Creating Furniture-Scale Deployable Objects with a Computer-Controlled Sewing Machine

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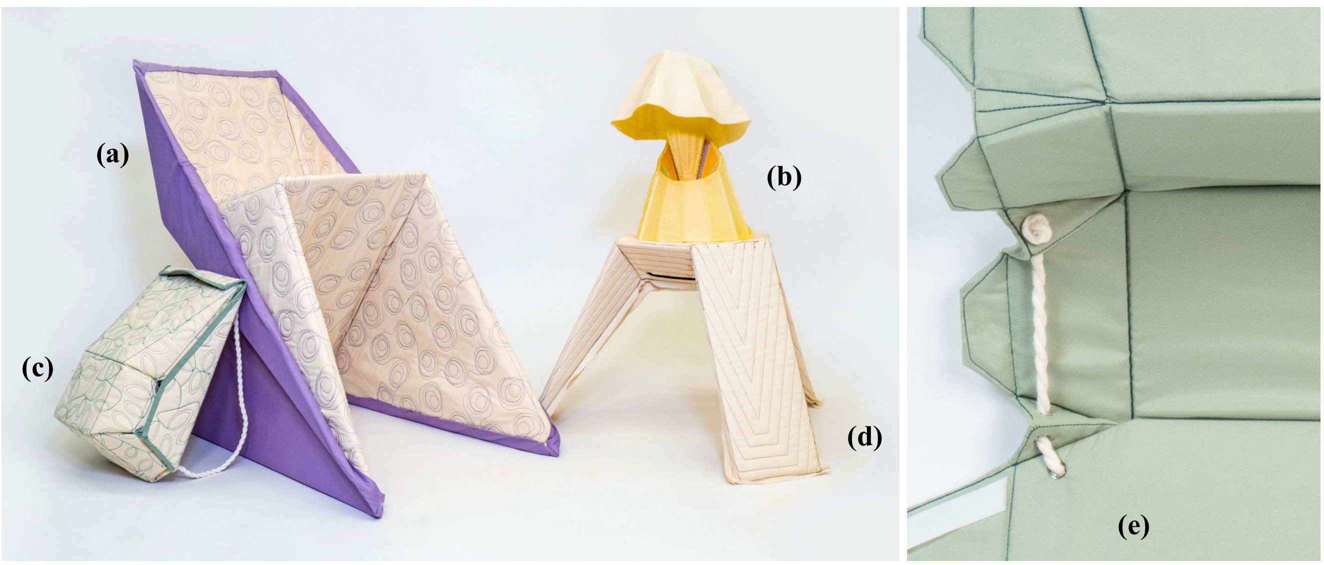

Figure 1: Our method can produce functional deployable objects including (a) a full-size chair, (b) a functioning table lamp, (c) a backpack, and (d) a side table. Each has both a flat configuration and a deployed 3D shape (shown). (e) Our flexible fabrication technique includes the ability to integrate tendon cords and attachments such as hook-and-loop fasteners.

Abstract

We introduce a novel method for fabricating functional flat-to-shape objects using a large computer-controlled sewing machine (11 ft / 3.4m wide), a process that is both rapid and scalable beyond the machine's sewable area. Flat-to-shape deployable objects can allow for quick and easy need-based activation, but the selective flexibility required can involve complex fabrication or tedious assembly. In our method, we sandwich rigid form-defining materials, such as plywood and acrylic, between layers of fabric. The sewing process secures these layers together, creating soft hinges between the rigid inserts which allow the object to transition smoothly into its three-dimensional functional form with little post-processing.

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CCS Concepts

• **Human-centered computing → Human computer interaction (HCI)**.

Keywords

Computational fabrication, textiles, CNC sewing, furniture

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1 Introduction

Sewing is an age-old technology that is integral to countless aspects of our daily lives. By joining existing sheet goods (typically along their edges), sewing enables fast manufacturing, often with disparate functional materials Computer-controlled sewing machines have further enhanced this capability, offering precision, reliability, and scalability. These machines, particularly large-scale ones (sometimes called *CNC quilting machines*), have the potential to fabricate sizable and intricate objects with minimal post-processing. Yet much of this potential remains unrealized; quilting machines are generally only used to produce flat, fabric-only goods such as blankets. In this work, we explore methods using these machines to fabricate large-scale flat-to-shape deployable furniture and household objects.

Flat-to-shape objects are those that can be transformed into a three-dimensional form from an initially sheet-like one, as seen in Figure 2. At smaller scales, flat-to-shape techniques have been explored as a means of reducing construction time on a 3D printer [7]; larger scales, these techniques are seen as an advantage in portability and configurability, but they often involve labor-intensive construction techniques such as the addition of hardware hinges [15]. Our method achieves high-quality flat-to-shape objects at furniture scale with little post-processing by leveraging a CNC sewing machine to construct shaped "pockets" between layers of parallel fabric. We insert rigid (or semi-rigid) "panels" before the pockets are sealed on all sides. By sequencing steps to form, fill, and seal pockets, we produce objects consisting of selectively rigid panels linked by flexible stitched fabric.

This technique offers significant modifiability for both aesthetic and functional objectives. Each panel can be augmented with further functionality, such as by adding LEDs for lighting applications or choosing thicker materials for increased strength. Many fabric types can be used, ranging from sturdier muslin for heavy-duty applications to delicate organza for decorative purposes. Lastly, our technique can integrate additional mechanisms, such as cords, magnets, and hook-and-loop fasteners, to direct and stabilize flat-to-shape transitions.

Through this work, we aim to showcase how shape-changing furniture and objects can enhance living spaces with lightweight, versatile, and aesthetically pleasing solutions, while also highlighting the potential of this fabrication process. A computer-controlled sewing machine is a reliable and capable fabrication technology that is underexplored in HCI contexts, despite the potential for computational control to unlock ways of working with sewn construction that would not be tractable otherwise.

This paper contributes:

- An exploration of the capabilities of large-scale computer-controlled sewing machines.
- A method for sequentially fabricating rigid sandwiched panels with soft fabric hinges.
- An examination of the design possibilities and customization options within this fabrication approach, including material selection, actuation, and locking mechanisms.

More broadly, we contribute a worked example of how to explore, develop, and characterize the possibilities of an often-overlooked computational machine technology.

Figure 2: This side table folds from flat to its 17"-tall (≈43 cm) final shape when a cord laced through grommets is pulled. (Materials: quilted muslin-batting-muslin top fabric, 3/16′′ plywood inserts, muslin backing fabric.)

Figure 3: A computer-controlled long-arm sewing machine for quilting.

2 Background

Sewing is the process of fastening fabric together with a needle and thread. As a fundamental process in textile fabrication, sewing can be done either by hand or by machine; it can be used to join cut (or otherwise shaped) fabrics together, to attach non-textile items like buttons, to reinforce a fabric surface, or even purely decoratively. Sewing machines were invented and refined hundreds of years ago, with the modern "lockstitch" machine established by the 1850s as the first home fabrication machine. Such machines use two separate threads that interlock around the fabric quickly and reliably, and the same basic mechanism is widely used in both industry and domestic contexts. More recently, sewing machines have been augmented with computer-numerical control (CNC).

In this work, we use a CNC sewing machine that is intended for *quilting*, in which a stack of materials—typically a top fabric, a fluffy *batting* material, and a backing fabric—are attached by sewing directly through the layers. (Note that quilting is often associated with patchwork [26], in which smaller pieces of fabric are sewn together to create intricate patterns. However, "quilting" refers to the technique of stitching through the layered fabrics, regardless of the presence or absence of patchwork.) The sewn stitches not only hold the layers together (historically, to prevent the warm batting material from all migrating to the corner of a blanket), but also serve as a decorative element, often meandering intricately across the entire surface of the quilt.

A quilting machine, then, is a sewing machine that enables large-scale patterned sewing on a surface. As shown in Figure 3, it does this by providing a large area to stretch the fabric out and a lockstitch mechanism with much greater reach (a "long arm") than the typical sewing machine used for garment sewing, in which the stitches are almost always within a few inches of an edge of the fabric. Because the lockstitch mechanism of a long-arm-style machine is mechanically coupled, the arm cannot be indefinitely long; our Innova-brand long-arm quilting machine has a reach of 32″ (0.81m). We follow the manufacturer's terminology in referring to the lockstitch mechanism as the "sew head," and we refer to the area bounded by the reach of the sew head as the "sewable area." The fabric to be quilted is tensioned by running over front and back beams onto take-up reels at the front and back of the machine, allowing different sections to be put into the sewable area. (Secondary "tension clips" attach to the sides of the fabric to help keep it taut for sewing.)

Quilting machines can be manually operated, with the sew head laying down stitches at set intervals as a human user guides its path, or fully computer-controlled. Ours can be operated in either mode, but we focus on the computer-controlled mode (called "Autopilot" by Innova) in this work. In this mode, the user can upload vector paths, scale and position them, and sew them automatically.

A more widely known kind of computer-controlled sewing machine is for *embroidery*, which is the use of sewing to reinforce and embellish the surface of a fabric. Machine embroidery typically uses dense areas of different thread colors for decorative effect, and it is commonly used to add logos or personalization to garments and soft home goods. Domestic embroidery machines are very similar to any other domestic sewing machine, with the addition of a computer-controlled motion platform that positions an *embroidery hoop* under the needle as the machine sews.

The obvious difference between quilting and embroidery machines is the size: domestic and most industrial embroidery machines are intended for detail work and can typically sew areas less than a quarter of a meter square. There are also subtler differences. Machine embroidery is typically done on just one or two layers of stable, non-stretchy fabric, held at an even tension by the embroidery hoop. Each cycle of the needle piercing the fabric and producing a new stitch is timed precisely with the motion of the hoop. On the quilting machine, the fabric is much looser due to the much larger area under tension and the typically thicker, bouncier materials. Additionally, because of the dual manual/computer-controlled modes of the machine, moving the sew head along a path and interpolating stitches along that path are handled by two separate control systems. The quilting machine, therefore, does not guarantee specific needle-down positions. It gives a constant number of stitches per inch along a path, so it is not very capable of the intricate shaded or filled areas that characterize machine embroidery; it is much better at outlines. Most critically, dual control systems mean that the motion of the sew head is not synchronized with the stitch cycle; the sew head can be in motion even when the needle is stuck in the fabric, so the fabric *must* have a some slack in it to avoid stressing and possibly breaking the needle.

In recompense, however, the quilting machine is able to stitch quite quickly through thick and somewhat unruly materials. Additionally, the closed-loop positioning means that the user can indicate a location on the actual fabric by physically moving the sew head there, enabling actions like aligning a path to an existing material feature. We make use of both of these advantages in this work.

In summary, sewing is a well-established, flexible technology with many interesting variants. CNC sewing machines come in two main varieties, and in this work, we are using a CNC sewing machine intended for quilting, which means that it is relatively imprecise, but can handle large designs, unusual materials, and high speed.

3 Related Work

Broadly, we hope to contribute to a conversation on exploring computational fabrication technologies that are not being used to their full potential. Such work includes augmenting vintage knitting machines [4], using laser cutters to manufacture robots [40], and designing computational jigs for hand tools [29].

In designing and fabricating furniture-scale foldable objects, we draw on related work from fabrication and textiles researchers, origami methods, and architectural and industrial design practitioners.

3.1 Furniture-scale

In this work, we focus on fabricating objects on the scale of furniture: items that are large enough for whole-body interactions such as sitting or wearing, or for carrying and displaying other items, while still being portable and integrable into an existing setting.

Architectural researchers have naturally investigated fabrication on larger scales, with a variety of techniques ranging from extrusion-based concrete processes [6] to robotic brick laying [16, 43] to hybrid artisan collaboration [53]. Robotic arms are commonly used with a variety of purpose-built fabrication end effectors for clay and concrete extrusion, plastering, or even felting [34, 54]. Due to a grounding in architectural practice, these methods often feature exotic materials and are typically best suited to immobile structures.

Within HCI, most fabrication research is focused on smaller, handheld object-scale items. Size constraints are often driven by the relatively small build volumes of typical computational fabrication equipment; with 3D printing, in particular, the relatively long printing time per volume of material produced is also a limiting factor. Researchers have investigated ways to scale up through modular construction and/or sparse assemblies. A small number of custom computationally fabricated components can be combined with existing stock materials like wood [33], plastic bricks [37], or empty plastic bottles [25] to reduce the amount of computational fabrication time required and take advantage of the strengths of the stock materials. By focusing the computational fabrication effort on the joints, only a very small amount of the overall volume of the output needs to be machine-generated. Research in furniture-scale fabrication with laser cutting [9] shows how using existing sheet materials reduces the fabrication time to a matter of cut edge length, not volume.

3.2 Foldable Forms

Objects that are fabricated modularly often must be assembled. Items with flexible "hinge" areas instead of fully separate pieces are easier to assemble and can be stronger once assembled [1]. Indeed, flexible folding can be re-done as part of the daily use of an object, to assist portability or stowability. This points toward toward another major area of related work: foldable and "origami" designs. Folded patterns have a long history of exploration in mathematics and the arts [39], and in HCI they have been explored as interfaces [35], as lightweight and inexpensive mechanisms [42, 56], and as a basis for shape-changing fabrication [7]. Material thickness constraints have also been assessed and simulated to allow for computational origami design to be fabricated in the physical world, sometimes with hinges[52] or even compliant mechanism surrogate folds [48]. Cross-hatching of flat planes has been used to make 3D volumes [20], and furniture [50]. We are also particularly inspired by the work of industrial designers who have explored portable and foldable furniture [5, 12, 51, 55], which, in HCI, has can be optimized for space saving [30] and multifunctionality [17].

In this work, we draw on this wealth of precedent as a basis for developing our specific fabrication technology.

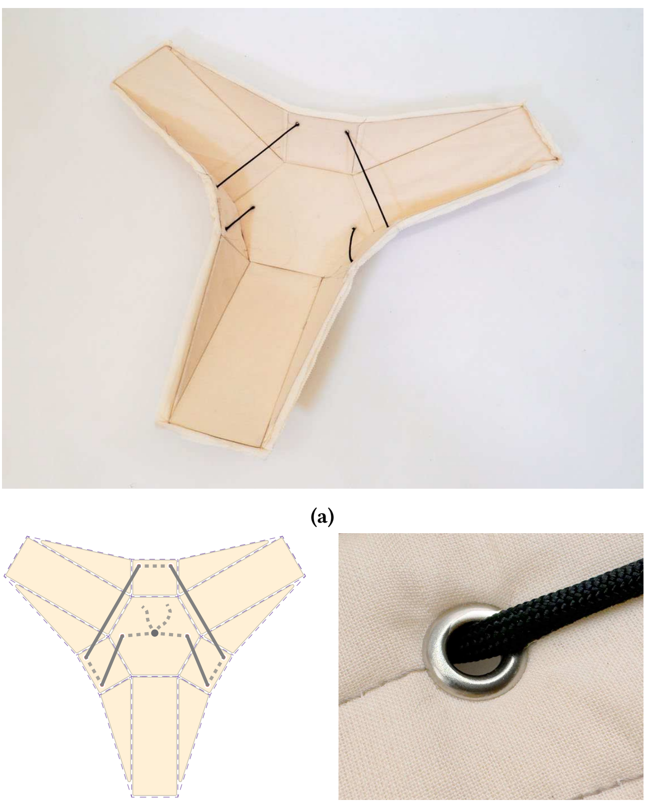
3.3 Fabricating Soft Structures

HCI researchers have previously investigated pairing the flexibility of fabrics with rigid surfaces through typical HCI fabrication techniques such as 3D printers [47], as well as novel fabrication machines such as a layer-based fabric printer [41] and "felting printer" [23]. Of course, HCI research has also incorporated hand sewing as a viable production method for hybrid textile objects, especially for research that incorporates computation in other ways, such as actuated smocking [8, 22].

However, much HCI research into soft fabrication builds, as we do, upon machine sewing. As mentioned in Section 2, machine sewing is a well-established fabrication technology. As the more common variety of computer-controlled sewing machine, embroidery machines have been studied particularly for precision fabrication of e-textile circuitry by attaching electronic components

[10, 21, 32], and creating traces [44] and complex fully sewn components such as sensors [2], speakers [45], RFID antennae [11], and bistable surface textures [24].

We are particularly inspired by work that views machine sewing as a general-purpose fabrication technology, capable of tasks that go beyond typical sewn manufacturing. A computer-controlled sewing machine can act as a site for gameplay [3, 28] and as a target for novel image-processing algorithms [31]. Sewing can alter the mechanical properties of the underlying fabric [36, 49], and it can even produce complex engineered structures that don't involve fabric *per se* at all: Rahimi *et al.* use machine sewing to position micro-tubing precisely within encapsulated micro-fluidics [46]. Machine embroidery can be incorporated with other computational fabrication processes to become a substrate for e-textile traces [18, 19] or pneumatic wearables [14], and it can be conceptualized as a kind of layer-based printer [27]. These works are aligned with ours in highlighting machine sewing as a robust and adaptable technology for both textile and non-textile materials. Our work diverges in being applicable to a much larger scale, and in being developed specifically for the edge-based patterning that a quilting machine handles best.



(a)

(b) **(c)**

Figure 4: (a) and (b): The underside of a semi-transformed side table showing the lacing of cord through panels to constrain the shape. (c) The tendon cord passes through grommets that are added after sewing.

4 Design Exploration

To demonstrate the potential of large-scale computer-controlled sewing machines, we developed a collection of functional artifacts – a side table, backpack, chair, and lamp – incorporating variations on a general method of sandwiching rigid panels within sheets of flexible fabric.

4.1 Method Overview

In our method, the fabric layers are first loaded with light tension between the front and back beams of the sewing machine, with tension clips helping to stabilize them, as shown in Figure 3. We embed panels sequentially: for each panel, the machine sews a set of *initial edges*, then we pause the sewing, insert the panel, and the machine sews a *closing edge* to lock that panel into place. These steps are repeated until all panels are enclosed. After sewing is complete, the object is trimmed to size and edge finishings can be applied. This basic method can accommodate varying materials and fastening techniques, which we discuss in Section 6.

Our method requires only very lightweight modifications to the hardware of the machine: when sewing very large objects, we modify the tensioning setup (described in Section 5.4), and, when sewing tightly against inserted panels, we remove the tensioning foot of the machine. We designated our edge-sewing sequence directly in AutoPilot, which is the software that ships with our Innova machine.

Unless otherwise noted, the items in this section were made with panels that were laser cut, and the fabrics are non-stretchy mid-weight woven fabrics.

4.2 Side Table

Our three-legged side table can be transformed from a 42.5″ by 37″ (≈108 by 94 cm) shape to a 17″ (≈43 cm) tall table (as shown in Figure 2) simply by pulling on its tendon cord.

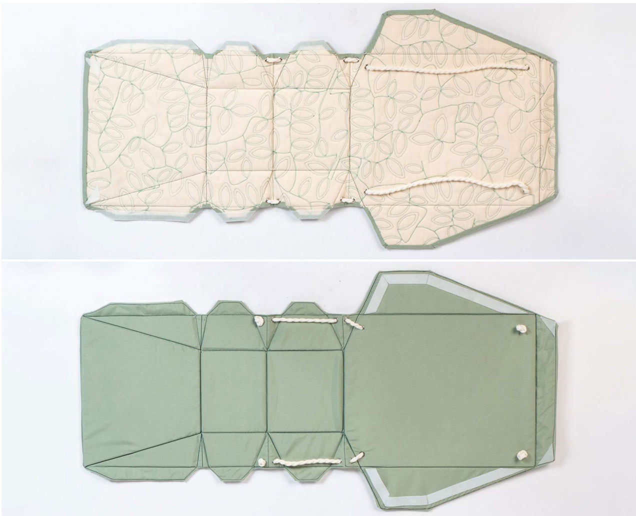
The table has a hexagonal top with alternating long and short rectangles extending from the edges to serve as legs and support struts respectively. As shown in Figure 4, the tendon acts on the short rectangular struts. In its fully deployed form, these struts meet in the center underneath the tabletop, constraining further actuation. The cord is held securely with a spring cord lock while the table is in use.

The side table's base fabric (shown as the outer surface of the table) is a quilt of cotton muslin with cotton batting, and its top fabric is a single layer of muslin. The inserts were made from laser cut 3/16″ (≈0.5 cm) thick plywood, with the lacing holes for the tendon cord included. The grommets were installed after sewing. Because the side table does not fit within the ≈25″ deep sewable area, the sewing was done in two parts. We discuss this method in greater depth in Section 5.4.

4.3 Backpack

Our backpack, inspired by packaging design, is a long 37″ by 18″ (≈94 by 46 cm) almost-rectangular silhouette when flat, and rolls into itself to fold up into the bag. These proportions takes advantage of the 11′ by 25″ sewing area on the CNC sewing machine.

As in the side table, the backpack has a tendon cord system to transform it from flat to its 3D form; in the backpack, the tendon



(a)

(b)

Figure 5: The backpack's tendon string doubles as straps. Hook-and-loop fastener patches on the flaps help it stay closed. (a) The top/outer surface of the backpack shows the decorative quilting, and the solid-colored bottom/inner surface of the backpack shows the location of the hook-and-loop patches. (b) The backpack as worn.

cords additionally serve as the straps. The cords are laced through the small gusset panels between the main facets of the shape; when the cord is pulled, it pulls these flush against each other, aligning the angled edges in the process (Figure 18(b)).

Similar to the side table, the backing fabric, which becomes the outside surface of the backpack, is itself a muslin-batting-muslin quilt. The top fabric, which becomes the lining of the backpack, is a polyester/tencel blend sateen bedsheet which provides a soft surface and color contrast.

The panels that make up the main surfaces of the backpack have 3/16′′ (≈0.5 cm) plywood inserts. The other panels serve as attachment flaps or gussets and do not have any material inserted. Similarly to the side table, holes were added to the plywood inserts at laser-cutting time, with the grommets for the cord added after sewing. Additionally, we manually added hook-and-loop patches to the attachment flaps to help selectively secure and lock the panels of the backpack (Figure 18(a)).

4.4 Table Lamp

Our lamp, shown in Figure 6 is a modification of a 3D printable pattern developed by the Brigham Young University Compliant Mechanisms Research Group [13] based on the popular Elliptic Infinity lamp designed by Lang [38].

Our version is 26′′ by 25′′ (≈66 by 63.5cm) in its flat state and contains four different panel types (Figure 7) to provide localized functions to specific areas of the lamp. Three are variations on 1/8′′ (≈3mm) thick frosted clear acrylic: the panels in the base of the lamp are made from visually and physically lightweight plain acrylic, allowing the fabric to be the primary visual element; the panels in the inner ring of the base are laminated with colorful cardstock for contrast; the panels in the upright section are "active" panels incorporating mounted LEDs. The fourth is the *absence* of panels, allowing the top edge of fabric to drape gracefully as the lampshade. A slight gap at the top edges of the inner radial sewing paths allows the electrical wires to connect between adjacent panels in that area.

Figure 6: Our lamp builds on an existing origami pattern, Lang's Elliptic Infinity [38], by incorporating panels with different functions.

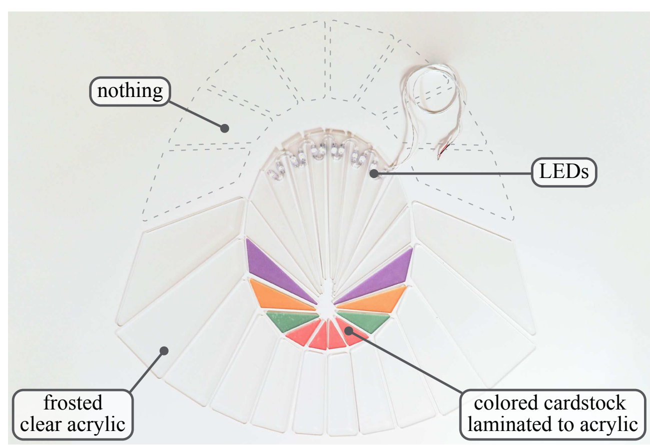


Figure 7: The lamp uses four different panel types.

(a) (b) (c)

Figure 8: (a) The plywood panels for the chair. The magnets are glued in place and covered with gaffer's tape; their locations are marked with pink circles on the righthand side of the image. (b) The finished lounge chair, flat. (c) The finished lounge chair, folded. The panels are aligned by the embedded magnets.

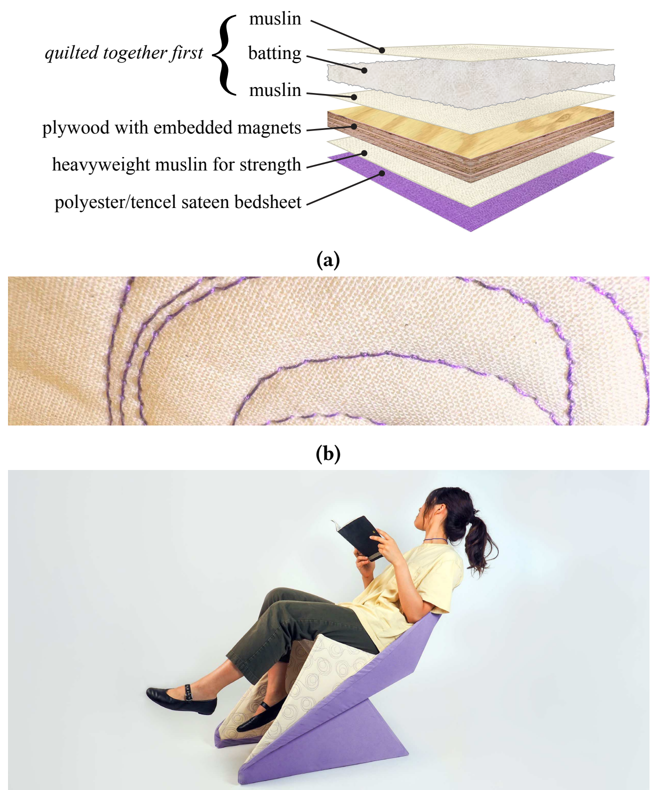
We used muslin as the base fabric, and an upcycled yellow "dotted swiss" (a loosely woven, visually sheer cotton fabric with decorative raised dots) for the top layer, which became the outside of the lamp. Because our sewing machine is engineered for thicker materials, we faced some difficulty in obtaining even thread tension on the sheer fabric. We found that adding a layer of temporary stabilizer greatly helped the fabric resist being pulled upward by the action of the needle, leading to cleaner stitches and more consistent tension. After sewing, the stabilizer was torn away. While purpose-manufactured stabilizers can be purchased at most fabric stores, we had success with thin, smooth institutional paper towels.

4.5 Lounge Chair

At 60″ by 56″ (≈152 by 142 cm) in its flat state, the lounge chair is the largest of the objects we fabricated with our method. It is also the one designed for the greatest loads. To support the weight of an adult, we made the insert panels from 1/2″ (≈13mm) thick plywood; because this is thicker than our laser cutter can handle, these were cut with a CNC router.

The fabrics are similarly heavyweight. As shown in Figure 9, the base fabric is a muslin-batting-muslin quilt for comfortable sitting, and the top fabric has a double layer of heavyweight muslin for strength paired with polyester/tencel sateen for a smooth finish and color contrast. The seat and backrest panels had an additional layer of batting laminated to them for extra padding.

We designed the chair so that the side panels meet face-to-face when the chair is in its deployed state. To hold these facing panels together, we included neodymium magnets glued into pockets milled into the inserts during the cutting stage. This allows the chair to "snap" into its deployed configuration (Figure 8). The design of the chair is such that the magnets keep the panels aligned but the loads on the chair are primarily carried by the panels and the fabrics.



(a)

(b)

(c)

Figure 9: (a) Six material layers are composed to make the full-size lounge chair strong and comfortable. (b) The quilting adds both decoration and padding. (c) The chair in use.

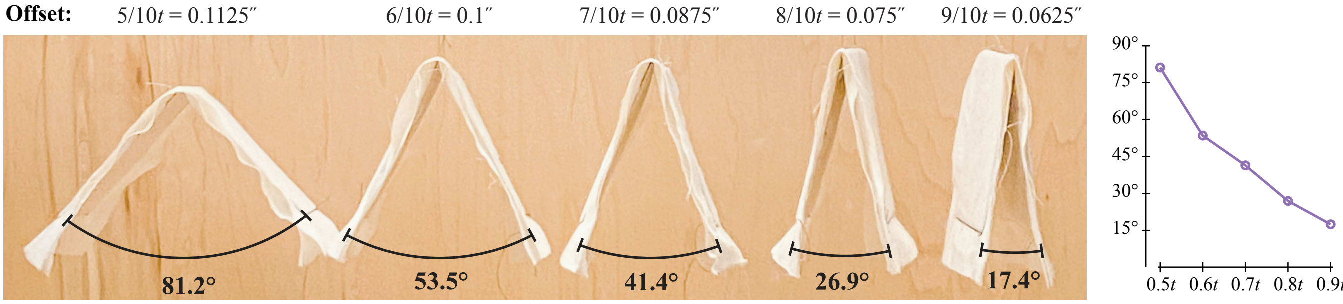


Figure 10: Five hinge swatches fabricated with 1/8″ plywood. Each panel is offset by 1/10ths (0.0125″) increments of the panel thickness. The swatches are hung on a thread connecting to the hinge and are under gravitational load.

5 Constructing Objects on a Quilting Machine

In this section, we present our findings on the technical aspects of producing foldable objects on a long-arm quilting machine. We describe the design factors of folded geometries suitable for our method, discuss fabric tensioning and our approach to making objects larger than the machine's sewable area, and document our panel sizing and sequencing algorithms.

5.1 Fold Patterns

Many of the demonstration forms explored in this paper draw inspiration from origami fold patterns by breaking down a final desired form to a pattern that can be actuated from a flat sheet. However, there are several key differences.

Thickness. Paper origami often relies on doubled-over sheets for rigidity and to avoid cutting. Conversely, we limit overlaps and doubling-over to reduce complexity and accommodate the thickness of our materials.

Folding Constraints. When working with rigid insert materials, the sequence of folding must be planned to achieve the desired three-dimensional form. When possible, we recommend incorporating points where panel edges or entire faces meet and constrain further movement. This approach ensures stability in the final structure. For example, in our side table (Figure 2), the side struts touch in the middle when the table is fully deployed, stabilizing the final form. In our lounge chair (Figure 8), the panel faces meet flat against each other in the stable deployed state.

Straight vs. Curved Edges. While many origami patterns incorporate curved folds, we found these to be intractable for our use because they concentrate stress, which could damage the fabric or seams of our objects. However, *approximately*-curved forms can be achieved by splitting the curving face into multiple narrow insert panels oriented in the direction of least curvature. This is what BYU's CMR lab did to adapt Lang's "Elliptic Infinity A" pattern, and we successfully replicated their design using our process for the lamp described in Section 4.4.

5.2 Panel Sizing

The panels in our designs are inset from the edges of their sewing path. This is both essential for fabrication and to provide flex at the hinges. Because our fabrics are not stretchy, an offset of half the

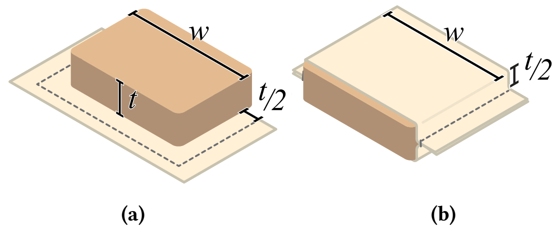


Figure 11: Panels must be smaller than the sewn perimeter of their pocket by at least half their material thickness (*t*), otherwise the fabric won't be able to wrap around the insert. (a) The panel sitting on top of the flat sewn area. (b) The panel inserted (cutaway view).

thickness of the panel material is the minimum necessary to allow the panel to fit in the fabric pocket (Figure 11). We recommend adding an additional margin of 1-3mm to account for the needle diameter and the small shifts of components that can occur during sewing.

We tested the effect of offset distance on hinge mobility by producing five swatches with variations in offset distance. With the sewn path kept constant, we cut panels with offsets incrementing by tenths of the panel thickness (on 1/8″ thick plywood, one-tenth of the panel thickness is 0.125″). We suspended each swatch by the hinge line to measure its resting angle under gravity as shown in Figure 10. Because the mass of the panel material affects the load, these swatches should not be taken as purely predictive. However, the tightest feasible offset distance – $0.5t$ – results in a noticeably constrained hinge; wider offsets allow greater ranges of motion.

Finally, in our experience, we found that rounding the corners of the inserts was helpful, particularly for sharper angles. During assembly, the rounded corners make sliding the inserts into their pockets easier; and during use, sharp corners can pierce and tear fabric.

5.3 Tensioning

During sewing, the fabric and insert sandwich must be held in sufficient tension for the needle to pass through the fabric and return; otherwise, the machine will be unable to form stitches. Tensioning also helps to avoid wrinkles or puckering during sewing.

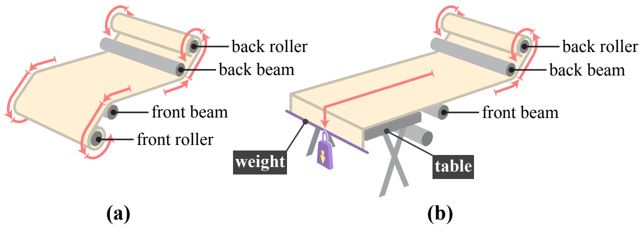


Figure 12: (a) Typically, the fabric is tensioned over the beams and rollers of the long-arm machine. (b) When sewing projects larger than the sewable area with rigid panels, we modify this setup with a height adjustable table and weight to tension the fabric.

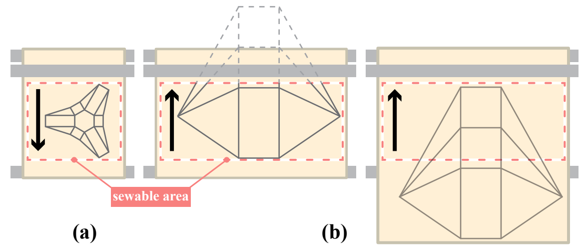


Figure 13: Panel insertion order is determined by the overall size and orientation of the object, as shown in these overhead views. (a) Objects that fit within the sewable area may be constructed from back to front, because the front edge of the top fabric can be gently detached to slide panels in. (b) Objects that do not fit in the sewable area must be constructed from front to back, because panels, once inserted, can be supported by the auxiliary front table but cannot be wound around the rear tension beam.

The fabric is mainly tensioned over the front and back beams (labeled in Figure 3) and onto corresponding rollers. As is typical for long-arm style quilting machines, the rollers are pre-loaded with canvas "aprons" with separable zippers along the loose edge. The fabric is pinned evenly to the other half of the separable zipper, and can then be zipped into place on the machine. Via these zippers, the rollers stretch the fabric along the Y-axis; auxiliary tensioning clips pull it taut along the X-axis.

In several of the objects we describe in Section 4, we selectively sew through just some layers first before incorporating the others. In this case, we attach the back beam zipper to all fabric layers but only attach the front beam zipper to the bottom-most fabric layer; the top layers can then be flipped up out of the way for the initial sewing steps, then brought back down without losing their alignment with the other fabric layers.

5.4 Objects Bigger Than the Sewable Area

The long-arm quilting machine used in this project has a reliable sewing area of 11 feet by 25 inches. Under the typical use of the machine to make soft quilts, the fabric runs over the front beam and under the back beam and is tensioned by the front and back rollers, as shown in Figure 12(a). Excess material that is not currently being stitched can simply be rolled up and "scrolled" into position by the operator to allow larger designs to be completed in strips. (A different style of large-scale CNC sewing machine, the "full frame" quilting machines, do not have a roller system; because their lockstitch mechanism is coupled electronically rather than mechanically, they are not limited by arm length. On these, the entire fabric is stretched in a frame like a giant embroidery hoop.)

However, the scrolling approach is not feasible for our process, since completed areas include rigid panels and cannot necessarily be rolled up. Instead, we introduce a height-adjustable table that is set to the same height as the front beam of the machine as shown in Figure 12(right). Material that is already sewn is draped over this table instead of being rolled up. Additionally, we use a long rod threaded through the edge of the fabric and weighted down to create tension, mimicking the effect of the roller and maintaining proper fabric tension and alignment during stitching.

Although our extended tension and support system allows rigid fabrication of larger objects, we do need to take into account its limitations when designing patterns and selecting a sewing order. Specifically, our flat support setup is only at the front of the machine, replacing the action of the front roller. Once an insert has been added, there is no way to wind the fabric containing the insert back onto the rear roller. This establishes a constraint on the order of panel insertion, which we discuss in Section 5.5: for larger-than-sewable-area objects, we worked linearly from the front to the back of the pattern. A subtlety of this constraint is that the trailing edges (that is, edges that are back-of-the-machine-wards from their corresponding panels) cannot be longer in the Y dimension than the sewable area. However, we did not find this constraint onerous to design for.

5.5 Path and Panel Sequence

Although, at first glance, it may appear reasonable to place all inserts into the fabric sandwich first and then sew all of the edges between them, this process is not ideal for two reasons. First, the process of sewing around inserts distorts the fabric enough that preplaced inserts – even if attached to the fabric – can be pulled out of position; second, this requires that the margins between all inserts be large enough for stable sewing.

We instead adopted an incremental fabrication process: alternating passes of sewing pockets and placing inserts. In this way, we were able to place the inserts snugly against the already-sewn sides of their enclosing shapes, allowing narrower margins and letting the pattern itself provide positioning cues.

We divide the task of planning into two stages: determining panel insertion order and then determining line-sewing order.

Due to our origami-like folding style, we assume that all panels are convex polygons. Each panel must be able to be inserted without being blocked by previous panels or by the constraints of the sewing setup. The constraints of the sewing setup include the beams of the machine and the throat depth of the sewing head. The base layer of the fabric sandwich is tensioned on the rollers (or, in the case of the large objects, is tensioned in the back by the roller and in the front by the hanging weights), and the top layer is tensioned by being pinned to the base along the front and back edges of the fabric. Panels can be inserted from the sides, but the back beam is an

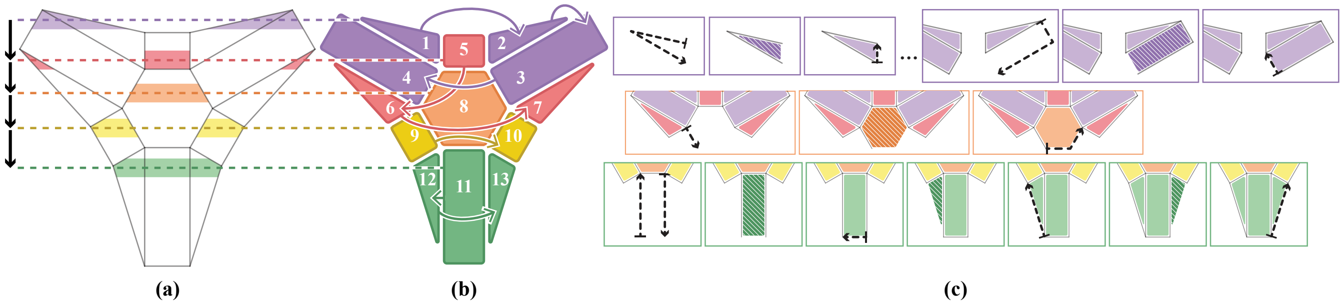


Figure 14: (a) We determine a panel insertion order by sweeping a section line from the top of the pattern to the bottom (corresponding to back-to-front in machine space). (b) Within each group of panels at the same sweep height, we proceed from the center outward. (c) Example edge-sewing sequences showing (from top-left): a simple triangle, a quadrilateral with one edge already sewn, a hexagon (requiring two closing edges), and a sequence of adjacent panels.

impassable obstacle and the front edge is a semi-obstacle as shown in Figure 13 (since the pins at the front edge can be temporarily removed to allow access).

When the pattern fits fully within the sewable area of the machine, we insert panels from front-and-sides, and panel insertion proceeds from the back to the front of the machine. When the pattern is bigger than the sewable area, we observe that areas that already have panels in them cannot be rolled onto the back roller, nor can they be allowed to protrude past it (because the sewing mechanism would collide); therefore panel insertion must proceed from the front to the back of the pattern, and the fabric must include enough margin behind the pattern to allow the furthest-back panels to be inserted without colliding with the back beam. For panels at equivalent positions within the back-to-front (smaller pattern) or front-to-back (larger pattern) ordering, panel insertion proceeds from the center outward.

After determining the panel insertion order, we determine the line-sewing order. For each panel, we must decide which of its surrounding sewing path edges will be sewn before the panel is inserted (the initial edges) and which will be sewn after (the closing edge[s]). We observe that in the ideal process it is easy to insert the panel without unduly disturbing the fabric (which could lead to misalignment) but that, once the panel is inserted, it is not easily dislodged. In other words, the closing edge should be as short as possible (as much already-sewn edge as possible to hold the panel in place) while still allowing the panel to be inserted in-plane and with a direct path. Therefore, we typically select the shortest remaining edge that would still *allow the panel to be inserted.* To evaluate whether an edge would allow the panel to be inserted, we sum its adjacent angles: given that the panels are convex, the two adjacent angles must add up to 180° or less, as shown in Figure 15a.

In practice, most of our panels were either triangles or quadrilaterals. For polygons with more than four sides, there may not be any edges through which the panel could be inserted (they all form obtuse angles with adjacent edges). In this case, we consider each pair of edges by calculating the angles that would result from directly connecting the outer endpoints of the pair of edges such as in Figure 15c. (Failing this, we would consider trios of edges, and so on.) If no valid line-sewing order can be found a new panel insertion order might need to be selected. (Though we did not encounter this situation in practice, we have not yet proven that it will not occur.)

Once the closing edge has been found, the sewing order of the initial edges can be determined. We favor sewing orders that minimize thread ends (*e.g.*, if an eligible edge begins at the needle's current location, we will start there) and doubled edges.

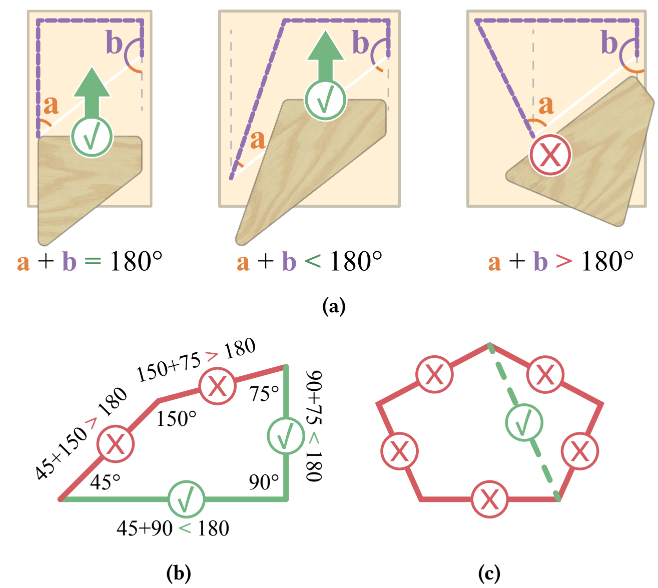
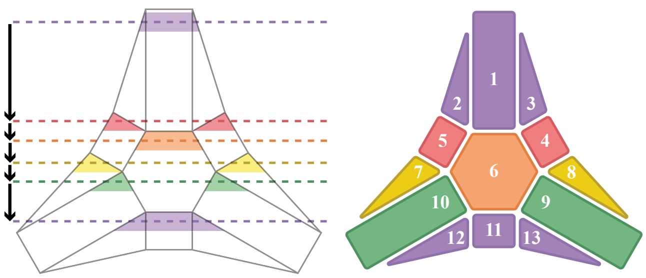
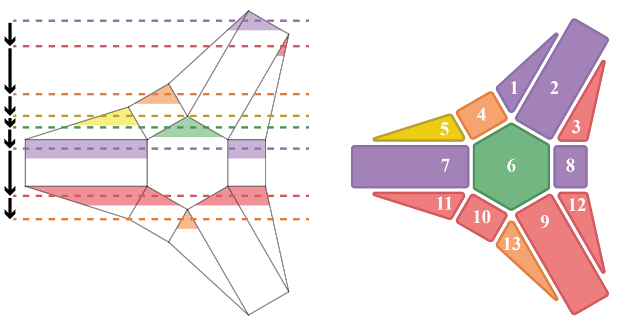


Figure 15: When planning path-sewing order, we need to know which edges (or sets of adjacent edges) could potentially be the "closing edge," which means that the panel could be inserted if that edge were the only one left un-sewn. (a) For a convex polygon, edges that satisfy this property can be identified by summing their adjacent angles: if they sum to at most 180°, this is a potential "closing edge." (b) A quadrilateral with two potential closing edges and two edges that could not be closing edges. (c) Adjacent pairs of edges can be considered by evaluating a new edge connecting their non-shared endpoints.



(a)



(b)

Figure 16: Two other possible panel insertion orientations for the stool. Orientation (a) takes up less vertical space than orientation (b), which is an advantage for fitting as large of an object as possible within the sewable area.

Because the selection of closing edge is affected by which edges have already been sewn (*i.e.*, edges that are shared with adjacent panels), which is itself determined by panel-insertion order and therefore by the orientation of the pattern with respect to the front/back axis of the sewable area, different orientations may result in more or less efficient sewing. In Figure 16, we show two alternate orientations for the stool pattern from Figure 14.

6 Materials and Finishing

An advantage of our method is the ability to easily customize fabrics, insert materials, attachments to deploy and secure objects, and edge finishing to achieve a wide variety of forms and functions.

6.1 Fabrics

The choice of fabric can affect both aesthetic and functional aspects of objects made with our process. For example, the sheer fabric we used for the table lamp, shown up-close in Figure 17 is both translucent (to allow light through) and patterned (for decorative effect).

To work well with our process, fabric should be stable and non-stretch, such as woven muslin or non-woven options like felt or Tyvek. Stretchy fabrics can cause skipped stitches and lead to difficulties with thread tension in any sewing machine system; these are particularly amplified in our large-scale machine. As we noted in Section 4.4, even the woven but sheer fabric we used for our lamp presented some difficulties, though the addition of tear-away stabilizer was sufficient to solve these. The outer layer of fabric itself can be a multi-layered structure. Many of our results feature a quilted layer in which a layer of batting is sandwiched and stitched between two layers of fabric. The padding provides additional strength by helping to prevent corners of insert pieces from piercing or ripping the fabric, and it can be useful to the function of the object, as in the seat padding in our lounge chair example. Additionally, the quilting pattern is a visual design opportunity; for example, the quilt pattern on our side table was designed to echo the overall panel boundary lines.

6.2 Inserts

A major advantage of our method is the ability to select the panel materials on an individual basis. Rigid sheet materials can be cut using various methods, including hand cutting (especially for prototypes), laser cutting, or CNC routing. Panels can incorporate "active" elements, such as the LED-augmented panels used in our lamp (Figure 6). Additionally, colored inserts can be paired with sheer fabric, allowing for aesthetic customization that complements the backing fabric's color and texture. Together, this adds up to a great deal of flexibility and modularity.

However, there are limitations regarding the thickness and weight of the panels. These variables can cause fabric to sag during the sewing process, and may require the use of stiffer, stronger fabric or additional layers of fabric to ensure overall strength and durability. We tested up to a half-inch thick plywood, which was adequate for our largest object, the lounge chair.

6.3 Attachments

We explored three primary methods of deploying and securing our objects: tendons, magnets, and hook-and-loop fasteners. Each of these is particularly effective for specific fold patterns and applications, though they can also be used in combination.

6.3.1 Tendons. The use of tendon cords leverages the tension and rigidity of the string in relation to the rigidity of the insert panels to control the folding sequence and ensure proper panel alignment. This approach is particularly effective when precise control over the fold sequence and direction (mountain or valley fold) is required.

Figure 17: The sheer fabric of the table lamp allows light and the color of the acrylic panels to show through.

(a)

(b)

Figure 18: (a) Cords laced through gusset panels. (b) Hook-and-loop patches allow for panels on the backpack to be selectively opened for easy access to goods inside.

For example, in the side table, the shorter rectangles must be pulled inward and underneath to achieve and lock the final form (Figure 4).

To ensure smooth mechanical activation, tendon paths should be carefully planned with consideration to friction and tension forces during the actuation. Incorporating grommet holes in the rigid inserts during the fabrication process allows the cord to be guided effectively, reducing wear and ensuring consistent movement. These details should be considered early in the design phase to facilitate clean integration during fabrication.

6.3.2 Magnets. Magnets can be embedded in the inserts to attract and align the panels, aiding both in the folding process and the stabilization of the final form. They also allow for a quick and easy dismantling of the form when faces are pulled apart. However, magnets are *not* a good choice in scenarios where they would be the main force holding the object in its deployed form, due to their sudden and complete failure when pulled apart.

Instead, we used magnets for guidance and alignment. As mentioned in Section 4.5, magnets were effective when panel faces meet flush against each other in the deployed form. This allows each magnet to be embedded into the rigid panels, and make face-to-face contact with its corresponding magnet.

6.3.3 Hook-and-Loop Fasteners. Patches of hook-and-loop fastener offer a reliable solution to secure the panels once they have been folded into their final configuration. They allow for easy attachment and detachment, making them ideal for designs that require repeated shape changes or access to specific panels, such as the top flap of our bag example, which allows entry into the enclosure without the need to flatten the entire form (Figure 18).

6.4 Edge Finishing

After sewing is complete, the panels are fully enclosed; for a prototype, it is sufficient to simply remove the excess fabric. For a more polished result, the edges can have one of several finishes applied (Figure 19). One simple method is to trim the excess material about 1/2′′ (1.27cm) away from the sewn line with pinking shears, which produce a zig-zag cut edge intended to prevent unraveling, as shown in Figure 19a. This is a classic and decorative finish; we used it in the side table and lamp examples. For the side table, the batting layer was trimmed closer to the sewn line and the muslin was left longer as a decorative edge. If the fabric is non-woven, such as tyvek or felt, or if the area to be cut has been brushed with a liquid stabilizer such as white glue, it can simply be trimmed with regular scissors and will not be prone to unraveling.

(a) (b)

Figure 19: (a) "Pinking shears" produce a stable and decorative zig-zag cut edge.(b) Wrapping one layer around the edge of the sewn object and securing it to the other face with hem tape provides a clean and attractive finish.

Lastly, a fold-over hem can be produced by trimming one layer close to the sewing line and cutting the other layer approximately four times the thickness of the panel material away from the line. The raw edge of the longer layer is folded once on itself, then wrapped around and attached to the other face of the object using an iron and "hem tape" (hot-melt adhesive in a tape form factor). This produces a clean and attractive finish, as shown in Figure 19b; we used it for our backpack and lounge chair, and we chose the colorful fabric as the wrapper for visual contrast.

7 Limitations and Future Work

Our results demonstrate the capabilities of large-scale CNC sewing machines as a tool for the fabrication of functional flat-to-shape objects. We believe that computer-controlled sewing machines enable methods that are a true departure from what is possible through handcraft alone, and encourage HCI researchers to explore their capabilities.

Algorithmic Assistance. Our path and panel sequencing heuristics, described in Section 5.5, are straightforward and worked for our examples. However, we have not proven they will always produce a viable or *optimal* sequence. Future work could implement optimization, for example by assigning a cost to discontinuous edges or by performing a combinatorial search.

Designed Hinge Constraints. In Section 5.2, we showed that the offset between the sewn lines and the enclosed panel could be selected to restrict the movement of the hinge. However, these samples were prepared to wrap the two fabric faces equally around the edge of the panel. In our prototypes, we noticed that it is be possible to vary the fabric tension between the backing and the top layer; this could open up a design space where the range of motion for the hinges can be reliably biased toward one face. For example, we noticed that if the top layer of fabric sits loosely on top of a tensioned bottom layer, the additional slack will be pulled from the top layer during fabrication, allowing easier folding toward the bottom layer.

Fabrication Space. We were able to test and implement a method for fabricating objects larger than the bed size in depth; however, our method does not extend to the creation of objects with a flat footprint wider than the width of the machine – in our case, 11′. Electronically-synchronized full-frame quilting machines may hold the key to extending our approach to yet-larger objects; while mounting an electronically-synchronized sewing mechanism to a pair of industrial robot arms would allow sewing quilted furniture of nearly unlimited size (and in non-flat starting configurations).

On the other extreme, hand sewing (and related techniques like lacing) are more flexible and less constrained than flat machine sewing; and there is nothing preventing one from taking the ideas we have presented herein and using them with hand fabrication techniques.

Especially for thicker inserts, the movement of the fabric caused by adding inserts requires re-aligning the machine to fabric (which we did manually when necessary); or adding a bit of extra margin to panels to avoid collisions. In the future, it would be interesting to explore methods to use computer vision to automatically reposition the sewhead; or simulation to automatically adjust subsequent sewing paths to account for this distortion.

8 Conclusion

This paper provides a methodological framework for harnessing the potential of large-scale computer-controlled sewing machines to fabricate deployable flat-to-shape furniture and household objects. We explore the playful, yet functional possibilities with customizing inserts and fabrics, and the design and fabrication context in which these objects can be created in. More broadly, we see the computer-controlled sewing machine as an exciting example of the wide world of reliable and capable fabrication technologies that have been overlooked outside of their niches. The simple-yet-powerful idea of quilting – of sandwiching materials into a complexly functional structure – can be applied to surprising and powerful results, and computational control can enable this work in ways that simply would not be tractable otherwise.

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