Awakened Apparel: Embedded Soft Actuators for Expressive Fashion and Functional Garments

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ABSTRACT
Each morning we select an outfit meant to suit our mood and our plans. What if our clothes could seamlessly morph with us as our attitudes and activities change throughout the day? We created Awakened Apparel; one of the first shape-changing fashions to employ pneumatically actuated origami. Our prototype draws from diverse disciplines including soft robotics and fashion to present a design vision that advances the growing field of dynamic interactive garments. We explore technical and fabrication approaches for shape-changing technology held close to the body and identify areas for further innovation.

Author Keywords
Interactive fashion; origami, pneumatics; soft mechanisms

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous

INTRODUCTION
Fashion is closely tied to identity and functionality. Our clothes affect our feelings and express them to the world—we put on loose pajamas when we need to be comforted and dress up in tailored suits for job interviews. They also can constrain or empower us—a bulky winter jacket protects us from the cold while a tight skirt inhibits our ability to walk.

Yet interaction with our clothing is limited—beyond the functionality offered by zippers and buttons, few garments fundamentally change their function and aesthetic.

As part of our design vision for the future of transformable clothing we created **Awakened Apparel—a pneumatic folding, shape-changing skirt** that is both aesthetically pleasing and functional. This work draws on diverse research in soft robotics, folding, and fashion.

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BACKGROUND
Pneumatically actuated shape-changing objects have been developed most recently in the field of **soft robotics**. Key research in this area [7,12] combines the varying material properties of stretchy membranes (e.g. silicone) and non-stretchy membranes (e.g. inextensible fabric or paper) to create inflatable actuators that bend in a prescribed direction [14]. The natural flexibility of fabric particularly befits this developing field of soft-bodied robotic actuators, such as OtherLab's Ant-Roach Pneubot [4].

Shape-changing garments have used many forms of actuation technology to transform: from electronically activated smart-memory alloy wire to inflatable actuation [3,11]. Garments such as Diana Eng's Inflatable Collar [11] use plastic air bladders encased in a fabric covering to create clothing that transforms shape while being worn. Ying Gao's Walking City dresses [11] use origami folds in the fabric to give additional structure to the inflated shape.

Awakened apparel builds on advances in **soft robotics** and **transformable fashion** by fusing **pneumatics and folding with garment design** to create aesthetically and tactilely pleasing **shape-changing mechanisms for clothes.**

MOTIVATION
What does a future of interactive shape-changing fashion offer us? Fashion's close connection to both identity and functionality affords many possible triggers for interaction—from changes in weather [11], to altered emotional circumstance [11], to safety concerns [6].

In this future of shape-changing clothing, a single garment can embody several functional states. Awakened Apparel presents a shape-changing skirt as an **inspirational storyline** that spans some of the use cases for shape-changing clothing. Motivations for state transitions can be:

- **informational**: acts as an ambient device [13] conveying abstracted information about the self or the world; e.g. shorter length with positive stock market performance [2]
- **emotional:** reacts to the emotion or situation of the wearer; e.g. more conservative under unwanted attention
- **functional:** allows the user to perform specific tasks, preserve safety, or maintain comfort, e.g. bicycle riding

Figure 1: Vision sketch of skirt in its many forms

SOFT MECHANISMS FOR SHAPE-CHANGING FASHION

Mechanism, materials and actuation

With the design storyline and values defined, we provisionally tested mechanisms, materials, and actuations that satisfy these constraints in order to determine the primary path of fabrication. Our work adds to this fruitful research space by **combining pneumatics, folding, and aesthetics** with the exploration of **suitable materials and actuation** in order to create a novel mechanism for **shape changing clothing**.

Pneumatic folding was selected over scissor linkages, nitinol wire [3], drawstrings, direct material folding [11] and other more traditional mechanical approaches to size and shape changing. Origami served as a basis for geometric construction; though other mechanisms can be very attractive [1], origami's thin form factor more closely satisfies the design values required for fashion garments, while pneumatics offer an organic and subtle shape change.

Materials must be carefully considered in developing shape-changing garments. Transformable fashion presents constraints not often found in mechanism design, as clothing must feel human, move with the body, and look pleasant. In order to ensure that Awakened Apparel remains wearable, materials used must be within the range of typical clothing in their:

- **Texture**: limit unpleasant textures such as extreme stiffness, sliminess, metal; use fabric whenever possible
- **Aesthetic**: colors must be pleasing and piece assembled to be complementary
- **Robustness**: materials must not be excessively fragile or unsuited to daily life

Mechanical actuation was selected over electronic in order to fit with the design goal, since it limits hard fragile parts and creates an intuitive and immediate interaction. In this demonstration, a foot operated pump eliminates the need for bulky batteries or tethered power supply. In the future, electronic pneumatic actuation will be achievable using advancements in soft robust electronics that will be incorporated into our design to provide precise airflow control and shape-changing detail.

PNEUMATIC FOLDING MECHANISM

Experimentation: origami pattern design

Design of the base origami pattern for the shape-changing skirt was informed by the following parameters:

1. Naturally curve around the body when folded
2. Decrease in length and width when folded
3. Simple enough for repeatable construction

Early designs were based on the **Miura fold**, a simple non-orthogonal fold that can create up to 90% vertical and horizontal size change [8]. We also tested the **spiral pinecone fold** pattern [9], a conical shape that can decrease in length by 80% when compressed. Exact design dimensions were tested in paper to optimize the shape-changing effect and aesthetic. The Miura fold satisfied design parameters 2 & 3 and the spiral pinecone fold satisfied parameters 1 & 2 but neither performed all desired functions, leading us to develop a combined design. Select geometric pattern experiments are shown in Figure 2.

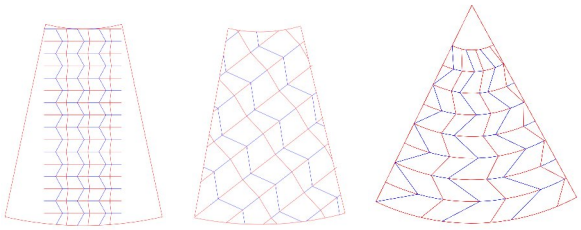

Figure 2: Origami pattern experimentation

An A-line skirt was selected as the primary form as it satisfies the design values and technical constraints: it has a pleasant aesthetic, is simple in form, and contains enough surface area to allow for versatility.

Experimentation: pneumatic folding & textiles

We tested several approaches to inflation-based folding and assessed them based on the following parameters:

1. Maximization of shape-changing effect
2. Allows mechanical inflation through hand or foot pump
3. Alignment with material design values (texture, aesthetic, robustness)

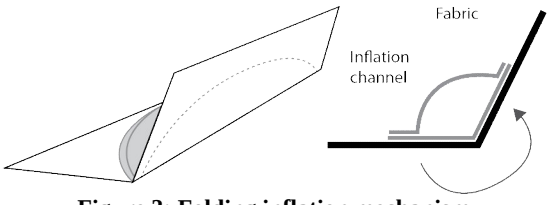

Figure 3: Folding inflation mechanism

Using inspiration from soft robotics mechanisms [12], initial experimentation into creating pneumatically actuated textiles showed that fusing a **long rhombus-shaped inflation channel** to one side of a piece of fabric caused it to bend towards the channel when inflated. The limited deformation in the inextensible fabric, combined with the greater moment force at the mid-length corners, causes the textile to fold towards the side of the more extensible

inflation channel. This inflation folding mechanism is visualized in Figure 3 and applied in further investigations.

Material explorations first built on soft robotics techniques [7] by casting **silicone inflation** pockets directly to the garment fabric. This method led to flexible pockets that were easily inflated and could fold over 40^{o} from their flat deflated state (Figure 4). However, due to the thinness of the silicone layers the approach was deemed insufficiently repeatable and durable to meet the design goals.

A more successful technique was **heat-sealing plasticized sheet materials** and fusing them to fabric. Layers of Mylar polyester film and paper fuse the Mylar edges when ironed, leaving an airtight inflation channel in the shape of the paper layer. This inflation channel is affixed directly to the fabric using double-sided fabric fusing material.

Figure 4: Select pneumatic experiments: silicon (L); Mylar (R)

FINAL DESIGN

The final design for the Awakened Apparel pneumatic folding skirt incorporates the following elements:

- A body-fitting shape created from a **modified Miura fold origami pattern** that curves when folded.
- **Heat-fused, laminated Mylar inflation channels** embedded into the fabric of the garment.
- Shape-change throughout the skirt generated from the **multi-sided mountain and valley inflation channels** and activated through use of a single foot-pump.
- **Unique aesthetic** inspired by the underlying origami pattern and a **clothing-appropriate texture**.

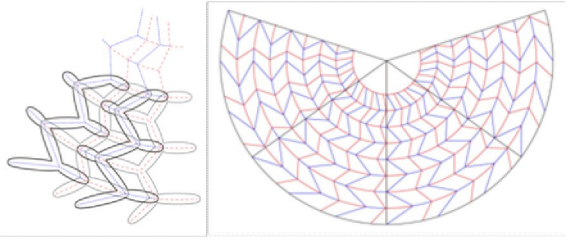

Figure 5: Inflation folding pattern—red channels are affixed to the underside of the fabric, blue to the topside

The **final origami pattern is based on a Miura fold** with curved radial fold lines, and varying angled vertical fold lines (Figure 5). The 'mountain' folds (undersides fold together) have angles 30-110% greater than the 'valley' folds (topsides fold together). This results in a curving conical shape, which decreases in length by over 90% and increases in curvature by up to 40% when folded. The simple repeated pattern enables easier construction.

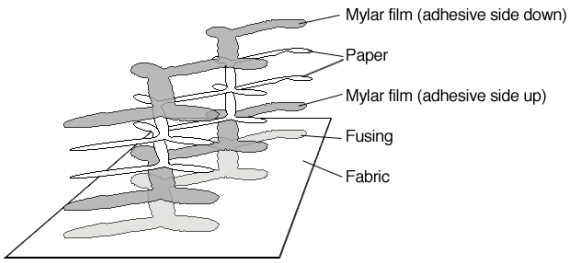

Figure 6: Inflation channel layers heat-sealed in fabrication

Heat-fused laminated Mylar inflation channels (Figure 6) satisfy all of the approach parameters as it provides a reasonable level of shape-change when inflated by foot-pump (folding up to 23^{o}), is repeatable and robust, and provides an acceptable softness and pleasing aesthetic.

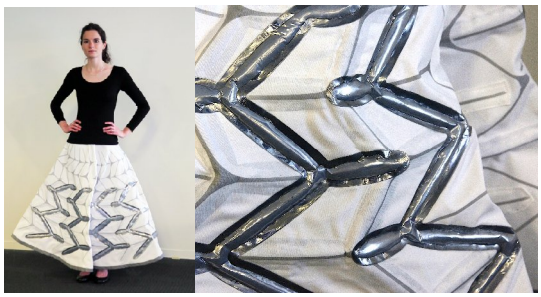

Figure 7: Final Awakened Apparel prototype

Figure 7 shows the **modified Miura origami** used with **heat-fused laminated Mylar channels**. Due to the single folding direction when inflated, the alternating mountain and valley fold inflation sections were distributed on the underside and topside of the fabric respectively to create the alternating directions of folding.

For maximum robustness, each air channel had its own inlet and is connected to the **foot pump via a tubing system** in the top of the skirt.

DISCUSSION

We created Awakened Apparel, a **pneumatic folding skirt** that values **aesthetics** and **functionality**, serves to motivate **material explorations**, and defines key dimensions for future **shape-changing fashion**.

Design goals, including material texture, aesthetic, and robustness were largely achieved. The piece was constructed primarily of clothing fabric paired with small sections of Mylar film that slightly increased material stiffness but were not offensively unpleasant. Texture could be further improved by limiting tubing sections used to connect skirt to the foot-pump. Careful selection of skirt form and colors—inspired by architectural examples and stormy sky palate suggested by pneumatic actuation—led to a fitting aesthetic. Materials displayed acceptable robustness, and automation of the assembly process would minimize leakage caused by human error. Satisfaction of the design goals lead to a truly wearable garment that serves as an initial embodiment of our vision.

LIMITATIONS

Basic actuation was achieved within the constraints of the design parameters, though further development is required to reach the full desired effect. Pneumatic folding was highly successful on small samples (up to 40% curvature increase), but the weight of the overall garment limited movement in the larger piece (8% curvature increase; 8% length contraction). Further work to improve the extent and detail of this shape-changing technology will explore additional techniques from soft robotics such as lighter materials, improved geometries, and soft electro-pneumatic control systems [4].

FUTURE WORK

A second prototype, which embodies the full storyline of our vision (Figure 1) and implements transitions between the various expressive states, remains as future, yet fully achievable, work. Currently, pneumatic actuation operates through a foot-pump and depends on manual intervention by the user. Through **future addition of electronics**—e.g. bluetooth, basic sensors—we will be able to acquire the information needed to make our vision of more fluidly responsive clothing a reality. Information-based transitions can rely on readily available open-source APIs to access data such as stock market results or weather conditions to transform clothing into an ambient device. As the field of affective computing advances, sensors could be incorporated into the design to achieve emotion-based transitions [5, 10]. Functional changes will be situational or temporal by calling on GPS location or time of day. They could also remain mechanical, controlled exclusively and unobtrusively by the user. Our vision for interaction serves as a launching point for further collaboration with the HCI community on shape-changing fashion.

CONCLUSION

Awakened Apparel is one of the **early examples of fully embedded, pneumatically folding, shape-changing fashion.** It draws on diverse fields to propose a framework for creating shape-changing garments that fuse the pleasing aesthetics of fashion with the functional inflation technologies of soft robotics. Awakened Apparel uses materials suited to the body and an inflatable structural design to truly embed shape-changing actuation into the fabrics we use in our everyday clothing. We hope our prototypes and design vision can serve as a launching point for future work in this multidisciplinary area of embedded textile actuators for expressive and functional shape-changing garments.

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