology could be used for designing interactive wearables, toys, and furniture.

ACM Classification Keywords

H.5.2 Information Interfaces and Presentation: User Interfaces

Author Keywords

shape-changing interfaces; textile; pneumatic; bending mechanism; soft shape-change; wearables; haptics

INTRODUCTION

Pneumatic actuation is a powerful mechanism used in many industrial applications. While traditionally investigated by the soft robotics community, the exploration of transformable materials for designing physical objects with dynamic shape output has been gaining increasing attention in Human-Computer Interaction (HCI) [2][24]. Most recently, pneumatically actuated soft materials have been investigated as both input and output devices for the design of Tangible User Interfaces (TUI) [23][13]. The compliance of soft actuators and the actuation speed and strength of pneumatic actuation make it well-suited for wearable applications. As shown in previous soft-robotics work [17, 9], external shape-deformation of such inflated structures creates variations in air pressure that can be used to infer human interaction on the inflated materials without directly embedding electronics. Previous work in HCI and soft robotics has demonstrated fabrication methods and compelling applications of soft materials that change their shape and stiffness as well as sensing different human interactions. However, these interfaces are typically made of rubbers and other elastomers and result from a complex fabrication flow that typically involves molding or lithography. This not only limits the use of the technique but also its application scope since these materials are unsuited for most wearables, toys, furniture and large scale structures.

In this paper, we introduce a unified heat-sealing approach that enables designers to easily create inflatable sheet materials from fabrics, plastics or paper. We propose a pneumatic hinge mechanism that allows to directly encode user-defined material's shape-changes within two-dimensional structures. This technique is very flexible and allows for a large variety of

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inflatable material behaviors while minimizing the complexity of the design and fabrication processes.

The design and fabrication pipeline that we propose, aeroMorph, includes a) a software simulation platform that predicts the shape-change and outputs vector paths for digital fabrication; b) multiple fabrication methods, including manual heat sealing, heat pressing with custom stencils and a heat-sealing head for 3-axis CNC machines; c) a tested material library with fabrication parameters that performs reliably with this method.

Our approach provides the following contributions:

- The introduction and the characterization of a universal pneumatic bending mechanism.
- Simulation and fabrication tools for designing shape-change materials based on the presented bending mechanism.
- An extended material library for inflatable shape-changing materials and transformation primitives.
- Three application prototypes that demonstrate how aeroMorph can be leveraged for HCI and design applications.

RELATED WORK

Pneumatic driven Shape-change Interfaces

Pneumatically driven soft shape-changing materials have recently been introduced to HCI [23, 12]. The PneUI project explored several shape-change primitives by compositing paper substrate with silicone rubber through a molding/casting technique. Niiyama et al. introduced a heat-sealing method to create PVC pouch actuators that can be easily attached to static objects to create simple physical animation. Perovich et al. [14] use this technique to create a shape-change garment that moved based on the wearer's emotion. Both projects investigate how a single airbag can be attached to another substrate to create bending . In this paper, we look at how to create arrays of airbags with the substrate itself (paper, plastic and textile), leveraging the interaction between the airbags to create folding. Our method encodes shape-changing by simply varying the shape of heat-sealed hinges, bypassing the complicated molding and casting process previously proposed for creating complex pneumatic shape-change [23].

Smart Materials & Folding Mechanism

Smart materials are gaining increasing attention in HCI as they enable designers to create interfaces that change material properties. Researchers looked at embedding electronic actuators into the fabric to create transformations [2, 1]. Among the different form factors, sheets are particularly interesting as they form 3D shapes out of 2D structures [4]. Raviv et al. [16] introduced a 3D printed water-responsive material to create a pre-programmable shape-change structure. POPAPY[24] used heat-shrink material to create pop-up toys. Miyashita et al. [7] studied how curved creases in origami can be used to design self-folding propellers. Roboticists also use printing as a way to fabricate foldable structures for soft robots [11, 6]

Computational Design and Fabrication of Inflatables

The field of fabrication-oriented computational design investigates new algorithms to facilitate the design and the fabrication of physical artifacts. Recent approaches include methods for translating functional goals such as appearance [5], deformation behavior [19] or kinematics [25] [3] into fabricatable objects. Closely related to our work are the tools to easily create complex 3D structures out of planar pieces that have been proposed for the design of clothes [21], plush toys [8] and inflatable structures [20].

DESIGN SPACE FOR INFLATABLE SHEET MATERIALS

The heat-sealing method presented in this paper creates programmable hinges that fold when inflated, to be fabricated out of various sheet materials. We introduce below the five dimensions for the digital fabrication of aeroMorph materials that clarify the choices in designing these transforming sheets (Figure 2). Additional details regarding these design dimensions will be provided later in the paper.

Material Library

Coating various materials with thermoplastic polyurethane (TPU) makes them airtight and heat-sealable. We applied this technique for creating airbags to three categories of materials: paper, plastic and fabric. In each category, we tested and quantified three to four specific materials.

Fabrication Methods

We show three fabrication processes to create heat-sealed hinges. *Manual sealing* is simple, does not require expensive hardware, and is best used for quick experimentation and prototyping. *Heat press sealing* offers a way of mass producing identical aeroMorph sheets. *Robotic sealing* can create complicated bending behaviors with high precision.

Inflation Layers

The thin form factor of the sheet materials allows to stack multiple layers without significantly increasing the thickness of the overall composite. With the robotic fabrication process, we can individually seal layers on a stack to create multiple overlapping hinges in one sheet composite.

Airbag Topologies

In this paper, we experimented with three types of complexities for designing pneumatic hinges and their transformations: stripy, square and polygonal. They can be layered to achieve more complex transformations.

Sheet Transformations

Customized aeroMorph offers a variety of design options for creating shape-changing structures as seen in Figure 2. The basic shape-change element is angular folding, which can be aggregated into *curling* and *twisting*. Designers are also able to create *double curved* surfaces by selective sealing from both sides. Micro airbags can be fabricated with extensible materials to create surface *texture change* for haptic sensations. Finally, by arranging the folding directions and angles, designers can create sophisticated origami-like, self-assembling structures.

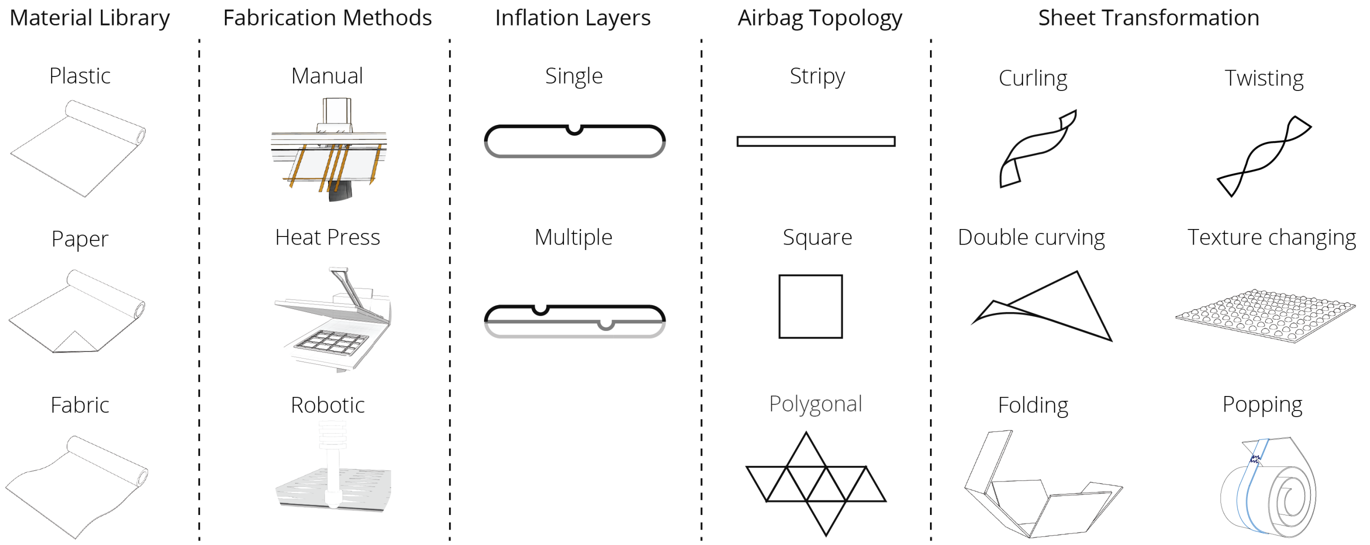


Figure 2. Five-dimensional design space for digital fabrication of custom aeroMorph composites.

DESIGNING INFLATABLE BENDING STRUCTURES

Hinge Mechanism

When a flat airbag, made of a quasi-inextensible material (material with high tensile strength), is inflated, the airbag tends to become spherical, like a balloon. Since the material cannot stretch, the silhouette of the airbag will shrink, implying a compressive deformation of the lateral seams. This deformation is not necessarily uniform and will depend on the original shape of the airbag. With a square shape for example, the seams will curve inwards. If we connect such two airbags on one seam, the structure will bend along that seam, since the seam is common to both airbags and cannot duplicate (Figure 3). The seam will continue to curve, and therefore the hinge to bend, until the volume in the inflatable is maximized. In the following, we describe how to control the bending direction and angle of this hinge structure.

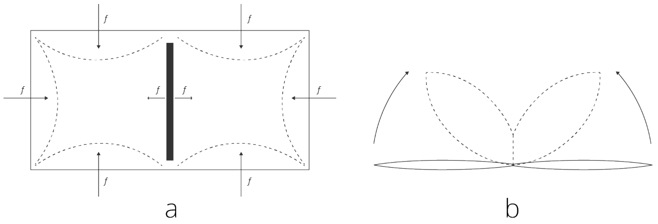


Figure 3. Under inflation, pressure forces make the structure's lateral edges curve inward, causing the composite to bend along the shared seam (Dotted lines indicate final shape). (a) Top view of the airbag deformation. (b) The bending effect caused by the pressure forces.

Bending Angle: We experimented with multiple seam shapes in regard to the repeatability of the bending angle at full inflation and identified three working shapes: line, arc and diamond. As shown in Figure 5, we can vary the dimension of these shapes to control the bending angle. In this paper, we chose to use the diamond shape for angle control, as it creates a stiffer hinge compared to a straight line and allows for a wider range of bending angles than the curved arc hinge since its width/height aspect ratio can be modified (the aspect ratio of the arc is fixed)

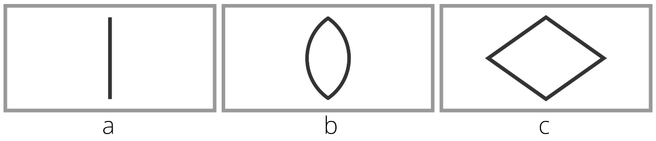


Figure 4. Three hinge shapes can be used to control the airbag bending angle: (a) Line; (b) Arc; (c) Diamond.

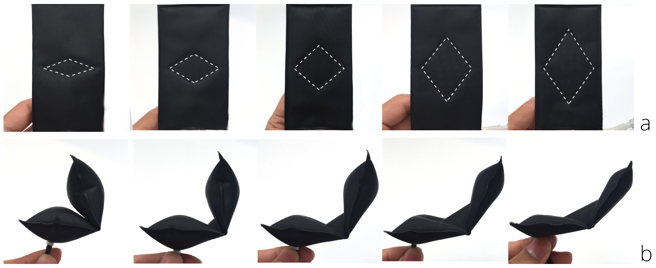


Figure 5. The width/height aspect ratio of the diamond hinge (a) determines the bending angle at full inflation (b).

Bending Direction: In this paper, we focus on airbags and hinges that are fabricated via heat sealing, either manually, robotically or with a heat press. Each of these techniques utilizes heat and mechanical compression to seal two pieces of sheet material, and each sealing process creates a gentle "folding crease", which slightly bends the fabric piece in the direction of the heating element. The bending direction can be controlled by determining from which side the material is sealed. As a heat-sealed hinge is inflated, the (undirected) bending force occurs and the folding crease determines to which side the material bends. This convenient mechanism allows the fabrication of complex self-folding structures similar to origami with its mountain and valley folds. Note that since the bending direction depends on the side on which heat is applied, we need to flip the piece of material during the sealing process to achieve bi-directional bending in the case of multiple layer structures. In addition to sealing orientation, the bending direction can be reinforced by a string to curve the hinge. Figure 6 shows how the curving direction of the hinge determines the bending direction of the airbags.

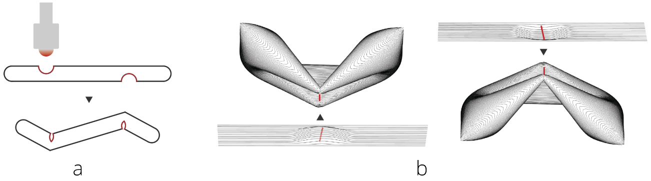


Figure 6. Indentation of the heat seal (a) and a string that slightly bends the hinge (b) can be used to control the bending direction.

Bending Simulation

In order to facilitate the design of seams with defined full inflation angles, we provide a tool that computationally generates hinge-structures, allows the designer to easily adjust the shape of the seams, and simulates the resulting inflated transformation.

Our tool relies on an inflation simulator that decouples the simulation of the airbags from the treatment of the seams. This approach is motivated by two key observations: a) if the pressure inside the airbags is high enough, tension forces dominate the problem and the shape of the airbags is not affected by the deformation of the seams; b) the deformed shapes of the seams are most affected by the material's resistance to compression and can be determined by simple geometric considerations if the shapes of the airbags is known. Therefore, we propose a two step approach in which we first *simulate the inflated shapes* of the airbags by assuming that the sealed seam regions can arbitrarily deform, then *compute the bending angle* corresponding to each hinge using the silhouettes of the inflated airbags. The main stages of our simulator can be summarized as follows:

- The user provides a polygonal mesh describing the topology of the inflatable structure.
- The sealed hinge geometry is created according to the the user specifications (see Control Interface).
- The bags are meshed using Delaunay triangulation [18] and inflated in the unfolded state using the method of Skouras et. al. [20].
- The bags are successively rotated so as to preserve the initial widths of the seams.

Airbags Simulation: We use the model of Skouras et al. [20] that relies on a relaxed energy formulation to compute the shapes of the airbags. Since the airbags are made of two identical panels, their inflated shapes will exhibit mirror symmetry. We first remove the faces corresponding to the seam geometry and compute the inflated shape of the airbags by assuming that their contours remain on this symmetry plane. Once the bags are simulated, we compute the maximal distance d between the two sides of each seam and use this value to estimate the bending angle of the hinge as described next.

Bending Angle Calculation: Rotating two airbags along a line connecting their two common vertices does not change their shapes but affects the shape of the common seam region. Since this seam is made of an inextensible material, the larger distance between its two sides cannot exceed the initial width w of the seam. Moreover, since the seam material generally resists bending, resisting forces will appear if the distance between the two sides is below the initial width of the seam. This implies that the angle θ between the two airbags is the one that exactly preserves the initial width of the seam (Figure 7). This angle can be analytically derived from the law of cosines as:

$$\theta = acos(\frac{a^2+b^2-w^2}{2ab}) \tag{1}$$

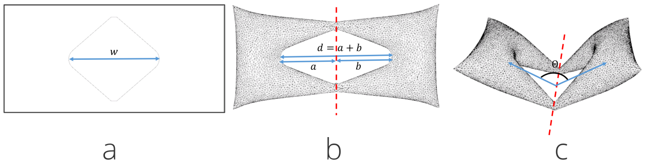


Figure 7. The width of the hinge diamond stays constant when the structure is inflated, causing the material to bend.

Note that the bending angle is affected by multiple factors in addition to the aspect ratio of the hinge (Figure 8). The bending angle is a function of the distance between the two sides of the seam, and this value is directly related to the amount of shrinkage of the contours of the bags, which is turns depends on the shapes and sizes of the bags: shapes that allow for a larger expansion of the bags, i.e. a larger increase in volume, will have a contour that shrinks more and hence create smaller angles, i.e hinges that bend more.

This algorithm is not restricted to two chamber structures and can be applied to simulate arbitrarily chained hinges as long as they do not form closed loops. We used it to simulate all the rendered results presented in this paper.

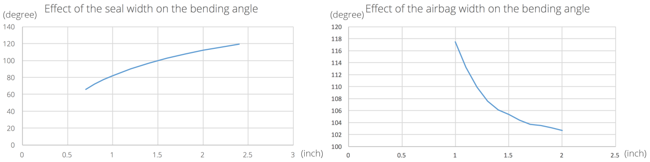
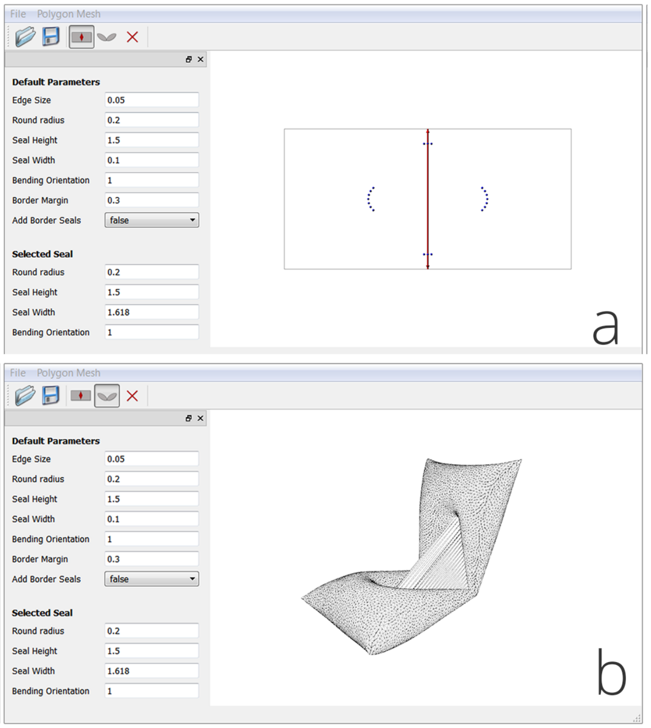


Figure 8. The sealed seam's width and the airbag's width affect the bending angle of an aeroMorph inflatable.

Control Interface

Our design tool exposes a control interface that allows the user to import a polygonal mesh representing the contours of the airbags and the locations of the seams. The system automatically replaces each internal edge of the mesh with one or several diamond-shaped seams whose dimensions can be specified by the user (height, width, and radius of the round can be controlled). A flag indicating whether the seam will bend in the convex or concave direction can also be set (Figure 9). Once the user has finished sizing the seams, s/he can launch the simulation of the inflatable structure. The seams can be edited and the simulation can be run as many times as desired. When the user is satisfied with the results, s/hen can export the final 2D-layout in dxf format that can be used to instruct most CNC-machines.



Default Parameters

Edge Size 0.05
Round radius 0.2
Seal Height 1.5
Seal Width 0.1
Bending Orientation 1
Border Margin 0.3
Add Border Seals false

Selected Seal

Round radius 0.2
Seal Height 1.5
Seal Width 1.618
Bending Orientation 1

Default Parameters

Edge Size 0.05
Round radius 0.2
Seal Height 1.5
Seal Width 0.1
Bending Orientation 1
Border Margin 0.3
Add Border Seals false

Selected Seal

Round radius 0.2
Seal Height 1.5
Seal Width 1.618
Bending Orientation 1

Figure 9. Our simulation tool allows the user to design hinge shapes of desired dimensions (a) and simulates the bending transformation of the resulting aeroMorph structure (b).

Pneumatic System

For the prototypes of all the following applications, we used the pneumatics platform Pneuduino (www.pneuduino.org). Pneuduino is a modular system that combines two solenoid valves and an air pressure sensor to enable programmatic, closed-loop control of small to medium sized airbags. Each module has two valves that can be either used for individual airbags or combined for more sophisticated control of one airbag. We used a stationary air compressor (available on www.silentaire.com) to generate the air pressure. Since our samples are relatively small, we used 1/8" thick tube and connectors (available on www.mcmaster.com) to channel the air.

SHEET TRANSFORMATIONS

By using the hinge mechanism described earlier, we are able to create a variety of compound transformations. We identified the following categories:

Stripe Curling and Twisting: Our approach can create strips that bend and curl as demonstrated in the paper PneUI [23], but without going through the compositing and molding/casting process (Figure 10) . It also allows us to create strips that have hinges bending in alternate directions enabling serpentine and helix shapes (Figure 11.b-c) .

Figure 10. Given an encoded composite (a), our simulator is used to predict the inflated shape of the structure (b), which is in close agreement with the actual physical performance of the fabricated artifact (c).

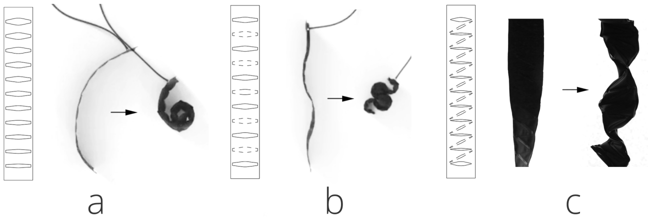


Figure 11. Different kinds of strip transformation can be encoded: (a) Gradient curling; (b) Serpentine curling; (c) Twisting.

Stripe Loop Morphing: One can fabricate a double-layer airbag stripe, with the head and tail connected via manual sealing, forming a closed loop. By using a different number of hinges for the two layers, different shapes can be achieved. The inner layer may have four hinges and therefore would form a rectangular shape when inflated, while the outer layer may have three hinges and therefore would form a triangle on inflation. The resulting composite can morph between the two shapes as the corresponding air pressure changes (Figure 12).

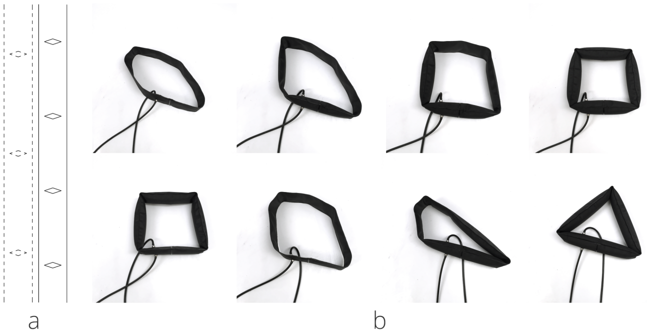


Figure 12. A closed ring strip can transform between rectangular and triangular contours. (a) The multilayer design. (b) The Transformation process.

Square Surface Curving: A square sheet can be covered with an array of diamond shaped hinges to create a surface with controllable curvature (Figure 13). The aspect ratio of the hinges can be tuned to set the bending orientation of the sheet (left-right or top-bottom), as the hinge always bends along the longer side of the diamond. A diamond with the aspect ratio 1 results in a hyperbolic surface (Figure 14.b-c). The size of the diamond tunes the curvature of the surface.

It is worthwhile to note that the hinges need to be chained in parallel in order to get the desired bending orientation because the bending of the hinge itself will accumulate to a large surface deformation. In the simulation we took this into consideration by computing the bending angle for each seam of the hinge independently using the formula above and keeping the smallest value for the rotation of the adjacent airbags, since this guarantees that no seam of the hinge will be stretched. Note that in practice the angle variation caused by multiple seam of a common hinge remains limited.

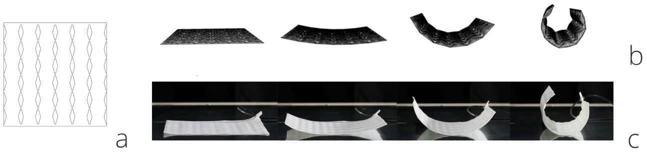


Figure 13. Surfaces can be encoded with a curling behavior. (a) User-specified initial layout for the square surface. (b) Simulated transformation. (c) Transformation of the fabricated artifact.

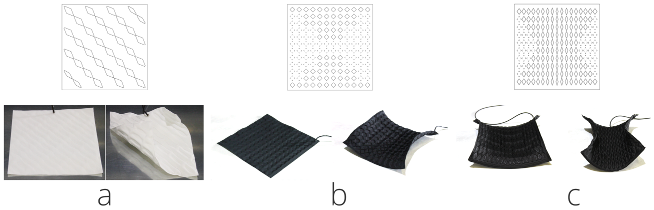


Figure 14. Different surface curvatures are possible, such as: (a) Diagonal curling; (b) Hyperbolic surface; (c) Hyperbolic surface with tunable curvature.

Square Texture Changing: A dynamic surface texture can be created by sealing two pieces of fabric together with an array of small cross-shape hinges (Figure 15). While this method works with all three materials, we found it works best with fabric, especially if one sheet is more extensible. The repetitive texture pattern is ideally created with a custom stencil and the heat press sealing method, which will be explained in more detail later.

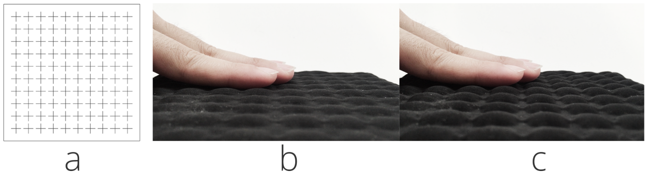


Figure 15. By creating micro identical circular airbags surface texture-change can be created. (a) The design of the hinge. (b-c) Fabricated artifacts.

Polygonal Self-folding: Since the bending direction and the angle of the inflated materials are controllable, we explored the use of this technique to create three-dimensional objects that can fold and unfold. For this paper, we created three 3D polyhedra. We can also create more sophisticated shapes with this geometric folding mechanism (Figures 16, 17).

Polygonal Popping: One advantage of the pneumatically-driven shape-change mechanism is the high actuation force.

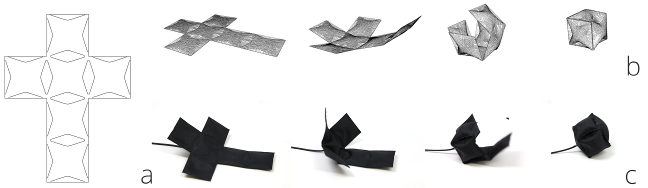


Figure 16. More complex seam patterns can be used to create self-folding polyhedra from flat sheets. Shown here are: (a) The design layout for a cube; (b) The corresponding simulated result; (c) The actual physical performance of the cube.

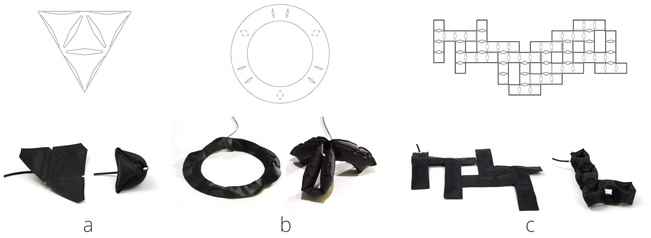


Figure 17. A variety of self-folding transformations can be achieved, including: (a) A tetrahedron; (b) A folding ring; (c) A sophisticated connected cube structure.

After folding an aeroMorph sheet with encoded transformations into a compact, mechanically constrained shape, the pneumatic force will make it pop into its transformed state explosively when the internal stresses of the constraining strip exceed the tensile strength of the material. Figure 18 shows one aeroMorph sheet folded into a small volume and taped tightly together. When inflated, the material pops up and forms two connected cubes.

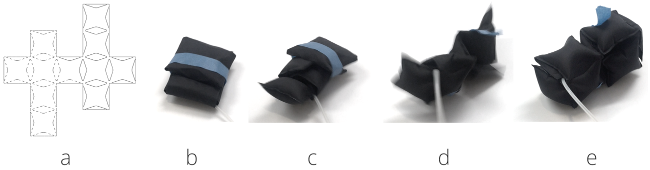


Figure 18. By using mechanical constraints (b, c), more explosive, popping transformations can be achieved (d, e).

Mechanical Test

While actuating sheet materials attracts a lot of attention in HCI, the actuation force is usually low compared to what one gets with electromagnetic motors. We examined the bending force of aeroMorph composites and found that the actuation force (torque) of the pneumatic hinge structure can be comparable to electromagnetic components, depending on the air pressure and the type of material used for the airbag.

For our force-test we used TPU coated Nylon fabric (available on www.rockywood.com). The sample was 2" wide and 4" long and clamped by a 4" by 4" U-shape aluminum plate on the edge. The plate serves as the pushing area for the test. The tests were executed with an Instron force measuring system with controllable air supply to the airbag. The measure results in Figure 19 show the torque increasing with the air pressure. We believe with stiffer materials like ABS, higher torques can be achieved under similar conditions.

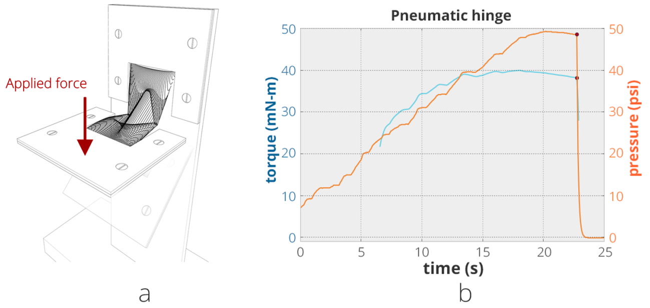


Figure 19. The torque of the pneumatic hinge rises with the air pressure until the material breaking point is reached.

FABRICATION PROCESS

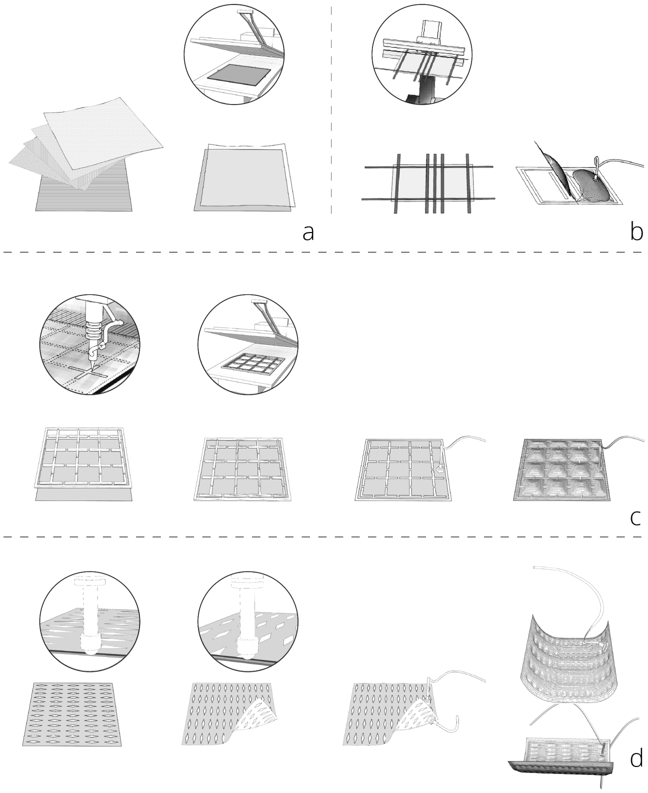


Figure 20. Coating the materials with TPU (a) enables three fabrication methods: (b) Manual sealing; (c) Heat press sealing; (d) Robotic sealing. (The circle indicates the equipments that was used for the particular method).

After the user has designed and simulated the shape of the airbags and hinges, the design has to be realized. This section explains the different fabrication methods that we developed for aeroMorph. After the materials are prepared (coating) (Figure 20.a), the designer can choose among three techniques to fabricate them (sealing). Three sealing methods are introduced: *manual*, *heat press* and *robotic* (Figure 20.b,c,d).

Coating Material

Thermoplastic polyurethane (TPU) is a type of thermoplastic elastomer that has been used as a fabric coating material in the textile industry for over 30 years. The hot melt film (available on perfectex.com) is airtight and has a versatile bonding ability that vastly expands the catalog of materials for inflatables. We used it to coat on 11 types of inextensible paper, plastics and fabrics (Figure 21). Our experience with this fabrication step indicates that this library could be easily extended to more materials. The coating process is done by ironing or heat pressing the material and TPU for 60 seconds at 260 °F . Once coated in TPU, the composite can be easily sealed with other sheets to create airbags and hinges. Compared to silicone based inflating materials and techniques, the TPU provides an instant, clean, and convenient lamination process for creating inflatables.

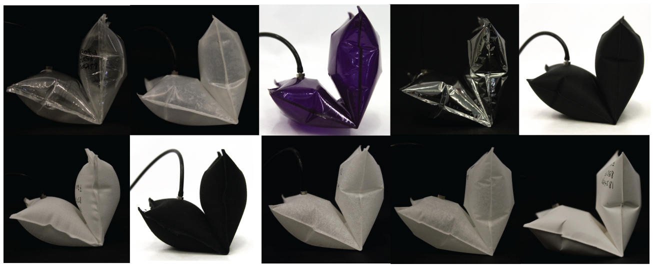


Figure 21. A wide variety of materials can be used for aeroMorph composites.

Manual Sealing

The quickest way of creating seals is manual sealing, which can be done with a commercially available heat sealer (www.mcmaster.com). As Figure 22 demonstrates, the full fabrication process includes: a) drawing the design on the fabric; b) cutting and taping copper stripes (dissipating the heat) to cover areas that should not be sealed (air channels); c) sealing the fabric based on the design (when inflated, the airbags will fold towards the side that is in contact with the heating element); d) placing a connector in one of the air chambers; e) inflating and testing the design.

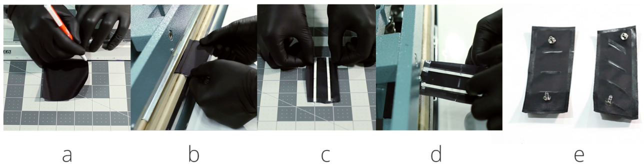


Figure 22. Manual fabrication with a heat sealer and copper tape.

Compared to the other two methods, manual sealing is easy to access, and fast for rough materials and bending angles testing. We successfully used it in multiple workshops as the equipment is relatively cheap. However, sealing more complicated hinges can become labor-intensive.

Heat Press Sealing

By creating a metal stencil with a CNC-mill or water jet cutter, we can use a heat press to create airbags (Figure 23). We mostly used a water jet cutter because it accurately cuts hinge shapes and etches air channels faster than a CNC-router. In our experiments, we used $\frac{1}{4}$" thick aluminum for the stencil. The etching depth is half of the thickness. The heat pressing time for sealing is 10 seconds at 260 °F. Thinner stencils or

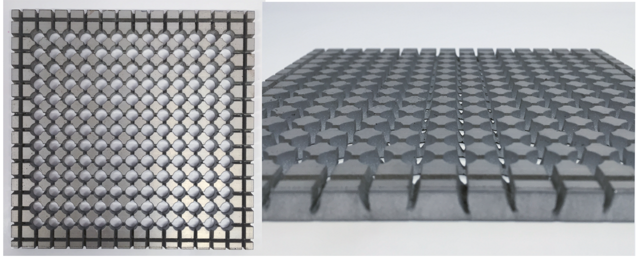


Figure 23. Heat press fabrication requires custom aluminum stencils (here made with water jet cutting and etching).

longer heating times might over-seal the material and block the air channels.

This method is particularly convenient to create repetitive patterns for surface texture-changes and mass producing transforming materials. The drawback is the material cost of the stencil which makes iterating expensive.

Robotic Sealing

Inspired by the 3-axis CNC sealing machine introduced in Sticky Actuators [12], we created a larger scale robotic sealing platform that allows one to seal a 36" by 36" sheet (Figure 24). With a re-designed sealing head and damping mechanism, the platform also allows the user to change the heating head to a knife module to precisely cut out the outer seam of the design (Figure 25, 26).

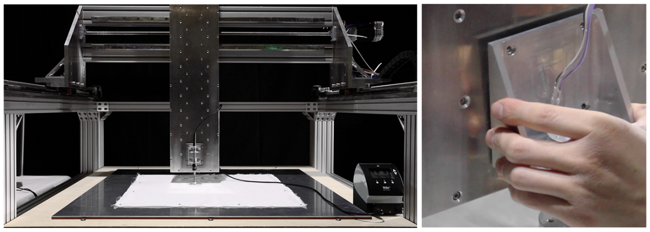


Figure 24. Our custom CNC router (a) has a modular design for tool head changes (b).

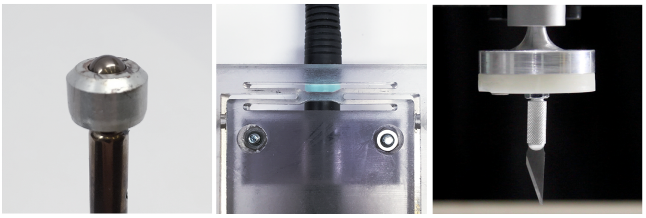


Figure 25. The sealer uses a ball transfer (a) and dampens the tool head at the pen holder (b). The tool head can be changed to be a knife for cutting sealed material (c).

For the sealing head we connected a metal ball transfer (ball diameter $\frac{1}{4}$") to a temperature variable soldering iron. The ball transfer enables smooth omnidirectional movement without causing wrinkles when sealing. We also designed a 3D printed mounting component with a spring to smooth out the sealing force if the surface is bumpy. Finally, since the platform is designed to be a modular system, we made a knife module that can be attached for the final cutout. While we used these techniques on a custom CNC machine, the modules can be easily adapted for use with robotic arms or other CNC routers.

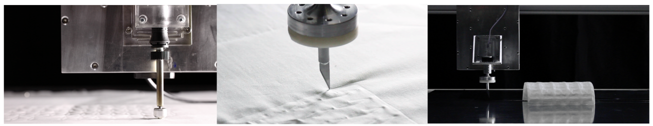


Figure 26. The robotic sealing steps are: (a) Sealing; (b) Cutting; (c) Inflating.

The robotic sealing system provides versatile and precise sealing capabilities. Similar to a laser cutter, we can tune the sealing parameters (pressing steps, sealing speed and temperature) to seal different materials without burning the material surface. The detailed parameter setup is provided in Figure 27. We can also seal multiple airbags layer by layer by tuning the machine to only seal the top two layers of the material stack. We used this method to fabricate the double layer inflation examples in the paper.

	Pressing distance (mm)	Sealing Speed (mm/min)	Sealing Temperature (F)
Polyethylene film	0.8	400	750
ABS film	1.5	300	720
Cellophane	1.5	300	850
Mylar	1.5	300	800
Nylon	0.8	250	720
Doub layer of Nylon	1.2 (1st layer)	100 (1st layer)	850 (1stlayer)
	0.6 (2nd layer)	300 (2nd layer)	850 (2nd layer)
Cotton fabric	1.5	300	850
Rayon Challis	1.0	300	850
Leather	good for heat press, not suitable for robotic sealing		
China paper	1.8	300	850
Tracing paper	1.5	700	850
Sketch paper (210g)	1.5	200	850

Figure 27. Sealing parameters for different materials using our robotic sealing system.

AIR AS SENSOR

As shown in previous research on soft robots, air pressure can be used to sense the amplitude of the shape-change [9]. Research in soft pneumatic interfaces showed how air pressure can be used to sense external shape-deformation [23, 22] and even infer a range of human interactions [23, 10]. For each of these applications, the materials used are a decisive factor for the quality of the sensor data. Thus, the choice of materials is not just important for the desired shape-change but also for the intended sensing applications. When trying to infer shape-transformations from air pressure, the material property that influences the data-quality the most is material stretchability.

When inflating a quasi-inextensible material, air pressure can be used to infer whether the full shape-actuation has been obtained, as can be seen in Figure 28. Only when the air inside the material fills the chamber to full volume does the air pressure increase. Any increase in the air pressure only marginally changes the shape of the airbag.

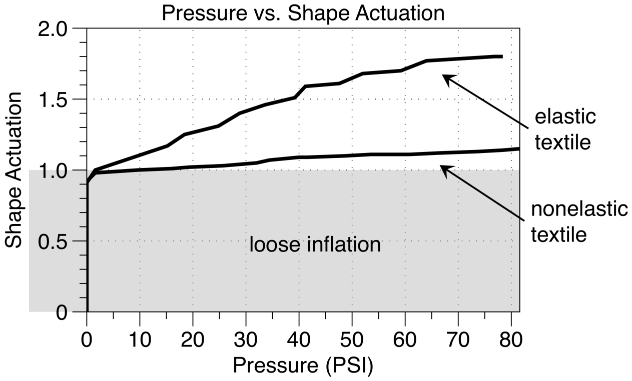


Figure 28. When using extensible fabric, the air pressure varies linearly with the amplitude of shape-actuation. This allows for more precise actuation control than with nonelastic fabric

Stretchy material structures showcase two stages of inflation with different sensing qualities. The first stage is identical to the one of the inextensible structure, in which the air pressure rises once the loose inflation volume is filled. In the following second stage, the extensible material increasingly stretches with the rising pressure. Hence, the amplitude of actuation can be computationally controlled.

For both extensible and inextensible fabrics, external shape-deformation can be sensed as soon as there is some air in the chamber. However, the sensing quality increases with the air pressure. We use the absolute pressure sensors (MPXHZ6400 and MPX5700ASX) to read the air pressure and an Arduino-based custom board to interpret the data and trigger pneumatic valves.

APPLICATIONS

Shape-change Packaging

Air cushions are widely used to protect fragile items during shipping. Using the ability of aeroMorph to create folds with and without large cushion structures (depending on the density of the hinges), we designed a light bulb packaging that can transform from a 6-sided box cushion to a curled lampshade (Figure 29).

We designed the curling behavior for the lamp by analysing its geometric properties. In particular, we observed that any 2D polygon that can be bent isometrically into a closed surface can be considered as a piece of a developed conic surface (Figure 30). This property enables an easy way to define the bending lines of a polygonal mesh that we can feed into our simulation tool to generate hinges with proper angles (Figure 31).

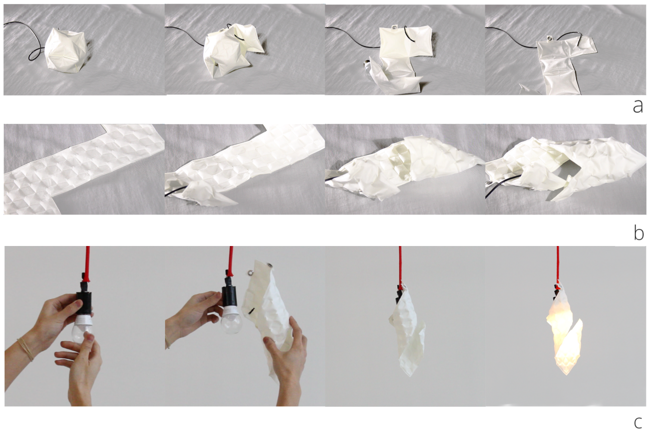


Figure 29. This shape-changing light bulb package has two functions: air cushion for transport (a) and lamp shade (c), between which it can morph (b).

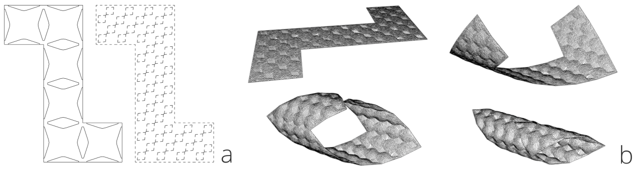


Figure 30. (a) The hinge design of the double layer structure. (b) Simulation of the lampshade folding.

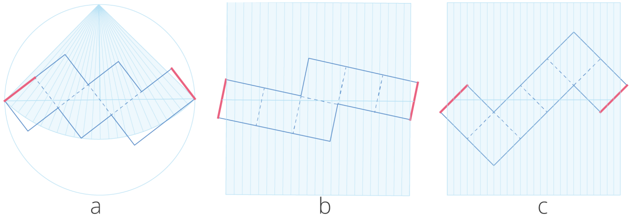


Figure 31. A cube can be unfolded into different connected squares. They all can be re-formed into a conical or cylindrical shape. In our application, the shape C is selected for aesthetic reasons.

The material used is TPU coated china paper. The three-stage shape-change is created by the multi-layer sealing method we outlined earlier.

Interactive Crane

Inspired by prior work [17], we designed a fabric crane that folds from a flat sheet to its 3D end shape. As Figure 33 shows, the crane has one air chamber for the base and two for each wing. They all inflate at the same time when the system is activated (Figures 32, 33). Once the crane has transformed, squeezing the tail/body/head can program the wings to flap (inflate and deflate) in a recorded rhythm similar to Topobo [15]. The system records the air pressure change at the body and plays it back on the wings.

Haptic Gloves

To demonstrate the application of texture change on fabric, we prototyped a pair of haptic gloves for biking. The gloves

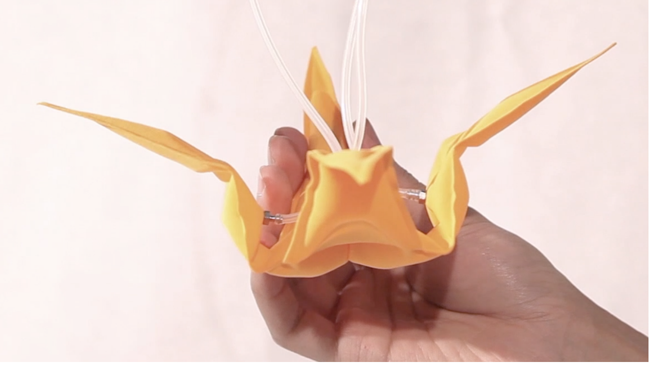


Figure 32. Self-folding crane. Squeezing the tail records a flapping rhythm that is played back through the wings.

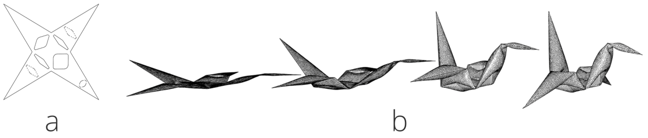


Figure 33. Self-folding crane. (a) The design of hinges. (b) The simulation of the transformation.

Figure 34. Biking gloves with changing surface texture on the palm. Gloves are made with cotton fabric.

contain small air chambers on the palm side and are controlled by a single air source (Figure 34). When inflated, the bumpy surface creates a strong haptic sensation to help the cyclist navigate without taking their smartphone out: the left glove inflates to turn left, the right glove inflates to turn right.

These gloves can also serve as a pressure sensor if the user squeezes their hand. We connected the gloves to the two turning lights at the end of the bike handlebars. When one hand squeezes, the light on the same side blinks bright white to indicate the turning. When both hands squeeze, the lights on both sides turn red to indicate braking (Figure 35).

Figure 35. (a) Gloves change the texture to indicate directions; (b) Squeezing one hand to light up the turning light; (c) Squeezing both hand to light up deceleration light.

DISCUSSION & FUTURE WORK

We have presented a design, simulation, and fabrication pipeline to create transformable plastic, paper, and fabric, enabled by pneumatic inflation. As demonstrated by our results, our universal bending mechanism can be used to create multiple shape-changing behaviors in a programmable way with several potential applications. Nevertheless, as discussed below, our system has some limitations and offers many exciting opportunities for future work.

Simulation

Our simulator currently assumes that the folded geometry of the inflatables can be estimated by computing the shapes of the airbags and the bending angles separately. While this works for structures without closed loops of airbags, simulating inflatables with arbitrary topology will require a simultaneous treatment of the bags and angles. We leave such a treatment as future work. Another interesting extension would be to combine the simulation with an optimization component that automatically adjusts the parameters of the seams in order to match target angles set by the user.

Fabrication

We are looking for new fabrication processes that can better encode the bending direction of the aeroMorph. Based on our experience, adding strings to the hinges will guarantee the correct bending direction. In the future, we would like to integrate that process in the fabrication. Beyond that, we are looking at how to control the inflation sequence by varying the hinge geometry, without affecting much the bending angle. We are also interested in adding a material feeding mechanism to the build platform. In the future, the machine should be able to work on long rolls of aeroMorph rather than just one square piece.

Material & Mass Production

As we mentioned above, the aeroMorph bending mechanism works across different inextensible materials. In the future, we would like to continue expanding the material library, and also to explore sealing methods beyond heat. How can we create inflatable metal sheets with programmable transformations? How to design new wearable fabrics that are encoded with shape-changes? Along that line, we would also like to see how this mechanism can be developed to meet the industrial roll-to-roll production standard, so that in the future, people can directly buy these transforming sheets off-the-shelf.

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