Folding Fabric: Fashion from Origami

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Abstract

This paper showcases some of the works in my origami fashion portfolio, which includes concepts like flat-foldability, bistability, and the Fibonacci sequence. It discusses the techniques I use for creating origami using fabric (adding rigid panels and heatsetting) and how I manipulate patterns to incorporate origami in garment construction.

Introduction

Folding has been a part of fashion for centuries, as evidenced by pleated skirts and ruffled gowns, so it is unsurprising that designers would eventually bring origami directly into the world of fashion design. Dior, Calvin Klein, and Guess have all produced collections that incorporated origami looks [8, 12, 2], but perhaps the designer most notable for creating origami fashion is Issey Miyake [4]. Fashion loves the juxtaposition of extremes. The idea that origami, a type of sculpture made from the fragile medium of paper, could be translated to something wearable and durable in fashion is certainly intriguing. For me, my expertise lies more with origami design than fashion design, so my approach to origami fashion comes from the perspective of an origami artist instead of a fashion designer. I wanted to give my artwork functionality, and fashion is one application of origami that still allows me to be creative and expressive.

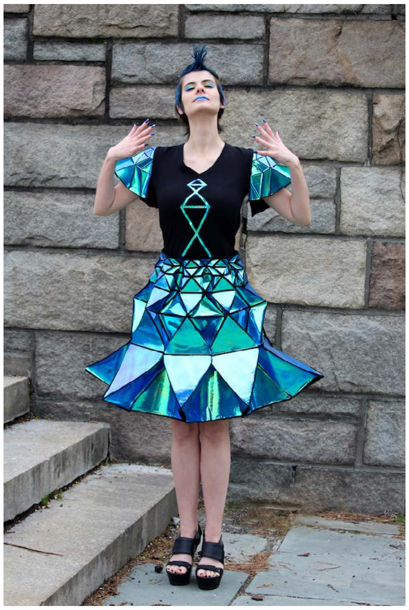
Ideal Materials for Origami and Fashion

Paper is an ideal material for origami. It has memory, so when you make a fold it holds the crease. It has a stiffness that makes it remain more or less planar in regions where there isn't a fold. Unlike paper, fabric has poor memory, so making folds can be easily undone by simply lifting a corner of the material. Fabric is also not as stiff, so gravity is more likely to cause it to drape. Rather than being cantilevered between the folds, regions of fabric have a greater tendency to simply pull the folds closer together or even break the folds. This can happen in paper but usually only when dealing with large-scale folding.

There are some ways to overcome the shortcomings in the material properties of fabric in order to get it to fold. This paper will overview my explorations with rigid paneling and heat setting. Other techniques, such as American smocking and 3D Steam Stretch [4], can be used to create origami textiles for fashion, but are outside the scope of this paper.

Folding From Fabric

One method I sometimes use is the adhesion of semirigid panels to all the regions that I want to remain planar and unfolded. These panels make up the facets of the desired crease pattern. I leave a gap (at least twice the thickness of that of the fabric and panels) between them so the exposed fabric can behave as the folds in the crease pattern. This will allow the fabric to mimic paper somewhat by localizing deformations to the creases and take on the folded structure of that particular crease pattern. However, adding rigid panels alone doesn't necessarily mean the fabric will hold the desired structure. It still lacks the folding memory of paper. Therefore, it is necessary to constrain the panels in a way that forces them into the desired configuration. An example of a work I created that uses this rigid paneling method is the Leaf Skirt (Figure 1a & 1b). I used a



(a) *Leaf Skirt with constrained vertices.*

(b) *Leaf Skirt without constrained vertices.*

(c) *STEM Skirt with vinyl panels and heatset folds.*

(d) *Fully folded STEM Skirt. Photo: Mark Stephen Kornbluth*

(e) *Fully folded STEM Skirt, worn.*

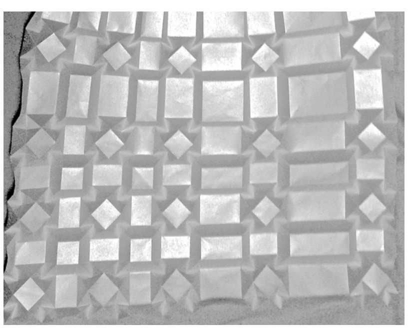
(f) *STEM Skirt without rigid panels.*

Figure 1: *Fibonacci Skirts, modeled by Elizabeth Kilson.*

soft fabric for the base material of the skirt, and I laminated iridescent vinyl and a stiff interfacing to all the facets. At certain points I added snap buttons to force some vertices to connect, which constrained the fabric into my desired structure (Figure 1a). Undoing the snaps causes the folds to flop open and it no longer takes on the same structure (Figure 1b).

In order to give fabric memory so that it can hold a crease, it needs to be heatset while in a folded configuration. Figure 1c - 1f shows two versions of my STEM Skirt, whose folds have been heatset, allowing it to hold its shape without the need to constrain the skirt with buttons. The version in Figure 1c has vinyl panels laminated to each of the facets in the crease pattern, giving it a structure more true to the paper version of the design (Figure 4a and 4b). The version in Figure 1f has no panels bonded to the facets and was made through heatsetting the folds alone, therefore it does not hold the shape as well. However, since it is softer, it is easier to sit down in and more comfortable to wear.

When heatsetting, I only use synthetic fabrics. Usually, I first fold a paper mold of the desired pattern. This mold consists of two identical copies of my design. Then I unfold both sheets of paper, sandwich a piece of fabric between them, and refold them so that the fabric is held between the sheets of paper in the shape of the folding pattern. I then bake this paper-fabric sandwich in the oven to set the folds with a tray of water underneath to add steam. I use a temperature that is in between the distortion and deformation temperatures of the material I am working with. Using too low a temperature doesn't create permanent creases. In the past, when baking at too high a temperature, I've melted holes into my material. I mostly use polyester, which I typically bake at 300°F. After baking, I take it out of the oven and let it cool, still in the folded configuration. Once it cools fully, the creases are more or less permanent. The process essentially melts the material slightly and then re-solidifies it in a new, folded shape. The fabric's memory has been changed from being a smooth sheet to one with a folding pattern.



(a) *Folded paper variation on Ron Resch's Linear Flower, used to create the Trinity Dress.*

(b) *Model: Trinity Dubuc Fraser Photo: Bao-Khang Ngoc Nguyen*

(c) *Model: Kirsten Lajoie Photo: Brett Carter Berman*

Figure 2: *Trinity Dress, part of the VOGEL Spring/Summer 2016 collection [13].*

Stiffer fabrics, such as taffeta and organza, will hold a crease better than softer fabrics, such as chiffon. Essentially, the closer a fabric's mechanical properties are to paper, the better it will fold. The fabric should have sufficient stiffness to counterbalance the effect of gravity that causes the fabric to just droop downward.

Another factor that helps with foldability is the distance between folds. If the facets are relatively small, it is easier for them to remain roughly planar than when they cover a larger expanse, as more material and therefore more weight will have to be supported. The use of semirigid panels can help mitigate this effect. However, if the distance between folds is sufficiently small, heat setting alone is sufficient to produce an origami pattern in fabric.

(a) *Parabola Crop Top*
Model: Harry Cullen

(b) *Sine Wave Top*
Model: Jen Tashman

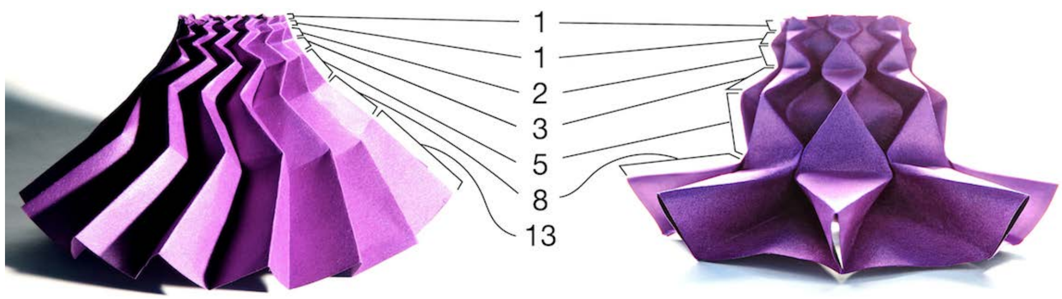
(c) *Semicircular Wave Scarf*
Model: Jen Tashman

(d) *2nd Order Hilbert Curve Top, Model: Jay Dalal*

Figure 3: *Articles designed using the methods described in“Folding Functions: Origami Corrugations from Equations” [11].*

Heat setting works best with flat-foldable designs. My first attempt at heatsetting fabric was part of a collaboration I did with Lea Freni for the VOGEL Spring/Summer 2016 collection [13]. One of the dresses we made used a variation of a Ron Resch corrugation (Figure 2). Corrugations are a style of origami where the entire surface of the paper is exposed [11]. I explored the Resch corrugation in greater detail in a previous work [10]. The regions where the fabric wasn't flat-folded didn't produce folds as sharp as regions which were flat-folded because the deformation wasn't as great. The end result was not as folded as we would have liked (Figure 2b), so we ended up having to sew certain vertices together to counteract gravity and have the textile behave closer to the desired result (Figure 2c). When creating designs that aren't flat-foldable (as with the Leaf Skirt), it becomes almost necessary to use rigid panels. Because rigid paneling is quite time consuming, I became a lot more interested in flat-foldable designs for the reason that they would heatset more successfully. Flat-foldability was a constraint in the paper I coauthored last year [11] specifically to give myself a class of designs that would be usable for heatsetting and fashion. That paper also summarizes the rules of flat-foldability and explains the concept in greater detail. Figure 3 shows some of my fashion results that were designed using the techniques outlined in that paper for various equations.

Design Concepts



(a) *How the Fibonacci sequence is used in the Leaf (left) and STEM (right) skirts.*

(b) *Paper STEM and Leaf Skirts, aerial view.*

(c) *Chevron Top and Arrow Pants. Photo: Jay Dalal*

Figure 4: *Fibonacci in Fashion. The spacing of folds utilizes the Fibonacci sequence.*

The Fibonacci Sequence

Aesthetically, I find the Fibonacci Sequence to be quite pleasing, and it can be found throughout my body of work. I designed the first iteration of a Fibonacci skirt for VOGEL's Spring/Summer 2016 collection [13] which was inspired by Bin Liu's design for a Miura-ori ring [7]. The original Fibonacci Skirt wasn't flat-foldable, and therefore the folds weren't as sharp as I would have liked. I later redesigned the Fibonacci Skirt to be cylindrically flat-foldable as the STEM Skirt (Figure 1c-1f) by changing the folding angles and created the accompanying Leaf Skirt (Figure 1a & 1b) which is also based on the Fibonacci sequence. Figure 4a & 4b shows the paper models of the STEM & Leaf skirts and how they use the Fibonacci sequence in the radial spacing from waist to hemline. An aerial view of both designs is also provided.

Another way I've utilized the Fibonacci sequence is in my Chevron Top (Figure 4c), which uses a variation of the Miura-ori pattern where the width of each chevron pleat follows the Fibonacci sequence starting from the center and moving outward. A sheer version of this top can be seen in Figure 5. I have also created a dress (discussed later in this paper) that has one, one, two, and three rows of "waterbomb" folds starting around the waist and moving toward the hem (Figure 7).

(a) *Antiprism Pants, short.* **(b)** *Antiprisms Pants, long.* **(c)** *Candy Backpack.*

Figure 5: *Antiprism Pants and Candy Backpack. Model: Jay Dalal.*

Antiprisms

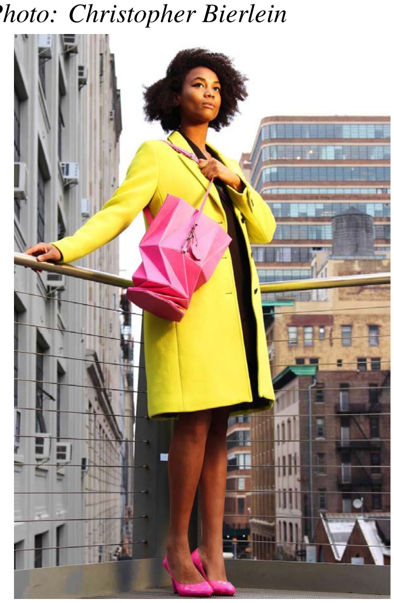
During my time in the Laboratory of Atomic and Solid State Physics at Cornell University, I researched the mechanical properties of flat-foldable origami antiprism columns, also known as triangulated cylinders. A summary of this research is available in the supplementary materials. This type of structure has also been explored by other individuals [1, 3, 5, 6] in different ways. I found that there existed a bifurcation point in the folding angles used where an antiprism would transition from being monostable to bistable [9]. Using this knowledge, I developed a multistable leather handbag (Figure 6). Due to the multistable nature of the structure, it was not necessary to give the creases memory through heatsetting. The limited stable geometries allow the bag to take on the desired configurations naturally, solely by adding rigid panels at each of the facets, without requiring further constraints (such as buttoning vertices together). The bag can be closed either by folding the top segment shut or by using the magnets inlaid in the top edge of the bag (Figure 6d). I also created a backpack utilizing this structure that can be opened from either end, mimicking a twisted candy wrapper (Figure 5c).

Taking advantage of its multistable behavior, I created a pair of pants that can change length by transitioning the antiprisms between flat-folded and extended states (Figure 5). These pants were made without rigid panels and used only heatsetting. The functional part of the crease pattern exists up to the knee. The crease pattern continues upward simply for aesthetic purposes to give the pants a consistent texture, but if it were to fold, it would have to physically pass through the wearer's leg. Though not yet executed, I also have plans to create a top with sleeves that can change length in the same way.

(a) *Some of the possible configurations of the Antiprisms bag. Photo: Christopher Bierlein*

(b) *The flattest configuration of the Antiprisms bag in use.*

(c) *Another configuration of the Antiprisms bag in use.*



(d) *The Antiprisms bag using the magnetic closure.*

Figure 6: *The Antiprisms Bag, Model: Soukie Dia.*

Pattern Construction with Corrugations vs Flat Tessellations

Flat-foldable corrugations can be stretchy, and therefore it is not always necessary to take into account the curvature of the body when pattern making. Rather than creating a curved pattern piece, which may interfere

(a) *Holographic Dress* **(b)** *Dress detail, unworn.* **(c)** *Dress detail, worn.* **(d)** *Dress pattern.*

Figure 7: *Holographic Dress. Model: Elizabeth Kilson*

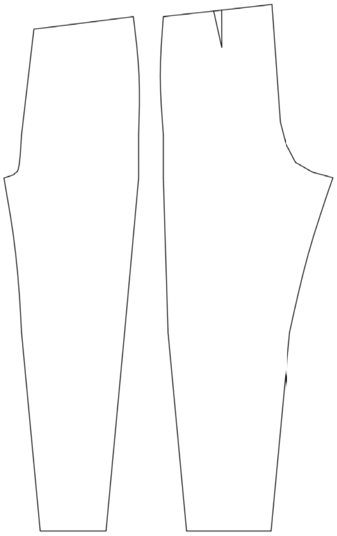
with the folds in the design, the corrugation can instead compensate for variations in width by changing dihedral angles and thus the final garment can still conform to the body. A dihedral angle of a crease is the angle to which that crease is folded. If a crease has a dihedral angle of 0° then it is not folded at all. A dihedral angle of 180° corresponds to the crease being flat-folded where the facets on either side of the crease touch. In narrower parts of the body the dihedral angles in the corrugation will be greater (fabric is more scrunched) whereas in the wider parts of the body the dihedral angles will be smaller (fabric is more extended). I used this concept to create the Holographic Dress (Figure 7). Figure 7d shows the pattern to create the dress. The black line is a cutting line, and the gray lines are folding lines. The front and back pattern is the same, though the depth of the v-neck cut can be varied. Despite the pattern piece's perimeter being rectangular, the dress is still able to hug the body of the wearer. In Figure 7c we can see that the corrugation is more sharply folded around the waist and knees but flatter around the hips and bust.

Another example of this technique's use can be seen in my Waterbomb Pants (Figure 8a). Traditionally, pants patterns are tapered and involve curved seams (Figure 8b). For ease of folding, I took advantage of the stretchiness of corrugations so that the seams could be linear and vertical and the folds could align across seams, except in the crotch (Figure 8c). In addition, I also varied one of the folding angles in the crease pattern moving from the ankle to the thigh to compensate for change in curvature as the thickness of the leg increases. It's difficult to spot in the crease pattern, but is noticeable in the final result, giving the pant a more uniform appearance instead of appearing to be unfolded in the thicker regions of the leg.

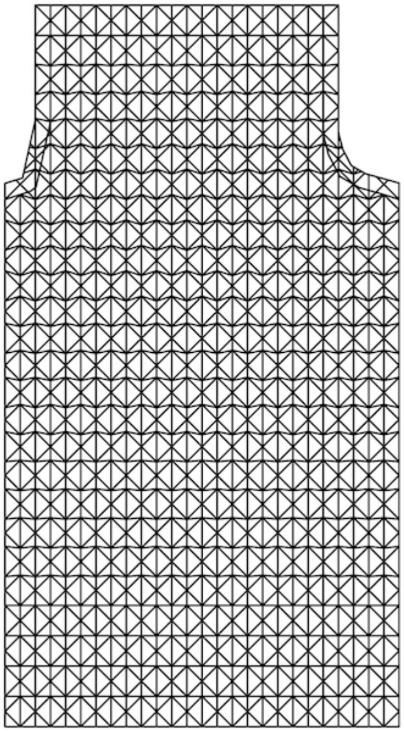
Using a corrugation can have an effect on the silhouette of a garment similar to gathering or ruching. Figure 9 shows pants with a corrugated cuff that demonstrates this concept. An approximate pattern for these pants is also provided to show how a sewing pattern should be modified to accommodate a corrugation of this nature. The design of the cuff is a hybrid between the waterbomb and Miura-ori patterns. The result is an iso-surface (both sides look the same) corrugation.

When using a flat tessellation, the folded tessellation can be treated as a normal piece of fabric, and no adjustments to the pattern pieces of a garment need to be made to account for the tessellation. The folding of the tessellation should be done prior to cutting the pattern piece out, whereas with corrugations, the pattern is

(a) *Waterbomb Pants*



(b) *Sample traditional front and back pants pattern.*



(c) *Waterbomb pants pattern.*

Figure 8: *Waterbomb Pants. Model: Harry Cullen*

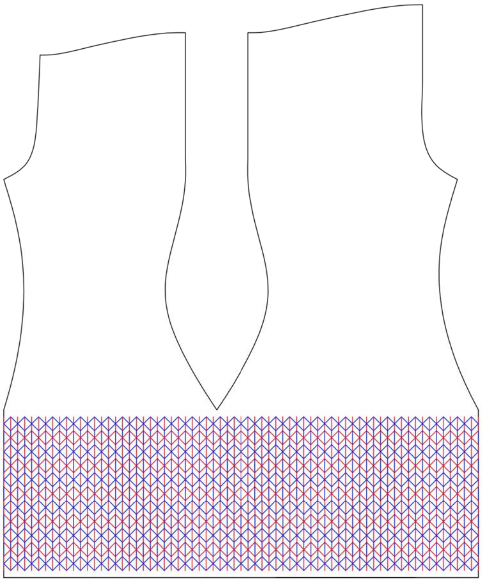


Figure 9: *Rooster Pants (Photo: Jay Dalal) and Pattern*

designed around the corrugation and cut prior to folding. An example of a garment that uses flat tessellation in this manner is my Arrow Pants in Figure 4c.

Future Work

I've used fashion and origami to represent various concepts in mathematics. While I use a lot of mathematics in my origami design process, having a more rigorous understanding of the mathematical constraints behind the construction of a fitted garment would enable me to improve my designs moving forward, both with and without origami elements. I plan to design both clothing that can be fitted and practical as well as garments that are more conceptual and artistic.

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