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Creating Manual Textile Craft Artifacts with Additive Fabrication

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Creating Manual Textile Craft Artifacts with Additive Fabrication

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Master of Science
in
Media Arts and Technology

by

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Abstract

Creating Manual Textile Craft Artifacts with Additive Fabrication

by

Ashley A. Del Valle Morales

New approaches to 3D printing have made it possible to create 3D-printed materials that closely resemble traditional textiles yet these filament-based textiles, while easy to produce, often lack the tactile qualities and visual appeal of fiber textiles. To address this limitation and explore new possibilities for personal textile production, my research focused on developing methods that combine established manual textile craft techniques with additive fabrication. Needlecrafts offer the possibility of embedding 3D-printed fabrics with yarn to achieve the visual and tactile attributes of traditional fabrics. This thesis presents a series of explorations of combining needlecraft with 3D printed elements. These explorations set the foundation for PunchPrint, a technique for integrating filament and fiber-based textiles by combining the 3D printing of a custom parametric fabric substrate with punch needle embroidery. By combining punch needle embroidery with 3D printing and employing a toolpath that mimics traditional textile weave structures, we can fabricate a flexible fabric that serves as a substrate for punch needlework. Furthermore, I present an evaluation of a two-day workshop conducted with textile crafters and enthusiasts. Through the workshop I explore ways to integrate computational design and digital fabrication with the manual craft of punch needle embroidery, leveraging the design tool provided by PunchPrint.

Contents

Chapter 1

Introduction

This thesis introduces a comprehensive set of guidelines covering various tools and practices for future endeavors in computational crafts [1]. I seek to develop methods to combine established forms of manual textile craft with additive fabrication to support new forms of personal textile production and interactions. Needlecraft enables craftspeople to manually create intricate textiles with different textures, shapes, patterns, and colors. From crafting complex three-dimensional objects, dresses, and accessories to cozy blankets, needlecraft offers a wide space for creative expression. Needlecrafts refer to a variety of textile craft practices that involve using a needle and yarn to create decorative and functional textile objects (Figure 1.1). Though many needlecrafts have been automated, manual textile production has continued to be practiced and cherished to create unique and personalized artifacts. Similar to needlecraft, additive fabrication possesses the remarkable ability of customization.

3D printing has become a popular tool for personal fabrication due to its ability to create intricate designs that can be quickly iterated and accurately produced at a low cost. Personal fabrication presents a vision for digital fabrication where people fabricate personal products and devices through digital tools [11].

Figure 1.1: Needlecrafts are a broad category of textile arts and crafts that entail using yarn and a needle to make decorative and functional textile objects [2–10].

One particularly exciting intersection of personal fabrication and 3D printing is the development of methods to produce textiles using fused-deposition modeling (FDM). Such techniques enable the fabrication of woven [12], flexible [13], and soft [14] materials and structures through a variety of methods that leverage the versatility of additive 3D printing toolpaths. These approaches have added benefit of being compatible with relatively inexpensive 3D printers and materials [15]. I will use the term 3D printed textiles to refer to programmable flexible structures that mimic traditional fabrics and are produced layer by layer through additive fabrication techniques.

Existing 3D-printed textiles are limited compared to traditional textiles in that they are entirely comprised of extruded thermoplastic filaments and other semi-rigid polymer-based materials. Thermoplastic materials have different visual and physical properties compared to fiber-based textiles. For example, creating fully opaque, multi-colored, single-layered textiles with existing methods is challenging. In contrast, fiber-based textile fabrication methods like knitting, weaving, and embroidery can be applied across a wide range of yarn gauges and colors to produce different patterns and textures

I see an opportunity to extend the expressive space of personal textile fabrication by integrating the equally rich but different domains of 3D-printed and fiber-based textiles. My aim is to understand the practical and theoretical aspects that arise when combining these fields. How can 3D-printed textiles achieve the desirable softness and vibrant colors commonly found in traditional fabrics? How can we integrate the workflows of digital fabrication and computational design with traditional textile crafts? And how can we support textile crafters in building meaningful projects with additive fabrication?

To address these research questions, I explored ways to integrate needlecraft with 3D-printed elements. Informed by the discoveries made in these explorations, I developed PunchPrint, a technique for integrating filament and fiber-based textiles. This involves combining the 3D printing of a custom parametric fabric substrate with punch needle embroidery. Additionally, I conducted a two-day workshop with textile crafters and enthusiasts to identify opportunities for supporting the integration of digital fabrication and computational design with traditional textile crafts. I designed a workflow to engage crafters with PunchPrint and create three-dimensional ornaments.

In this thesis, I propose an approach for embedding 3D-printed textiles with yarn through the manual textile craft of punch needle embroidery as a way for 3D-printed textiles to achieve the desirable soft and colorful attributes commonly found in traditional fabrics. To support this integration and expand the design space of punch needle embroidery PunchPrint was developed. Lastly, I discuss future opportunities and challenges of integrating punch needle embroidery with our PunchPrint system.

1.1 Attributions

PunchPrint was developed in collaboration with Mert Toka and Alejandro Aponte, graduate students from the MAT department, and professor Jennifer Jacobs. This work previously appeared in the Proceedings of the 2023 ACM Conference on Human Factors in Computing [16].

Chapter 2

Background and Motivation

To fully explore the possibilities and challenges of integrating punch needle, a traditional form of textile production, with 3D-printed textiles, it is essential to have a deep understanding of each field individually. 3D-printed fabrics have fundamentally different materials, design spaces, communities, and workflows. In these differences, I see opportunities for enriching both 3D-printed textiles and traditional fiber-craft practices.

2.1 3D-Printed Textiles

I will employ the phrase "3D-printed textiles" to designate flexible structures that can be programmed to imitate traditional fiber-based fabrics, created through additive fabrication techniques. There are four common methods for fabricating 3D printed fabrics: chainmail, Gcode, infill, and CAD modeling (Figure 2.1).

In the chainmail method, several small individual pieces are linked together to make a relatively flexible material [17]. Chainmail patterns can be highly customizable, allowing for intricate and complex designs to be realized. One notable drawback of this method is the time required for fabric assembly. However, certain designers have addressed this

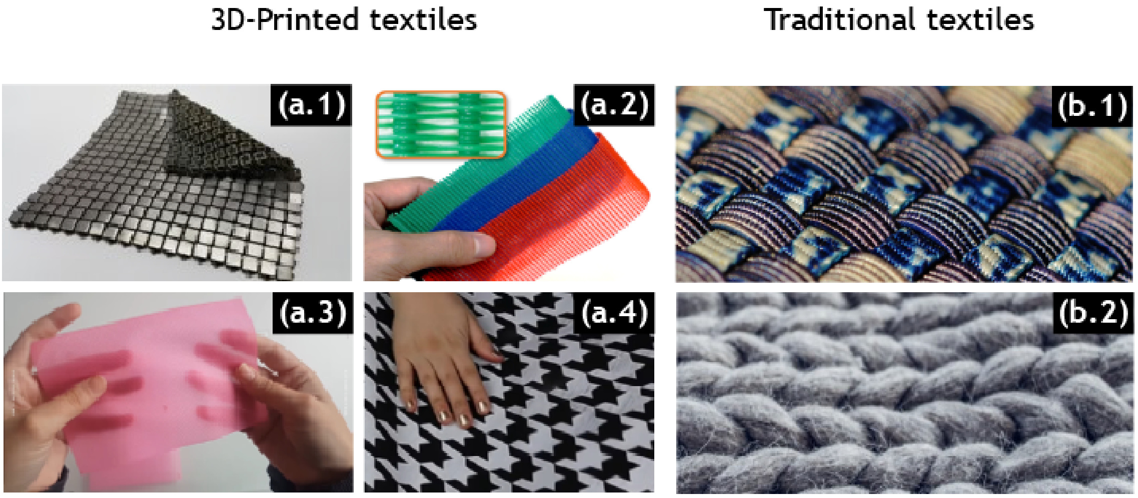

Figure 2.1: four common methods are used to create 3D-printed fabrics, each varying in difficulty and expressiveness. (a.1) shows a 3D-printed fabric done with the Chainmail method, (a.2) fabric was developed by programming G-Code, (a.3) used the Infill method, and (a.4) was made following the CAD modeling approach. 3D-printed fabrics still lack the look and feel of (b.1) woven or (knitted) fabrics fabricated through more traditional approaches.

limitation by developing specialized structures that enable printing multiple interlocked pieces simultaneously, reducing the overall assembly time [18]. The G-code method enables the creation of intricate and customizable 3D-printed structures through low-level instructions that control the nozzle of the 3D printer. Gcode enables precise control over a number of printing parameters, including temperature, layer height, infill density, and print speed [19]. Designers can tailor the fabric's characteristics, such as strength, flexibility, and density, to meet their particular needs and improve the printing process of the fabric. Complex fabric designs can need manual programming or the use of specialized software tools in order to create Gcode instructions. Due to its steep learning curve and the need for specialized programming and mathematics knowledge, this technique might be difficult for beginners. The infill method takes advantage of code built into a slicer to easily create fabrics with diverse patterns [20]. This approach requires fewer technical skills in programming and modeling. However, if the design of the fabric's general form is constantly changed, it might result in a complicated workflow between the slicer and the modeling software. Lastly, Computed aided design (CAD) is a common approach to creating shapes and patterns that can be easily modeled [20]. CAD software offers many advantages from design precision, visualization, and simulation to design iteration and customization. Nonetheless, CAD software typically requires specialized skills and training.

3D-printed fabrics are explored in various fields, including the realm of fashion. Notably, renowned fashion designer Iris van Herpen has embraced the use of 3D-printed materials to create avant-garde clothing pieces that beautifully blend traditional craftsmanship with cutting-edge 3D printing methods [21]. Adidas has introduced 3D-printed fabrics in their *future-craft* line of running shoes [22]. NASA's *space fabric* is a highly innovative textile material designed specifically for use in space exploration [23].

2.2 Punch Needle Embroidery

Fabric-based needlecraft techniques involve stitching designs onto a pre-existing foundation fabric, combining two textile structures into one fabric. The most common fabric-based needlecraft is embroidery, which has different subcategories depending on the fabric, thread a technique used. Among these types of embroidery, we have punch needle. In this section, we describe the punch needle stitch structure and common methods to convert traditional punch needle textiles into functional artifacts. We identify the challenges and limitations of traditional punch needle techniques as well as the advantages of integrating this technique with 3D-printed textiles.

Figure 2.2: Craftspeople commonly use punch needle textiles to produce craft artifacts ranging from decorative pieces to accessories, to garments. Examples include (a) The Wise– a visual artwork by Sara Luna [24], (b) Embellished Clutch– a handbag by Micah Clasper-Torch [25], (c) Stool Top– upholstery by Arounna Khounnoraj [26], (d) Untitled–tapestry by Adeline Wang [26].

2.2.1 Punch Needle Stitch Structure

In punch needle embroidery, the craftsperson uses a pointed needle with a hollow stem and an eye hole to create loops of yarn in a woven foundation fabric. Yarn is threaded through the needle and punched through the foundation fabric, creating loops along the back of the fabric and flat stitches along the top [27]. The side with the flat stitches is more detailed and resembles traditional embroidery, while the side with the loop stitches is textured like a rug.

Unlike regular embroidery stitches which interweave yarn back and forth between the fibers of the foundation fabric, punch needle structure relies on fabric tension to hold stitches in place. When the needle pierces the fabric, the warp, and weft are displaced. As the needle is pulled out, the tension of the woven structure holds the yarn in place and creates a loop [29]. This tension mechanism limits craftspeople to specific foundation fabrics.

The appearance of a punch needle textile is determined by the gauge of embroidery yarn and the structure of the foundation fabric. Loose woven fabrics like primitive linen, monk's cloth, rug warp, and weaver's cloth are the most common [30]. See Figure 5.4

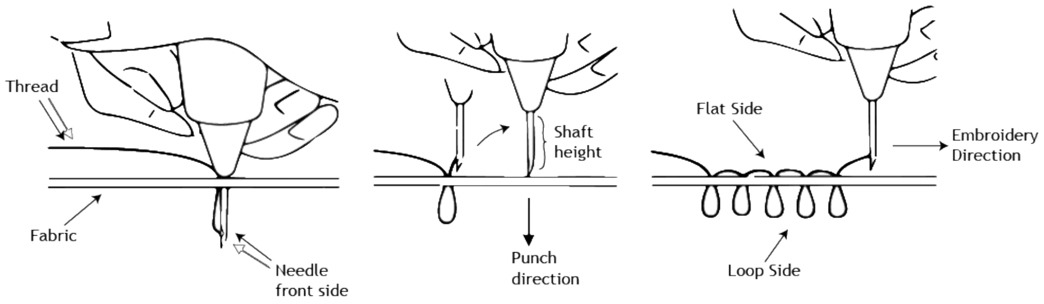

Figure 2.3: To create a punch needle stitch, a craftsperson perforates the foundation fabric with a specialized needle and then glides a small distance to insert the needle into the next location, creating a loop and a fat stitch simultaneously. (Diagram adapted from Zweigart [28]).

for examples of foundation fabrics. Woven textiles are measured by the number of warp threads or ends per inch (EPI). To punch needle with a desired yarn gauge, the craftsperson must select a foundation fabric with a suitable EPI. Larger gauge yarns require a lower EPI and finer gauge yarns require a higher EPI. The craftsperson must also select a needle diameter that is compatible with the EPI of the fabric. The lower the EPI, the smaller the needle. Incompatible needles increase the risk of fabric breakage during punching.

The thickness of the yarn is also constrained by the size of the needle. Yarn needs to continuously slide through the needle's handle during embroidery. If the yarn is too thin for the diameter of the needle, the needle will stretch the foundation fabric to a point where the fibers cannot create enough tension to keep the yarn in place [30]. Punch needles are available in a range of sizes to accommodate different yarn gauges and foundation fabrics. Large needles are best suited for thick yarns and low EPI foundation fabric. Small needles are required for delicate yarns and high EPI foundation fabric. Smaller yarn gauges require greater manual skill to embroider; however, they can produce delicate and detailed pieces.

2.2.2 Traditional Punch Needle Workflow

Craftspeople use punch needle textiles to create garments, accessories, and decor. While approaches vary, the crafting workflow generally includes the following steps:

1. *Transferring the design template:* The craftsperson draws, traces, or irons on a reference pattern to the foundation fabric to guide their stitch pattern [31].
2. *Securing the foundation fabric:* The craftsperson mounts the foundation fabric in a hoop to create a taut surface to allow punching with ease and efficiency.
3. *Punching the design:* The craftsperson threads the needle and, using a pen-like grip, punches rows of stitches (Figure 2.3). Craftspeople use different punching strategies such as staggering the stitches, punching across corners on an angle, or maintaining a constant stitch length to produce more consistent outcomes [30]. The craftsperson can vary the length of the flat stitch to create different aesthetics. Craftspeople can vary the length of the flat stitch to create different aesthetics.
4. *Post processing:* Craftspeople commonly incorporate punch needle textiles into decorative pieces, accessories, and garments (Figure 2.2b). To create a finished artifact with a punch needle textile, it is crucial to secure the edges of the foundation fabric to prevent them from unraveling. Craftspeople sew or glue the edges to avoid fraying. Sewing often takes longer but can result in a better aesthetic. Craftspeople often select a method for securing edges based on their project. For example, when making pillows or bags, craftspeople usually sew the edges and add additional functional components like zippers, clips, and other fabric.

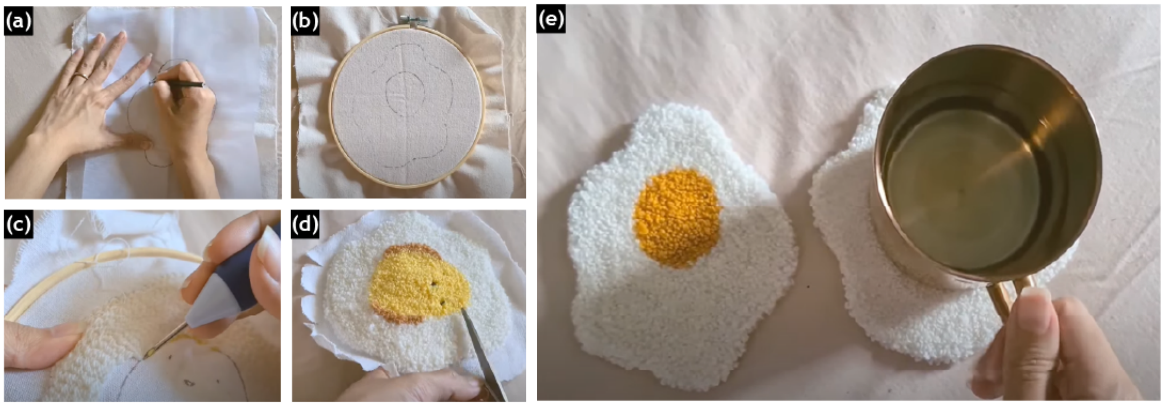

Figure 2.4: The workflow for punch needle is relatively simple, the craftsperson (a) transfers the pattern (b) secures the fabric (c) punch needle, and (d) secures the edges. (e) This workflow offers a flexible and enjoyable approach, allowing the craftsperson to freely improvise and iterate on their designs, providing a fulfilling creative experience [32].

2.2.3 Traditional Punch Needle Limitations

Traditional punch needle is versatile but presents several key limitations. Craftspeople are limited to using specific foundation textiles with proper EPI and durability. Foundation textiles are usually thick and stiff to maintain adequate yarn tension and withstand the punching process. This decreases the flexibility of punch needle pieces and constrains the scales and forms that are possible [30, 33]. Small delicate pieces are particularly difficult to create and stiff textiles can limit the production of flexible garments. Thin, lightweight fabrics can easily and irreversibly break, fail to adequately tension the loops, and create loops with inconsistent height [33].

Woven foundation textiles fray easily if unsecured. Much of the labor in punch needle involves post-processing steps to secure the edges. The more complex the outer perimeter of a design, the greater manual skill is required to secure the edges without altering the initial outline. Since the fabric frays when cut, designs with holes or hollow spaces on the interior of the structure are extremely difficult to achieve without a high degree of manual skill and labor.

2.2.4 Opportunities of Punch Needle Embroidery for Embedding 3D-Printed Fabrics with Yarn

Unlike other types of needlework, punch needle stitches do not require the craftsperson to knot or otherwise secure the stitch ends, and rows of stitches can be removed from the foundation fabric with ease. Punch needle stitches present advantages over other forms of embroidery because the craftsperson does not need to knot or otherwise secure the ends of the stitch and rows of stitches can easily be removed from the foundation fabric. These qualities suggest punch needle is an ideal craft to explore quick and easy ways for embedding 3D-printed fabric with yarn. Furthermore, punch needle's limitations are closely related to its foundation fabric. By using a 3D-printed fabric instead, we can provide a sturdy foundation fabric, giving the craft more opportunities for creating all sorts of new projects.

Chapter 3

Related Research

This chapter focuses on evaluating research done in the field of human-computer interaction (HCI) regarding 3D-printed textiles and the integration of textiles and digital fabrication.

3.1 3D-Printed Textiles in HCI

Researchers have explored a range of additive fabrication methods to produce flexible materials with similar properties to fiber-based textiles. Rosenberg and Rosenkrantz developed a system for designing flexible hinged modules that support selective-laser-sintering (SLS) printed construction of flexible garments without manual assembly [34]. Beecroft used SLS to produce a series of textiles with a warp-based structure that exhibits the same properties of traditional knitted textile structures [35].

Researchers have also used FDM printing to produce textiles. FDM printers are often more affordable than other 3D printing technologies and suitable for at-home use [15]. Takahashi and Kim used FDM to print textiles with a warp and weft structure where a single strand of filament is woven around a series of columns. Forman *et al.* under-extruded filament to produce large sheets of flexible semi-transparent fabric. They demonstrated applications in garment prototyping and aesthetic patterning [13]. Li *et al.* created extrusion-based sheet materials with sliding qualities through a toolpath that prints an arc-shaped channel over the crossing strand [36]. Rivera and Hudson modified a desktop printer to support the electrospinning of textile structures in combination with standard polylactic acid (PLA)-based printing [37]. We also seek to support desktop textile fabrication with FDM equipment. We create a 3D-printed textile suitable for fiber-based textile integration. Rather than woven structures or under-extrusion, we use a toolpath that reinforces the joints of a 3D-printed grid structure to produce a fabric that is robust enough for punch needle applications by reinforcing the segments at the filament crossings. Further, we develop a method compatible with TPU filament. This is critical to provide adequate elasticity to support punch needle insertion and yarn tensioning without breakage.

One key advantage of 3D-printed textiles is that they are programmable, meaning they afford a range of material and aesthetic properties depending on their print parameters. Researchers have developed general-purpose tools for designing toolpath behaviors for desktop 3D printers. Pezutti-Dyer and Buechley created a GCode generation programming library based on Turtle geometry that enables the creation of a range of flexible structures including textiles [14]. Subbaraman and Peek extended the p5.js programming library to control the behavior of a 3D printer. Their system enables the creation of bridged structures, compressible materials, and other forms [38]. As systems like these expand the design space of desktop printers, I see opportunities to further grow that space by developing methods to integrate established craft practices with material exploration in 3D printing.

3.2 Integrating Textiles and Digital Fabrication

The combination of craft, computational design, and digital fabrication can engage digital fabrication newcomers in personally relevant craft practices [39] and create new economic opportunities [40]. Researchers have added to the design space of textile craft through digital fabrication. One approach is to extend existing computer-numerically-controlled (CNC) embroidery machines. Sketch & Stitch enables craftspeople to convert hand-drawn sketches to CNC embroidery patterns. Craftspeople can embroider with conductive thread and integrate circuit elements to create interactive textile artifacts [41]. FabricClick showcases methods to create haptic buttons in fabric through an integrated workflow of embroidery and 3D printing [42]. In the adjacent domain of e-textiles, researchers have explored using punch needle for rapid prototyping [43]. Likewise, researchers have also extended the design space of CNC machines through computational design tools. Codeable Objects allows people to design and export the toolpaths for a laser-cut lamp [44].

Researchers have developed novel CNC machines that are compatible with craft materials. Hudson created a 3D printer that uses a modified layered felting process [45] and Peng *et al.* developed a method to laser cut and fuse 2D sections of fabric [46]. Digital textile fabrication is widely used in industrial production; however, industrial computer-controlled looms and knitting machines are prohibitively expensive for individuals. Albaugh *et al.* sought to broaden digital textile fabrication through the creation of a tabletop programmable Jacquard loom [47]. Moyer developed CNC machines for fabricating braided [48] and woven [49] textile bracelets. Similar to our integration of 3D printing and manual punch needle, Albaugh and Moyer's weaving machines deliberately incorporate hand-weaving. Most closely related to this work, He and Adar present a low-cost alternative to industrial punch needle machines by adapting an x-y plotter to support machine-automated punch needle fabrication [50]. I also aim to make digital textile fabrication more widely available and compatible with textile craftspeople workflow. Rather than developing automated textile fabrication machines, I aim to create a method for printing punch needle-compatible fabrics with desktop 3D printers.

This work builds on prior work that integrates digitally fabricated and manual craft materials. Rivera *et al.* developed a set of techniques to 3D print rigid structures and components directly onto fabric to produce composite rigid objects with embedded flexibility [51]. The ClothTiles technique extends this work by integrating shape memory alloy into 3D-printed fabric composites to create soft actuated structures [52]. PunchPrint takes a reverse approach. Instead of augmenting fiber-based textiles through the addition of 3D-printed components, we create a composite by using a filament-based fabric as the reinforcement.

Other researchers have also used digitally fabricated structures as scaffolds for manual crafting. Hybrid Reassemblage [53] and Hybrid Basketry [54] integrate 3D-printed pieces as a structural foundation in ceramics restoration and basket weaving, respectively. The unique structures possible through 3D printing can facilitate otherwise challenging craft outcomes like novel joinery in carpentry [55]. Digitally fabricated structures can also guide the craft workflow. Torres *et al.* use 3D-printed scaffolds to aid in shaping materials for wire sculpture [56]. For textiles, EscapeLoom uses soluble 3D-printed substrates and custom heddles to guide hand-weaving and 3D-printed scaffolds to aid in creating rigid geometry [57]. EscapeLoom also uses 3D-printed TPU guides to aid in weaving craft objects. This approach is the most closely related to our method. We use punch needle rather than weaving and therefore create structures that tension yarn loops rather than provide warps for woven fibers.

Chapter 4

Explorations

This chapter presents a series of explorations to study ways in which I could integrate needlecraft, mostly punch needle embroidery, with 3D printed elements. These explorations were in response to my first research question: How can 3D-printed textiles achieve the desirable soft and colorful attributes commonly found in traditional fabrics? I propose an approach in which we augment 3D-printed textiles. Needlecrafts offer the possibility of embedding 3D-printed fabrics with yarn to achieve the visual and tactile attributes of traditional fabrics.

4.1 Crocheting on 3D-Printed Elements

I began my research by combining crochet, my primary skill, with 3D-printed components. I designed a Grasshopper system to parametrically design a 3D-printed piece that could support crochet. Even though this method produces interesting and distinctive artifacts, the 3D-printed structure's properties remain essentially the same. The finished product still consists of rigid 3D-printed components with fabrics added for embellishment. This insight made me narrow my explorations to punch needle embroidery.

Figure 4.1: Using crochet, I am able to seamlessly integrate 3D-printed components with yarn, resulting in captivating and one-of-a-kind creations, nonetheless this approach does not fundamentally change the qualities of the 3D-printed structure.

4.2 3D-Printed "Woven" Textile

I decided to experiment with a woven-like 3D-printed fabric designed by Haruki Takahashi [12], inspired by the traditional foundation of punch needle crafting. This fabric, created using a custom Gcode approach, consists of three main parts: a base, pillars, and fibers. The base provides support and keeps the entire structure in place, similar to the way it's done on the bed. The pillars act like the warp in traditional weaving, while the extruded fibers across the pillars function as the weft. I wanted to see if I could punch needle on this fabric, so I made a wristband using this technique. Though the fibers moved when the punch needle pierced the fabric, most of the pillars of the fabric broke. This exploration demonstrated that it was possible to embed a 3D-printed fabric with yarn through punch needle. Nonetheless, it highlights the challenges of using rigid and brittle materials like PLA.

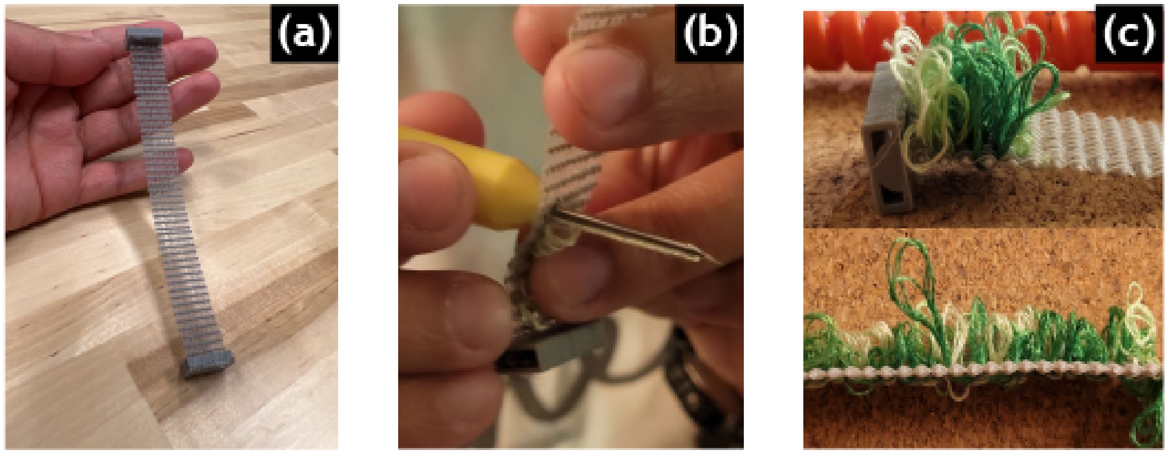

Figure 4.2: (a) I fabricated a 3D-printed woven fabric shaped as a wristband. (b) This exploration demonstrated that it was possible to embed a 3D-printed fabric with yarn through punch needle. (c) It also highlighted the challenges of using rigid and brittle materials like PLA.

4.3 Line and Grid Infill Method

During this experiment, I used the infill method and a flexible filament called TPU. Infill in 3D printing refers to the internal patterns found inside most 3D printed parts. There are many types of infill patterns, for example triangular, honeycomb, line, grid, or gyroid. The infill method takes advantage of the code built into the slicer to create these patterns to create complex and appealing 3D-printed fabrics without much effort. The first step of this method is modeling the fabric in CAD software. Step two is importing the geometry into the slicer and removing the top and bottom layers so we can expose the infill pattern. I focused on the line and grid patterns since these patterns mimic the structure of punch needle foundation fabrics. With this method, I was able to fabricate flexible 3D fabrics that resembled traditional punch needle fabrics. By varying the density of the infill pattern, I explored ways to fabricate fabrics that could support different yarn gauges. This approach provided a stronger fabric than the previous 3d-printed fabric explored, nonetheless, it still presents major challenges. For instance, once the design is imported it cannot be fundamentally changed, the design must be edited on the CAD software and then re-imported to the slicer. Additionally, both the line and grid infill pattern generates weak points and poor adhesion between layers. Unfortunately, this leads to fabric breakage when punch needling.

Figure 4.3: (a) The infill method offers a rapid way to produce TPU 3D-printed fabric. (b) Fabrics created with the grid or line infill pattern can be effectively used for punch needling. (c) The presence of weak points within these patterns results in the fabric breaking when subjected to the force of punching.

4.4 Computer-aided design modeling method

In my last experiment, I followed a CAD modeling method. I created a Grasshopper system that could parametrically design a grid-like fabric with any outline or shape. We can start designing the fabric by manually drawing a curve or importing a vector, then the system will generate a grid structure inside of the shape. Once the geometry is in Rhino it can be exported, sliced, and 3D printed as any other geometry. This approach generates a robust fabric that can withstand punch needle without breaking. This method also enables the integration of solid geometries, like hooks, and common assembly methods found in additive fabrication like press-fits. These new design opportunities open the door for the design of functional punch needle pieces with both rigid and flexible components. Nonetheless, This system heavily depended on Boolean operations, and processing particularly large fabrics is unreliable and often crashed the system. Moreover, fabrics that could be printed often had unexpected and inefficient toolpaths.

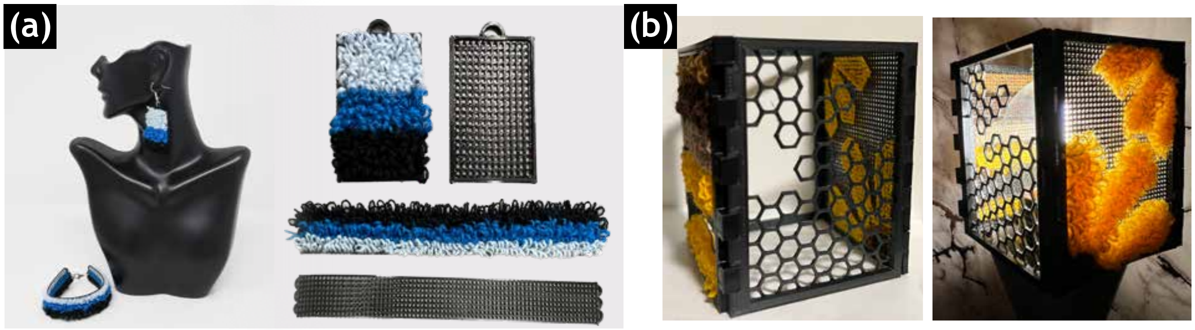

Figure 4.4: I modeled grid structures in Rhino to create programmable 3D-printed fabrics with different shapes. This method also enables (a) the integration of solid geometries, like hooks, and common assembly methods found in jewelry as well (b) common assembly methods used in additive fabrication like press-fits.

4.5 Takeaways

These explorations led to the following takeaways:

- It is possible to use punch needle embroidery to embed yarn into 3D-printed fabrics.
- A flexible grid-like structure can mimic the look and behavior of traditional foundation fabrics.
- We need granular control over the 3D-printed fabric to ensure an efficient toolpath and minimize the weak points.

With these insights, I noticed that there are no tools that can support the design of a 3D-printed fabric with these qualities. Hence, I seek support from fellow Media Art and

Technology students to develop a new tool based on the insights and necessities identified by through these explorations.

Chapter 5

PunchPrint system

This chapter focuses on the PunchPrint system, done in collaboration with Mert Toka and Alejandro Aponte. PunchPrint combines the takeaways from the explorations with new possibilities for expanding the punch needle crafting space. PunchPrint is a technique for integrating filament and fiber-based textiles by combining the 3D printing of a custom parametric fabric substrate with punch needle embroidery.

5.1 PunchPrint Design Goals

We analyzed the workflow and constraints of traditional punch needle practice to identify the following design goals for a method to integrate 3d-printed textiles and punch needle craft.

- **Programmable structure:** We seek to develop a 3D-printed textile that can vary in flexibility, thickness, and density while maintaining a structure that is robust enough to support manual punch needle stitches.

- **Novel textile properties through composite materials:** We aim to extend the design space of punch needle embroidery by incorporating affordances of filament-based textiles while also broadening the aesthetic and textural qualities of 3d-printed materials.

- **Support for new workflows in punch needle craft assembly:** We seek to integrate construction methods from both 3D printing and traditional textile craft to create new opportunities for punch needle craft.

5.2 3D Printing a Foundation Fabric for Punch Needle Embroidery

The initial component of our technique is a 3D-printed foundation fabric. We mimic the woven structure of fiber-based punch needle foundation fabric by printing a TPU-based grid structure that reproduces the behavior of textile fibers while providing visible holes for needle insertion. Our approach supports a wide spectrum of fabric densities with significantly reduced thickness and increased flexibility compared to traditional foundation textiles.

5.2.1 PunchPrint Fabric Development Process

Traditional woven punch needle foundation fabrics are comprised of vertical warp and horizontal weft fibers woven tightly together. When a needle with yarn goes through a hole in the fabric, its fibers move outwards. When the needle is retracted, neighboring fibers contract and force the yarn to stay in place (Figure 5.1a).

We designed PunchPrint fabric geometry to resemble this construction using intersecting filament extrusions. FDM manufacturing uses a hot end to melt and fuse filament strands. We use this property to avoid weaving warp and weft structures. Instead, we print horizontal and vertical filaments in two fused layers, creating a two-dimensional

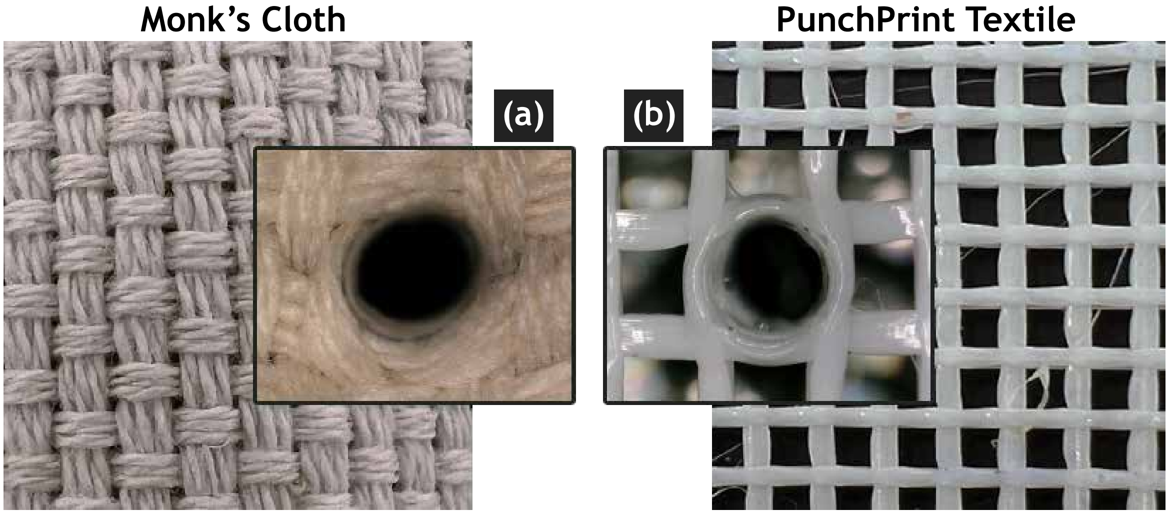

Figure 5.1: PunchPrint mimics the warp/weft construction of traditional woven fiber-based textiles using a grid structure. Here we show 12 EPI Monk's cloth– a popular punch needle foundation fabric. (a) By magnifying (50x) and piercing Monk's cloth with a 2.5 mm punch needle, we can observe how the threads in the fabric are displaced. (b) As a 2.5 mm needle perforates our material, we can observe a similar deformation in the cell, analogous to the displacement of threads in traditional fiber textiles.

grid structure. Figure 5.1b demonstrates how PunchPrint fabric performs similarly to fabric fibers: The filaments stretch outwards as the needle goes through and compresses as the needle is withdrawn, keeping the yarn in place.

Limitations of Existing Printing Methods

During my explorations, I attempted a naive approach of creating a fabric with a grid toolpath produced by slicer software. In FDM printing, it is common to fabricate grid structures as *infill* to speed up the printing process and reduce material usage. Commercial slicer software tools like Ultimaker Cura[1] support grid (Figure 5.2a) and line (Figure 5.2b) infill methods that can produce a visually similar grid structure to the PunchPrint fabric.

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[1] `https://ultimaker.com/software/ultimaker-cura`

These methods create robust structures for rigid volumetric prints but introduce weak points for flexible sheets with a small number of vertical layers. We conducted exploratory tests by printing two to four-layer grids using Cura grid and line infill methods and punching into the resulting fabric. We discovered these initial fabrics frequently broke as the needle was inserted during punching. We observed that grid infill produces weak points in the material at the point of intersection when freshly extruded material passes over a previously printed filament (Figure 5.3i,a-c). At the intersection, the melted filament collides with the solidified filament. Following the collision, the filament will under-extrude for several steps (Figure 5.2a).

The line infill avoids collisions by printing perpendicular lines at different layer heights (using a 100% offset) and allowing gravity to deposit the extruded filament on the layer below. This introduces weak points as the material stretches in the air as the nozzle moves away from the intersection (Figure 5.3ii,a-c). The increased layer height of line infill also results in poor layer adhesion (Figure 5.3ii,d-e) and creates thicker structures because it requires twice the layer height as the grid method for the same number of layers. The lack of adhesion in the line infill method can be reduced by increasing the infill extrusion rate to 150% (Figure 5.3iii,d-e).

We tested the infill methods using the support blocker feature in Cura which allows the printing of regions with exposed infill in combination with solid structures. However, using support blockers with non-cubic geometry is challenging since the feature only supports rectangular shapes. The combination of the structural weaknesses of standard infill methods and the absence of expressive design tools for grid toolpaths led us to develop a custom toolpath method that combines the benefits of grid and line infill methods to make a robust fabric for punch needle embroidery. We conducted initial exploratory tests by printing grids using both the grid and line infill from Cura and then punching into the resulting material. We discovered several key failure points of these infill methods when printing fabric with 2-4 layers. When initially punching on both line and grid infill, the fabric frequently broke as the needle was inserted. We found that for the grid infill method, when the fabric held up to needle insertion, a 2 layer grid infill fabric could produce adequate tension to hold the yarn loops securely in place. We theorized that the weak points in the grid infill led to the breakage. This limitation prompted us to develop a custom toolpath method that combines the benefits of grid and line infill methods to make a robust fabric for punch needle. Figure 5.3 shows an optical comparison of the infill methods and our method. Note that the infill method displays weak points regardless of the fabric stiffness. Also, the size of the weak point is independent of the EPI and most likely related to the nozzle diameter.

PunchPrint Iterative Development

To create a robust 3D-printed punch needle foundation fabric, we developed a custom GCode generator that allowed us to have granular control over toolpath generation. We implemented both grid and line infill in our generator and reduced the print speed and deposited extra material, but the process still produced weak points at the intersections. We then attempted to reinforce the line infill method by experimenting with increasing the height of the second layer by increments of 25%. We found that a height increase of 50% or lower produced notable weak points due to a considerable material collision between filaments, whereas 100% created poor layer adhesion.

To produce an even continuous filament with strong intersection adhesion, we printed the second filament layer that crosses the first layer at 175% of the layer height. This overlap of 25% of the layer height produced adequate adhesion at intersections without disturbing the material flow (Figure 5.2c). This small overlap at intersecting filaments still causes minor weak points. We addressed this by reversing the print direction and order of horizontal and vertical filaments in successive layers. This ensures that the

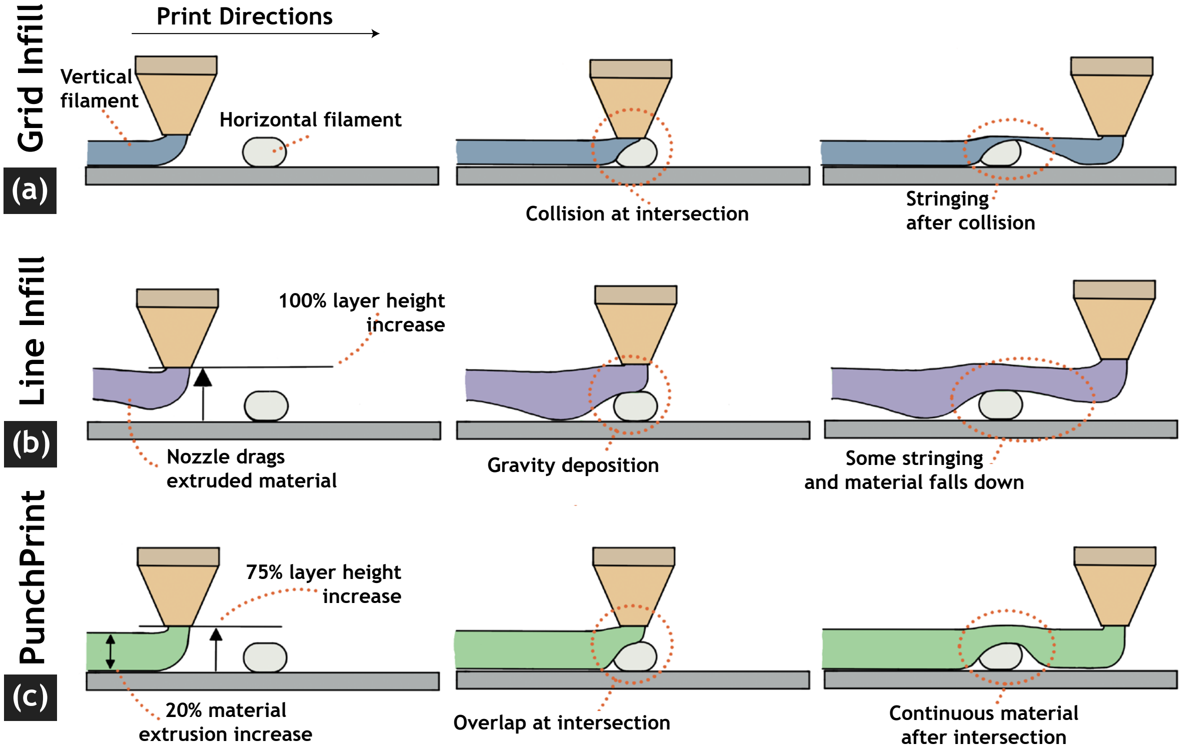

Figure 5.2: This figure illustrates the difference between the PunchPrint toolpath and the two infill methods in Cura slicer. The grid infill method (a) extrudes fresh material at the same layer height as the previous filament and creates a weak point at the intersection. The line infill method (b) extrudes fresh material at 200% of the initial layer height (next layer), resulting in poor layer adhesion between the previous and current extrusion. Our method (c) extrudes fresh material at 175% of the layer height and a 20% flow rate increase, resulting in continuous material flow and strong layer adhesion at the intersection points.

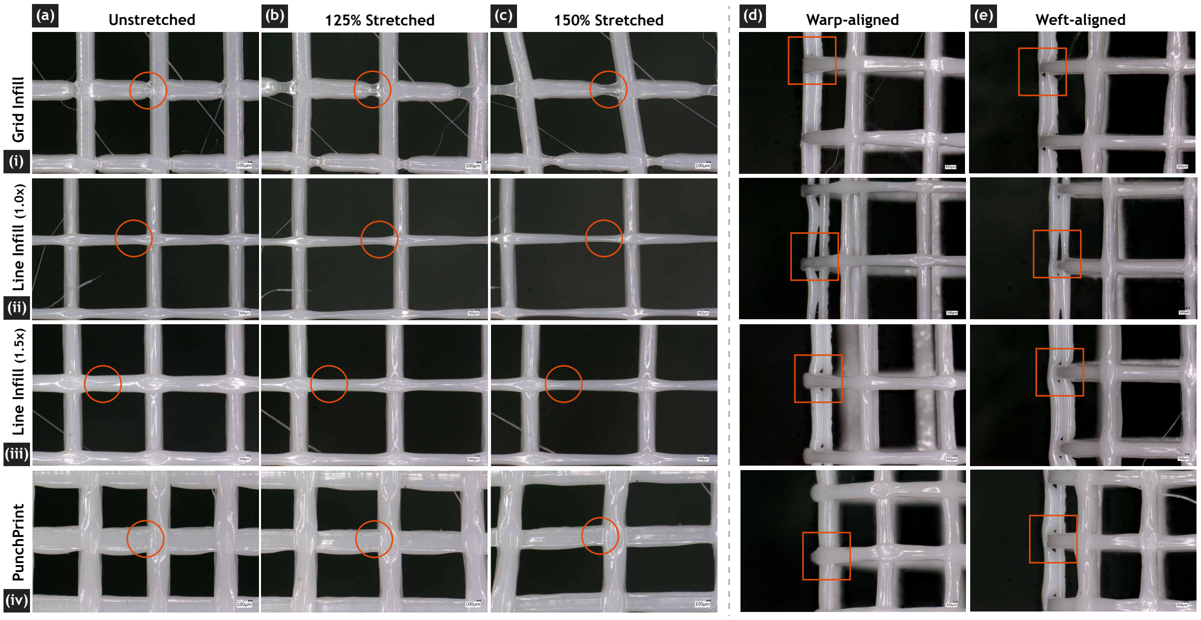

Figure 5.3: We fabricated two-layer textiles and compared the intersections of the grid infill method (i), line infill method with 100% flow rate (ii), line infill method with 150% flow rate (iii), and PunchPrint (iv) at 50x optical magnification. (a-c) shows the top view of the fabric when stretched laterally: (a) shows unstretched fabric, (b) and (c) show the fabrics stretched in one direction at 125% and 150% of their original size (corresponding to 6.35 mm and 12.7 mm displacements), respectively. (d-e) showcases the side profile of fabric walls: Warp-aligned view (d) displays the side profile of the first printed filament, and weft-aligned view (e) shows the side profile of the other direction of the fabric grid. Red circles identify the weak points' position and red boxes identify the under-extruded regions at the intersections.

minor weak points do not concentrate on a single spot (Figure 5.3iv,a-c). We found that alternating the order of horizontal/vertical filaments and increasing the material flow rate of the second filament by 20% ensures stronger layer adhesion (Figure 5.3iv,d-e). This combination of techniques produced a sturdy fabric that did not display visual weak points when stretched and held up when punched.

5.2.2 Characterization of PunchPrint

In this section, we provide comprehensive print parameters and present the results of a needle compatibility test with various needle diameters and fabric densities. We compare the tensile strength of our fabric to the grid infill method, which produces fabric of a similar thickness.

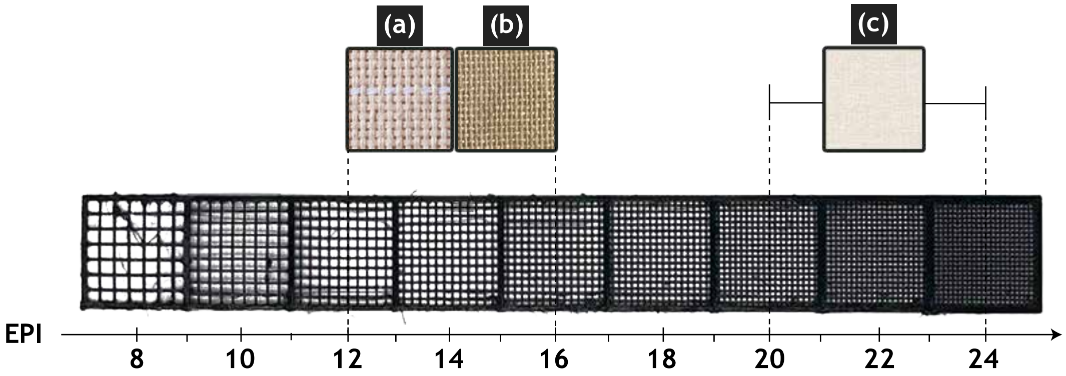

Figure 5.4: In comparison to traditional punch needle foundation textiles, our method supports a range of fabric densities with significantly reduced thickness and increased flexibility. We can create fabrics with varying ends per inch (EPI) and combine them in a single piece of fabric. The bottom strip shows nine ~2.5 cm squares with increasing EPIs, and the top images compare three commonly used fabrics for punch needle embroidery: (a) Monk's cloth (12-16 EPI), (b) primitive linen (12-16 EPI), and (c) weavers cloth (20-24 EPI).

Characterization Metrics and Properties

In characterizing our foundation fabric, we adopt EPI as the primary metric for the fabric *density*. In Figure 5.4 we compare commonly used fiber fabrics and our filament-based solution. While smaller EPIs support thicker needles and yarn, higher EPIs provide a foundation for intricate designs with thinner needles (Figure 5.5). In addition to the density, we can control the *stiffness* of the fabric by controlling the number of vertical layers. As the number of layers increases, the fabric becomes stiffer and harder to stretch. Note that fiber-based textiles do not have such properties and stiffness is unique for 3D-printed textiles.

Printers and Print Parameters

We printed our foundation fabric using elastic TPU95 filament with a 0.4 mm nozzle diameter and 0.2 mm layer height. We used a nozzle temperature of $220°C$ and a bed temperature ranging from $50°C - 60°C$. We tested our method on two different printers– the Creality Ender S1 Pro, which currently retails for $479 USD[2] and the Ultimaker S5, which currently retails for $6,950 USD[3]. Ultimaker and Ender use filament diameters of 2.85 mm and 1.75 mm, respectively. We observed no significant difference in printing qualities across either the Ender or the Ultimaker. We used 10 mm/s as the retract speed, 20 mm/s as the fabric printing speed, and 30 mm/s for other geometry. Since TPU is an elastic material and buckles if the filament retracts too far, we used a 1.5 mm retract distance. We use extrusion multipliers of 1.5 on the first layer (the direction that corresponds to the warp in woven fabrics) and an extrusion multiplier of 1.8 for the second layer (the direction that corresponds to the weft). As we describe in section **??**, our method is compatible with printing solid elements including walls, borders, tabs, and loops. We do not modify the extrusion rate for these elements.

Punching Testing

The programmable nature of PunchPrint enables us to vary the EPI of the fabric to support different yarn types. Even though our substrate is flexible, it will break when stretched by a needle of an incompatible diameter. We, therefore, sought to understand the behavior of different PunchPrint EPIs with different punch needles. We characterized needle compatibility by printing two sets of nine test fabrics with varying EPIs for one-layer and two-layer stiffness values. We then punched each fabric with a gradually increasing needle size. To evaluate representative methods in punch needle craft practice,

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[2] `https://store.creality.com/products/ender-3-s1-pro-3d-printer`

[3] `https://www.matterhackers.com/store/l/ultimaker-s5`

we selected a range of popular needle sizes that comes in most punch needle kits instead of sampling needle diameters from a uniform distribution.

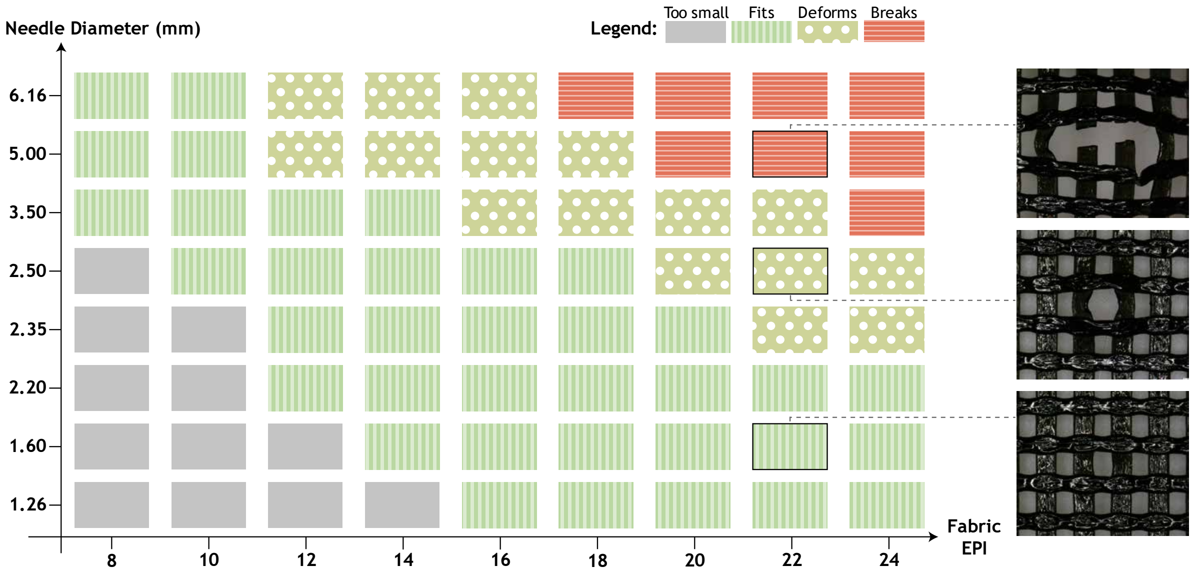

Figure 5.5: Using PunchPrint's parametric design interface, craftspeople can design foundation fabrics for desired needle sizes and yarn gauges. (Left) This chart shows the compatibility of different needle sizes with various foundation fabric densities. The color codes are as follows: *Gray* with flat background signifies that the needle is smaller than the hole; *green* with the vertical stripe pattern signifies the needle is compatible with the fabric hole; *green-yellow* with the circular pattern signifies the needle deforms the fabric hole, yet still is compatible for punch needle; *red* with the horizontal stripe pattern signifies the fabric breaks). (Right) 50x magnified optical results of punching a 22 EPI foundation fabric with 1.6, 2.5, and 5 mm needles.

We report our findings in Figure 5.5. We present a single value for both the one-layer and two-layer conditions for each EPI setting because we found that layer count did not affect needle compatibility. We performed each punch test three times. We present the outcome of the majority voting. Our results demonstrate that our method successfully fabricates materials that are compatible with standard punch needle diameters. For each needle we tested, we fabricated at least two compatible fabric EPIs. Our results also show that our method creates individual EPIs that can accommodate a wide range of different needle diameters. In the majority of cases, a single EPI supported five or more different needle diameters without permanent visual deformation or breakage. This suggests that a single PunchPrint fabric can support a range of different yarn gauges.

Mechanical Stretch Testing

PunchPrint provides a flexible substrate for foundation fabric that can be stretched as a craftsperson works with it. However, we observed that the high-stress points (intersecting filaments) are prone to breaking if there are discontinuities along the fabric filaments.

We performed a tensile stress test to demonstrate the stretch limit of our fabric and estimate the load capacity compared to the Cura grid infill method. All PunchPrint artifacts, with the exception of one, use a two-layer fabric (see section 5.4). We found that two layers create a flexible and lightweight material suitable for wearable and deformable products. We compared our two-layer fabric to Cura grid infill because grid infill produces a fabric of comparable weight. Printing a two-layer line infill fabric produced a result that was substantially thicker than our fabric. We also compared three-layer PunchPrint and grid infill fabrics to examine if three layers increased tensile strength.

We designed a fabric test geometry based on the commonly used dog bone design for tensile tests. We created the test specimens with TPU95A with solid flaps in the fixture points and a 76.2 mm x 25.4 mm (3 in x 1 in) fabric with an external wall in the middle section. We recorded displacement and load during each test. Figure 5.6a and 5.6b present load vs. displacement for each two-layer and three-layer test specimen. In both graphs, the behaviors are consistent for the grid infill and our method. Across both layer counts, the grid infill method showed signs of rupture at different intersection points along the fabric. Our method shows a consistent increase in the load and displacement. The only rupture points that were consistent in both pieces occurred at the outer walls, which were printed using a toolpath without modifying layer height when crossing already

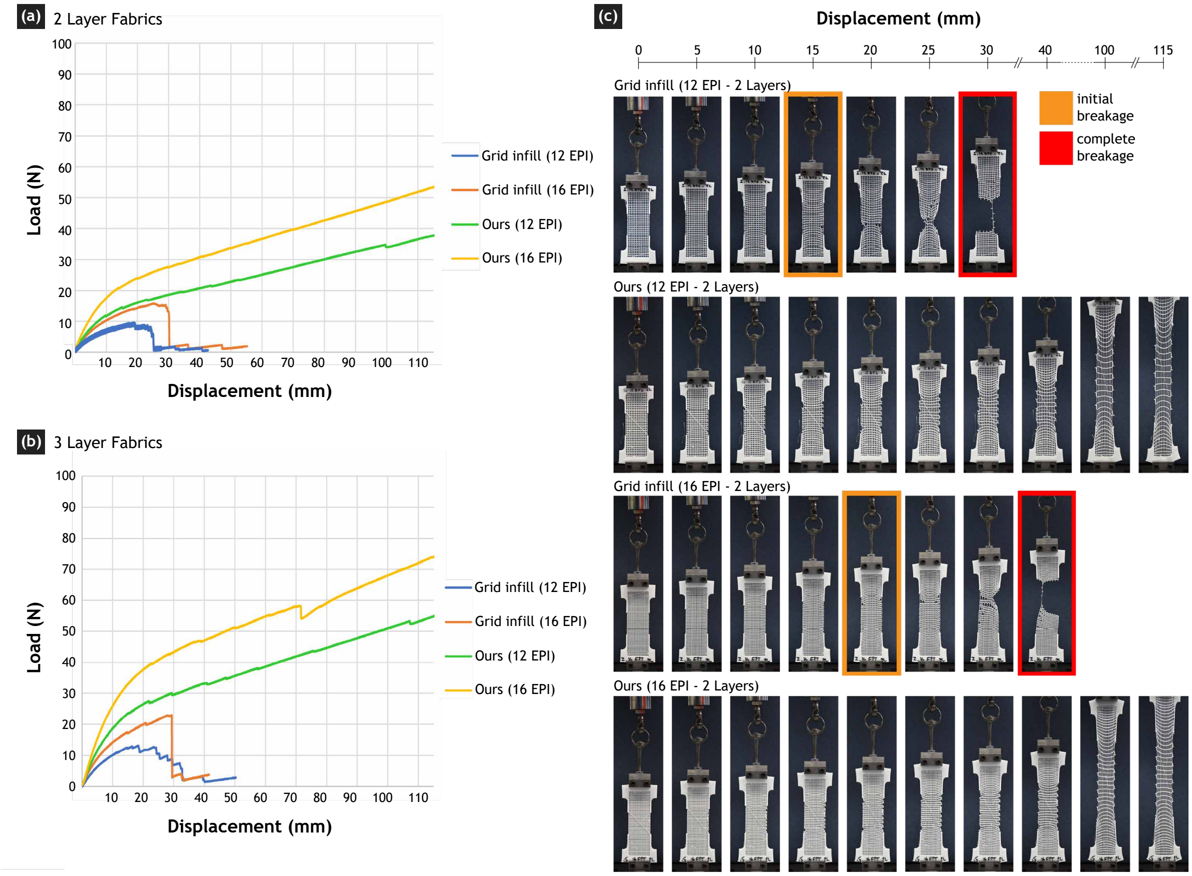

Figure 5.6: Tensile test analysis showing the mechanical superiority of our fabric method to the grid infill method by comparing load and stretching capacity. Load vs. displacement graph for test specimens with 12 and 16 EPI for infill and our method with (a) 2 layers and (b) 3 layers. (c) Tensile specimen deformations based on displacement for 12 and 16 EPI for the 2 layered pieces. Our method substantially outperforms infill in all performed tests. The sudden load drop for the sample using our method at 16 EPI with 3 layers was due to slight displacement of the specimen at the grips.

extruded filament. We found our method could stretch three times its original size with no break points in the fabric. [4] In contrast, the grid infill method began breaking at 15 mm of displacement for two-layer 12 EPI fabrics and 20 mm of displacement for three-layer 16 EPI fabrics, respectively. These results validate our printing approach; by changing the toolpath to optimize for material extrusion, we can create a grid-like fabric with stronger mechanical properties using the same material and desktop 3D printing equipment. We report the full outcomes of our static tension tests for 2 and 3-layer fabrics in Figure 5.6.

5.3 PunchPrint Design Workflow

We integrated our fabric toolpath process into a parametric design tool for craftspeople to control fabric properties and integrate other design elements into the print. Our approach supports a new punch needle fabrication workflow that can expedite the punching process and help integrate complex patterns and shapes without having to punch them. Our tool also allows the incorporation of 3D-printed structural elements into the foundation fabric which can reduce labor and support new assembly methods. To fabricate a robust substrate integrated into a surrounding form, PunchPrint proposes a design workflow for punch needle embroidery by taking the best practices from punch needle craft and digital fabrication.

5.3.1 Preparing the PunchPrint Geometry

We developed a Rhino and Grasshopper-based parametric system [58] that enables craftspeople to create punch needle foundation fabric by designing a form comprised

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[4] It is unlikely any fabric would need to withstand 115 mm of displacement for punch needle artifacts. We report results at this stage for completeness.

of simple curves to be filled with foundation fabric. We implemented a PunchPrint Grasshopper component with two parameters for controlling fabric structure: *EPI*, which controls the fabric density, and *stiffness*, which is the number of vertical layers of the fabric. The PunchPrint component has a third parameter that accepts any closed planar curve as input. Our tool will constrain the dimensions of the fabric within the boundaries of the input curve. By adjusting sliders for the EPI and stiffness and altering the input curve, the craftspeople can produce a range of fabric geometries with different structural properties.

Our tool also allows craftspeople to create *design guides* and *holes* on the fabric geometry using simple curves. Design guides evoke the guides craftspeople manually transfer onto fabric in traditional punch needle practice. The design guides in PunchPrint consist of continuous filaments printed over the foundation fabric. We can adjust the thickness of the guides to either produce thin structures hidden by the yarn or thick structures that act as design elements in the final piece. Design guides can be specified as an additional curve input to the PunchPrint Grasshopper component. The same process can be used to create arbitrarily shaped holes in the fabric geometry. The PunchPrint component contains a “hole” parameter that accepts curves as input and produces a gap in the printed fabric that conforms to the hole curve geometry.

The PunchPrint component has different settings for internal and external walls. The curves that designate the fabric and hole boundaries can also act as additional structural geometry by forming internal walls or external frames. The dimensions of these features can be specified by the *width* and the *height* parameters of the walls.

We also developed a workflow that allows pre-sliced 3D geometry to be incorporated into our fabric to leverage commercially available slicers to generate highly optimized toolpaths for complex 3D parts. In this workflow, we design a 3D form in any CAD software and export a 2D-profile curve that corresponds to the base of the 3D form. We then use this curve as input to the PunchPrint Grasshopper component to generate the toolpaths for fabric that fits their part. We export the toolpaths for the fabric and create an STL file for the 3D geometry. We slice the STL in a commercial slicer with print parameters that correspond to our fabric. This results in two GCode files– one for fabric and one for the 3D geometry. We append each layer of the fabric GCode to the start of the corresponding layer of the sliced geometry GCode. We insert the correct extrusion position (G92 E#) before and after the fabric code to overcome the discrepancy between the two toolpath creation methods. We use this approach to create both the butterfly jewelry (Section **??**) and 3D chess pieces (Section **??**) in our applications section.

5.3.2 Embroidering PunchPrint Fabric

Creating punch needle stitches in PunchPrint fabric is nearly identical to the traditional punch needle technique, with the notable exception that fabric structures do not need to be secured in a frame or hoop. This is because, unlike fiber-based fabric, PunchPrint fabric does not require considerable force to pierce the fabric. The grid structure also facilitates consistent stitch spacing and length, and design guides can aid in following the contours of the pattern.

5.3.3 Post-processing and Assembly

Unlike woven fabric, PunchPrint does not require post-processing to secure the fabric edges. We, therefore, eliminate one labor-intensive step in the traditional punch needle workflow, particularly when creating small, detailed, and irregularly-shaped pieces.

PunchPrint also supports a range of assembly methods to create artifacts that are not possible to print as a single piece. PunchPrint pieces can be sewn together using methods that are nearly identical to those for fiber-based textiles. Because PunchPrint

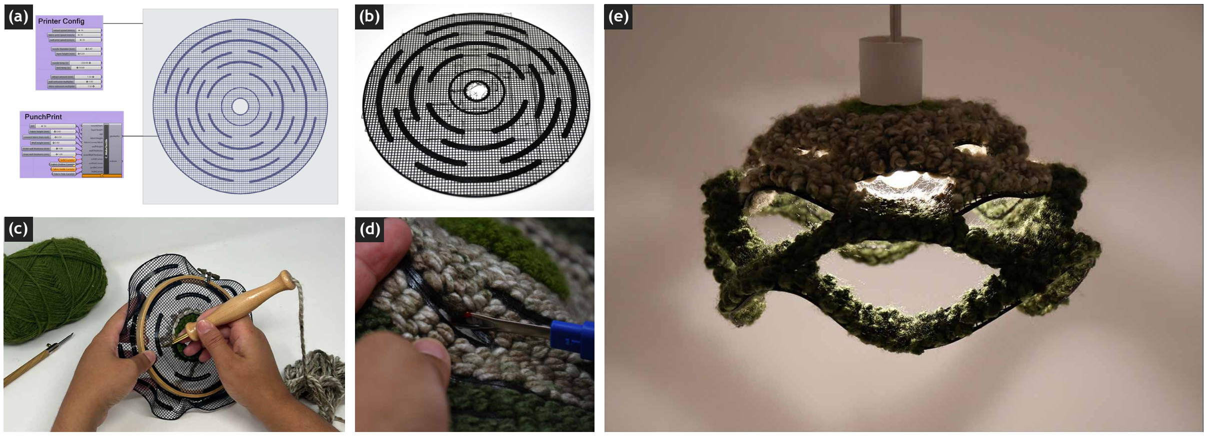

Figure 5.7: PunchPrint design workflow for punch needle kirigami lampshade: (a) Grasshopper parametric design tool that generates a toolpath for 3D-printing of a textile substrate; (b) fabricated 2D fabric with unopened holes; (c) attaching an embroidery hoop to punch needle the fabric with yarn; (d) cutting the stringing material inside holes with a seam ripper; (e) final artifact assembled with a light bulb.

fabric does not need to be secured along the edges, pieces can be sewn together along the fabric frame using the exterior holes in the grid. Like traditional sewing, stitches can be easily removed and pieces can be disassembled. Sewing, while more laborious than other forms of assembly, was well suited for connecting multiple curving pieces while maintaining flexibility.

Like traditional punch needle craft, PunchPrint pieces can also be assembled or finished with craft connectors like hooks, loops, and buttons. Rather than manually attach connection points for these pieces, we directly print the connection features as part of the PunchPrint material.

Lastly, PunchPrint pieces can also be assembled through common methods in digital fabrication including press fit joints and mechanical assembly. By changing the shape and size of the fabric frame, we can generate sturdy insertion points and tabs for snap and press fit features.

5.3.4 Limitations

PunchPrint relies on TPU which is notoriously prone to stringing in comparison to other thermoplastic filaments [13]. Although our printing method limits stringing, when it occurs, it can cause the layer to de-adhere or break at the intersections. We address this by printing fabric structures of two or more layers which can compensate for missing portions in the previous layer. Another issue with stringing is that it can interfere with the embroidery process. It is necessary to remove excessive stringing manually using a scissor or utility knife. We found in practice this took 1-5 minutes depending on the scale of the piece.

The PunchPrint slicer insertion workflow requires accurate specification of a few key parameters to function correctly. Namely, it is important to overlap the sliced geometry and fabric to have proper form, but aligning these two separate processes can be challenging. Developing a script to automate the GCode insertion process would address this issue and could be implemented in a future PunchPrint system.

PunchPrint fabric has a flexible quality not found in traditional foundation fabrics. If the holes are stretched too far, fibers that are punched with the needle may not be properly tensioned. This issue is less likely when needle size and yarn thickness match well with the fabric EPI, as demonstrated in Figure 5.5. To avoid the fibers slipping through the fabric, some craftspeople prefer placing glue on the flat stitches. However, glue does not couple the fiber into the TPU-based fabric as effectively in comparison to fiber-based foundation fabrics.

5.4 Applications

By integrating punch needle methods with 3D-printed textiles, we can expand the applications of both domains. Here we demonstrate the expressive potential PunchPrint to fabricate composite garments with 3D-printed and fiber-based textile structures and enable the production of small intricate jewelry pieces. We further demonstrate how we can build on standard assembly methods in 3D printing to re-envision common hobbyist 3D printing projects in punch needle form.

5.4.1 Crafting Multi-material Reversible Garments

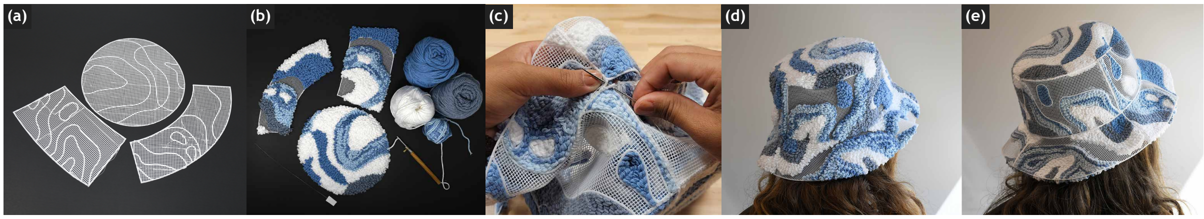

Figure 5.8: PunchPrint design workflow for punching a reversible bucket hat that consists of four brim pieces, four side pieces, and one crown piece: (a) One crown, side, and brim piece fabricated using PunchPrint's parametric workflow; (b) the same pieces punched with yarn; (c) assembling the hat using an embroidery needle and white sewing thread; (d) the looped side and (e) the flat side of the final artifact. Reversing the hat also demonstrates the bendability of embroidered PunchPrint fabric.

Both traditional textile craft and 3D printing provide opportunities for personalizing and fabricating garments. To demonstrate how PunchPrint supports the construction of punch needle garments that can be shaped or bent to fit the body comfortably, we fabricated and assembled a reversible bucket hat (Figure 5.8). This piece exemplifies how PunchPrint enables the creation of highly bendable 3D-printed textiles by augmenting the methods of textile garment sewing to create reversible garments. We used an existing sewing pattern as a fabric printing template and eliminated the need to cut and secure the edges of the individual pieces of the punched textile.

To create the hat, we converted an existing 9-piece traditional sewing cut pattern (crown, four sides, four brims) into a series of Rhino curves. We manually drew additional curves within each cut pattern to serve as design guides for different yarn colors. We set the design guides to a width of 2 mm so they would be entirely hidden by the punch needle loops but visible on the reverse flat-stitched side. We used the cut patterns and design guide curves as input to PunchPrint Grasshopper tool to generate a set of fabric toolpaths with 12 EPI. We printed each piece in white TPU on a Creality Ender S1 Pro (Figure 5.8a). The total print time was approximately 6 hours. We punched the hat with a 3 mm needle and 4-medium gauge worsted cotton yarns in various colors to correspond with the design guides. We deliberately left some portions un-punched to create stylized ventilation patterns in the design (Figure 5.8b). After punching, we used a standard embroidery needle and white thread to sew each piece together by looping thread through the holes in the PunchPrint textile (Figure 5.8c). The completed hat is reversible with a plush appearance on the looped side (Figure 5.8d) and a fabric-like appearance on the reverse with visible white plastic design guides (Figure 5.8e).

5.4.2 Reducing Labor and Ensuring Consistency in Small, Intricate Designs

Crafting small-scale punch needle pieces like jewelry can be difficult. It requires a high degree of manual skill to produce consistently tight stitches and the post-processing of small-scale items is challenging. For example, most punch needle earrings are limited to simple geometric profiles due to the complexity of post-processing a small fabric artifact [59, 60]. We developed two Monarch butterfly-themed earrings to demonstrate how PunchPrint facilitates small-scale punch needle embroidery artifacts (Figure 5.9).

We imported a 2D butterfly SVG design into Rhino and extruded it into a 3.5 mm-high 3D solid with holes corresponding to the veins of the butterfly's wings. We modeled loop anchor points and merged them with the extruded butterfly pattern. We used the original 2D butterfly outline as input to the PunchPrint Grasshopper component (Figure 5.9a) and generated a fabric toolpath with 18 EPI. We exported the 3D butterfly

Figure 5.9: PunchPrint supports the creation of programmable and robust 3D-printed foundation textiles that are compatible with punch needle crafting. We present a design tool and fabrication workflow that reduces labor while supporting the production of detailed composite artifacts. Here we show how PunchPrint enables crafting small detailed designs. (a) We provide a parametric design interface for fabricating a flexible, filament-based textile substrate with design guides and hooks to facilitate assembly; (b) The craftsperson inserts fiber elements using standard punch needle embroidery methods on the 3D-printed foundation fabric; (c) The assembled final artifact with earring hooks and beads.

form as an STL, sliced it in Cura, and appended the fabric GCode into the sliced GCode. We printed the resulting code twice on the Ultimaker S5 using black TPU. Each earring took approximately 25 minutes to print. The smaller scale resulted in a significant amount of stringing, which we removed by hand. To maintain the details of the design, we matched a 1.6 mm needle with three strands of embroidery floss. We punched with a loop height that corresponded with the height of the 3D butterfly geometry (Figure 5.9b). We assembled the butterfly pieces into earrings by placing jump hoops and beads in the anchor points (Figure 5.9c), enabling the earring to dangle and move freely without any risk of damaging the fabric. The completed piece showcases how our PunchPrint enables the creation of small-scale punch needle designs with minimal finishing effort and fine-grained details in both the loop and flat side.

5.4.3 Extending Common 3D Printing Techniques and Projects with Punch Needle Aesthetics

The previous two examples demonstrate how we can reduce challenges and support new design opportunities in traditional punch needle crafts. PunchPrint also provides opportunities to use common desktop 3D printing techniques to construct composite 3D-printed textile artifacts. 3D printing and other forms of digital fabrication allow for the design and fabrication of precise joints and fixtures for modular assembly. Inspired by the common desktop 3D printing chess set project[5], we created a press fit knight piece (Figure 5.10i-j).

We followed a similar workflow as the butterfly earring. We extruded a 2D knight outline with a tab in the middle into a 3.5 mm-high border and sliced it in Cura (Figure 5.10a). For the base, we created a 5 mm-high extruded exterior hexagonal border and the interior border with a hole supported by four narrow cross-sections. We also sliced these forms in Cura. We appended the knight and base GCode from Cura to corresponding fabric toolpaths generated in Grasshopper with 16 EPI (Figure 5.10c-d). We printed the parts with white TPU on the Creality Ender S1 Pro in approximately 30 minutes each (Figure 5.10e-f). We punched each piece using a 2.20 mm needle and embroidery floss. We used a small loop height on the knight body to preserve the 3D-printed eye and nose details and a large loop height on the mane and base to mimic the appearance of hair and grass (Figure 5.10g-h). Once the punching process was complete, we press-fit two pieces together without using adhesives. This approach allows for a seamless intersection of two perpendicular fabric surfaces which is difficult to reproduce with traditional fabric alone. The completed piece exhibits a 3D rigid structure and fine-grained details produced through TPU and varying punch needle stitch structures.

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[5] https://all3dp.com/2/3d-printed-chess-set-pieces/

Figure 5.10: PunchPrint design workflow enables integration of our fabric method and complex geometry sliced with commercial slicers in the same print. It also creates an opportunity in assembling punched pieces together using press fit methods: (a) Surrounding geometry sliced with Cura; (b) our fabric generated in Grasshopper; (c) inserting the fabric GCode into sliced GCode results in a unified form; (d) the same procedure as in (a)-(b) repeated for the base of knight; (e) fabricated and (g) punched knight piece; (f) fabricated and (h) punched base piece; (i) the looped and (j) flat sides of the final artifact (6.5 cm).

In addition to adapting 3D-printed mechanisms, PunchPrint also allowed us to extend other common desktop 3D printing projects. Lampshades are popular among personal 3D printing projects because the build volume of desktop 3D printers can accommodate the dimensions of a lampshade [15]. 3D-printed lampshades often include perforations to allow light to pass through– a design feature previously not possible in punch needle lampshades. We used PunchPrint to create a kirigami-based lampshade with gaps to allow the light to shine through (Figure 5.7e). We imported an existing kirigami cut pattern into Rhino and used the PunchPrint Grasshopper component to specify interior curves that would serve as holes, an exterior border, and a fabric fill with 10 EPI (Figure 5.7a). We deliberately printed the cut pattern as semi-fused borders to mimic the kirigami process and retain a cohesive material for punch needle embroidery. We printed the shade on the Ultimaker S5 using black TPU (Figure 5.7b) in 1 hour and 20 minutes. We punched the resulting pattern with two different yarn gauges and corresponding needles (Figure 5.7c). We used a 3 mm needle for the green yarn and a 5 mm needle for the multi-color (green and beige) yarn. Because the lampshade print was round and had no extruded borders, we secured it with an embroidery hoop to speed up the punching process. We used a seam ripper to open the kirigami holes in the shade (Figure 5.7d) and attached a light fixture. The completed lamp shows how our method incorporates hollow regions in a punch needle design with minimal post-processing.

5.4.4 Shaping and Actuating PunchPrint Fabric

The butterfly earrings and the chess piece demonstrate but a fraction of possible projects only possible by the integration of 3D printing. This last example aims to dive a little deeper into future punch needle artifacts. Inspired by [61], we design a punch needle butterfly automata, alighting on a tulip flower (Figure 5.11c). This example showcases the creative potential of adding channels to PunchPrint fabric. This example has three PunchPrint artifacts: the grass, a pivoting butterfly (Figure 5.11a.2), and the tulip petals (Figure 5.11b.2). The stem of the flower was made with crochet while the rest of the parts were 3D printed using PLA (pot) and PETG (mechanism parts).

This example presents two ways of using channels. The butterfly's channels serve as a pivotal point (Figure 5.11a.1), the body is fixed on a base while the wings are connected to the connecting rod of the mechanism. The wings of the butterfly are made of black TPU while the body and head are black PETG. The fabric is designed to be 14 EPI fabric and was punch needled using a range of pink and purple embroidery floss.

The petals support the integration of wires into the fabric (Figure 5.11a.1), enabling the creation of precise shapes, contours, and structural elements. This technique offers enhanced flexibility and opens up new possibilities for sculptural designs in punch needle embroidery. Inspired by a common crochet technique to create realistic tulips with a wire hidden on the edges, we designed six individual tulip petals made with yellow TPU.

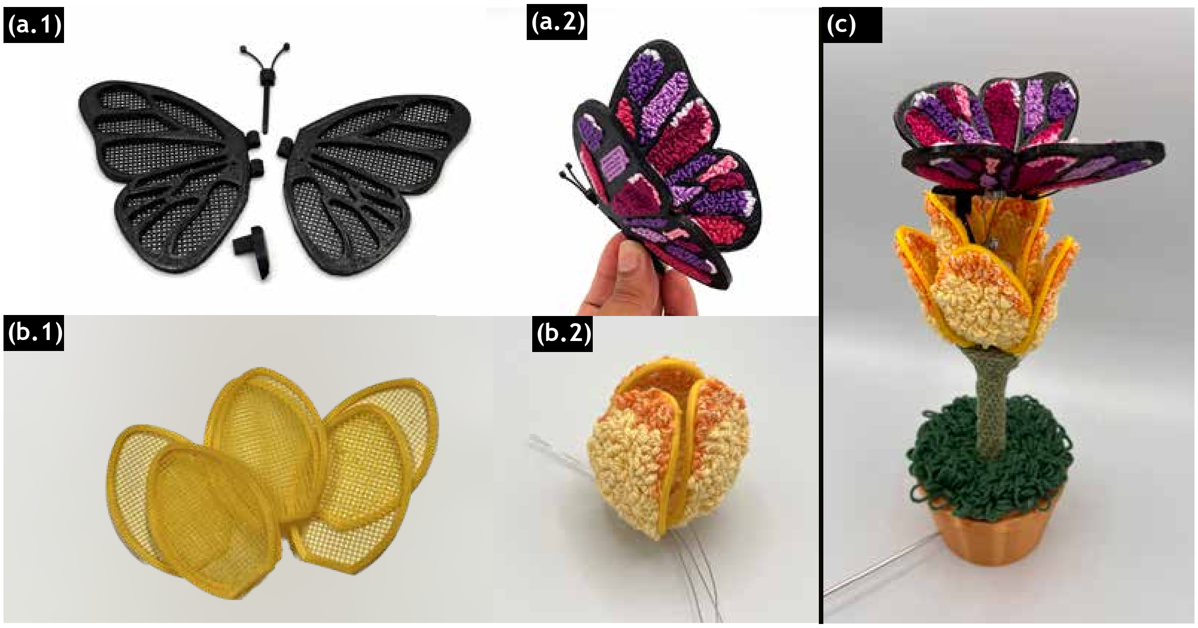

Figure 5.11: PunchPrint enables the integration of channels which expands the assembly opportunities while making possible (a) PunchPrint pieces that can move or (b) be combined with shaping materials, like wire, to achieve complex and specific forms. (c) We present manually operated automata made almost exclusively with 3D-printed parts.

Each petal has a channel along the edges to support a 22-24 gauge wire. Similarly to how it is done in crochet, the wires' ends are used to attach each petal to the stem. To avoid the wire from slipping out of the channel we looped the wire on the frame of the fabric. The tulips had a 12 EPI fabric and were punch needle using cotton yarn.

Our manually-operated automata use a scotch yoke mechanism to move the wings up and down. The project includes several essential components, namely a holder, a lengthy metal stem, a crank, and a pot (figure 5.12. The holder is used to fix the butterfly in place at the top of the flower. The metal stem hides the connecting rod used in the scotch mechanism, which is hidden in the pot. The mechanism has two states, up and down.

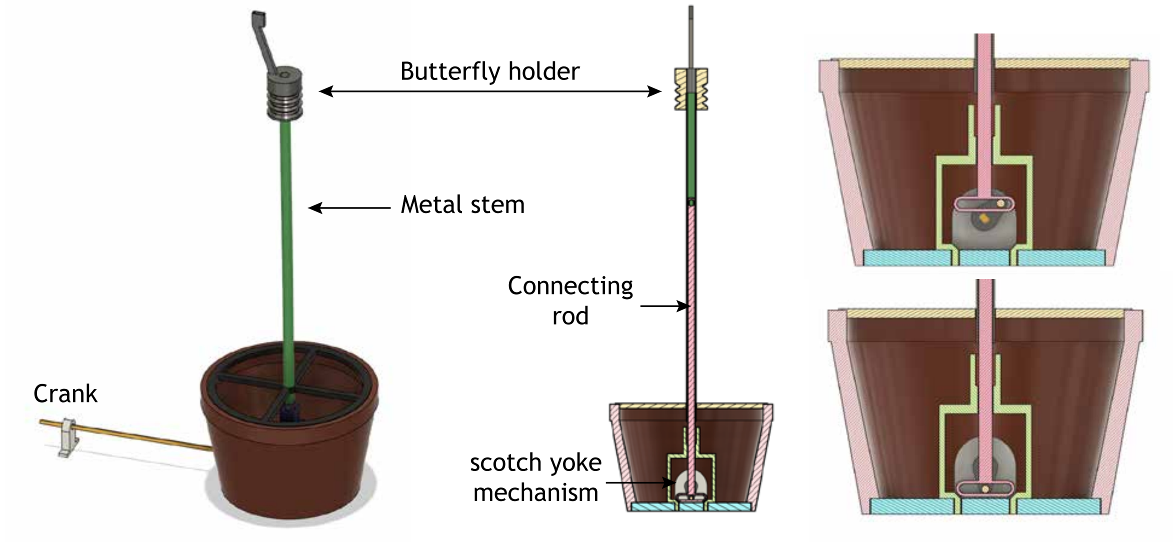

Figure 5.12: We developed a manually operated scotch yoke mechanism to move the wings of the butterfly up and down as the crank is turned. All of the pieces in the mechanism are 3D-printed except the stem, which is a metal rod.

5.5 Discussion

Based on our development and explorations with PunchPrint, we argue that toolpath programming is crucial to support new interactions and interactions between textile crafts and digital fabrication. In this section, we examine how the PunchPrint fabric and software may align or conflict with established punch needle craft workflows. We also discuss the reparability and car of PunchPrint artifacts.

5.5.1 Toolpath Programming to Develop New Specific materials

To create a 3D-printed fabric capable of accommodating punch needle embroidery, a detailed programming approach was needed. Through extensive exploration, we found that by programming our own toolpath (creating custom Gcode) we could obtain a durable fabric with customizable shapes, suitable for punch needle embroidery, while incorporating various aspects of additive fabrication that are not possible in the traditional craft. PunchPrint demonstrates how toolpath programming can achieved designs and material properties not possible through other methods and how this approach expands the traditional craft. We argue that toolpath programming can similarly benefit other types textile crafts while acknowledging the difficulties or mismatch es it can create to the craftsperson and existing workflows.

5.5.2 PunchPrint Compatibility's with the Punch Needle Craft and Workflow

The punch needle workflow is relatively simple compared to PunchPrints' yet PunchPrint workflows offers new advantages. While designers have full manual control over the designs, fabrication and assembly in traditional punch needle, PunchPrint offers a hybrid approach between digital and manual. Traditionally, a craftsperson can manually transfer the pattern in the fabric, either by drawing or ironing an existing pattern, the craftsperson has full control over the design and is completely attached to their manual skills. Meanwhile, PunchPrint approach relies more heavily on the computer design technical skills, this can include from basic skills of moving a computer mouse to understanding specific actions on design software. This can result on a step learning curve for craftspeople with little computer skills. On the other hand, craftspeople who may rely more on digital tools for their art or craft may thrive quicker. Nonetheless, PunchPrint offers a wide space for craftspeople to design, iterate and explore different ideas without compromising the fabric or needing additional materials (transfer designs or fabric marking pens).

Another key distinction that PunchPrint brings to the workflow is the fabrication process. The craftsperson must familiarize themselves with a 3D printer and acquire the necessary skills to achieve successful printing of their pieces. The level of difficulty associated with this step can vary depending on the type of printer used. For example, in our development process, we discovered that modifying from bowden extruders to direct extruders for printing resulted in a higher likelihood of failure. Since the PunchPrint fabric has an optimized toolpath, it prints efficiently and with few problems. Overall, the following steps of the PunchPrint workflow work follow a similar approach to the traditional punch needle: the craftsperson punches on the fabric and add the finishing steps to conclude their projects.

5.5.3 PunchPrint Fabric

PunchPrint fabric offers new qualities and interactions to the craft. We demonstrated that it is possible to use an embroidery hoop for support for larger textile structures. Though, if leftover time, the fabric can deform taking the shape of the hoop. For irregular and less flexible PunchPrint textiles, we could extend our design software to enable the 3D printing of a rigid frame similar to an embroidery hoop, which could be cut away upon completion. We chose to avoid this strategy to reduce material waste. We found in practice that punching without a hoop was highly effective. It is also possible to manually mend the PunchPrint fabric. We found we could re-fuse broken strands together with a 3D-printing pen and then punch into them (Figure 5.13). The fused strands are maintained adequate tension to hold the stitches.

To better understand the durability of the fabric we performed an assessment with an everyday object. We fabricated a PunchPrint iPhone case and I have been using it for over five months. Figure 5.14 shows the case before and after a month of regular use. These initial results are encouraging. Aside from minor fiber compression and visible wear on lighter yarns, the case has held up and all yarns remain in place. These figures/mending_revised.pdf

Figure 5.13: We can repair the PunchPrint fabric with a 3D pen in case small portions get damaged. (a) We cut the fabric for demonstration purposes and marked it red. (b) Applying heat using a 3D pen to mend cut pieces. (c) Using a 3 mm needle to punch the mended portion and (e) yarn stays in the fabric.

results suggest that regardless of the flexible property of the fabric, it will hold the yarn in place for an extended period of time and constant use. Unlike traditional punch needle fabric, PunchPrint design guides can obstruct some holes in the fabric, making it challenging to pass the needle through these components. We found that we could still pierce these partially obstructed holes thanks to the material's flexibility. We also found that for larger gauge yarns or designs with higher loops, we could skip the obstructed cells without impacting the appearance of the design.

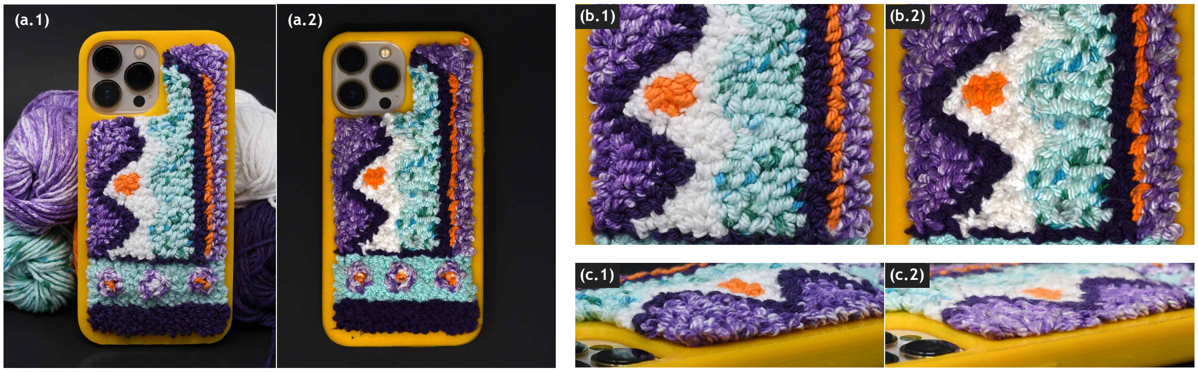

Figure 5.14: We explored the longer-term use of PunchPrint artifacts with an iPhone case that Ashley used for 55 days. We found no major issues with usability or durability during this period. (a.1) shows the full case immediately after fabrication, and (b.1) and (c.2) show close-up front and side views. (a.2) shows the state of the case following 24 days of use. (b.2) shows a close-up of the minor discoloration on the lighter yarn segments from perspiration and placement on different surfaces. (c.2) shows the compression of the yarn fibers, similar to how a rug pile is compressed over time.

Chapter 6

Experimental Embroidery Workshop

3D-printed textiles offer exciting possibilities for textile crafters. I firmly believe that craftspeople can embrace these innovations, integrating them into their craft practices and transforming their workflows, just as they have embraced cutting machines. To support this future, we must address the crucial differences between creating 3D-printed textiles and manually producing textiles through traditional needlecraft techniques. Digital fabrication can improve and supplement traditional fiber-crafts methods. Similarly, traditional crafts can influence the development and application of new digital fabrication tools and techniques. In this chapter I share work done in the form of a workshop to investigate: How can we integrate the workflows of digital fabrication and computational design with traditional textile crafts?

6.1 Objective

The objective of this workshop is to identify possible opportunities in which we can support textile crafters to engage with the PunchPrint system. Additionally, I aim to study the crafter's reactions towards our 3D printed fabric and interest in integrating

3D printed fabrics into their practices. Lastly, I will design and evaluate a workflow to engage textile crafters with the PunchPrint design tool and fabric. Ultimately, I aim to dive deeper into the challenges of engaging craftspeople with computational design and additive fabrication with textile crafts.

6.2 Challenges of Integrating Digital and Manual Workflows

The integration of computational design and additive fabrication with textile craft workflows can be challenging. Among the challenges [44], I find the following particularly interesting.

- **Limited perception of the applications of computation:** Craftspeople do not find the computational design and digital fabrication tools and skills relevant to their craft practice nor do they see how they can support future interests.
- **Design Integration:** Integrating computational design and digital fabrication into existing crafting workflows requires adapting or rethinking traditional approaches followed that are strange to textile crafters.
- **Material Limitations:** There is a fundamental difference in the aesthetics and tactile sensations between materials used for digital fabrication and those used in textiles. Each material possesses specific affordances, so far, 3D printing is limited to plastic materials.
- **Technical Complexity:** The technical complexity of the tools and software used in computational design and digital fabrication can be daunting for crafters with

limited technical expertise. Additionally, some techniques have convoluted workflows.

6.3 Workshop Design Workflow

The PunchPrint workflow I designed has four steps (Figure 6.1): First, participants select the shape of their fabric, they can choose any geometrical shape or one of the sixteen pre-made designs. Then, participants may add design guides to provide extra details to their design. Afterward, participants have the option of placing loops on the top, bottom, or on sides of their shape. Once the participant is finished editing the design, they can start customizing the fabric. Lastly, participants will punch needle their final projects. Due to the short amount of time, participants could not interact with the fabrication or post-processing of the 3D-printed fabric.

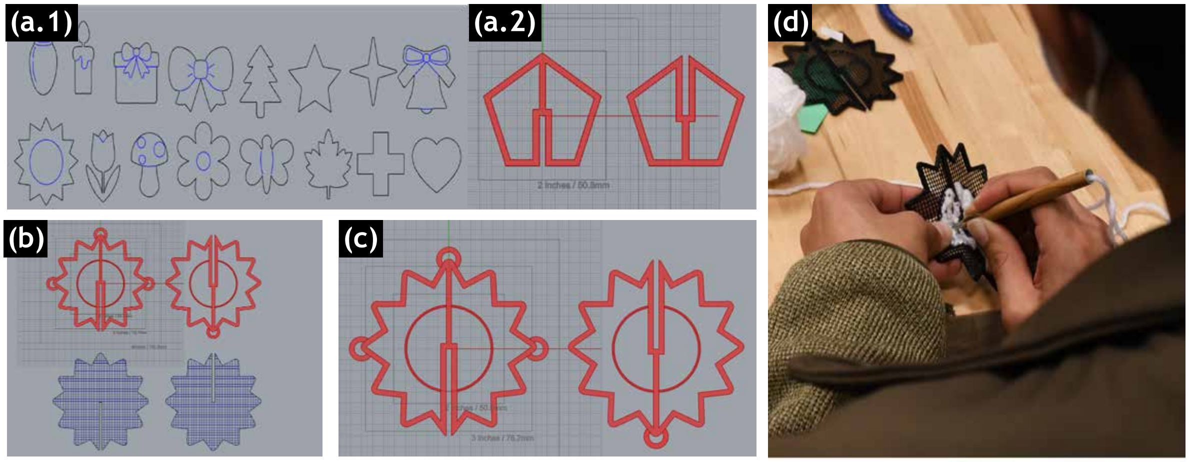

Figure 6.1: I design a specific workflow for this workshop. First, participants select the shape of their fabric, (a.1) they can choose one of the sixteen pre-made designs or (a.2) any geometrical shape. (b) Afterward, participants could add attachment points on the top, bottom, or on sides of their shape. (c) Once the participant is finished editing the design, they can start customizing their fabric thickness, EPI design guides, or holes. (d) Lastly, participants will punch needle their final project.

6.4 Workshop Methodology

The workshop was aimed at textile crafters and textile craft enthusiasts. Participants had diverse backgrounds in textile crafts, programming, digital art, and 3D printing yet no previous experience was required. The workshop was divided into two separate sessions of three hours each. During the first session, we received fifteen participants while in the second only seven participants were present. The analysis and takeaways of this workshop focus mainly on the seven participants that attended both days. We gathered data in each study by recording discussions, administering surveys, and documenting participant artworks.

ID	Textile Crafts	3d Printing	Digital Vector Illustrations	Non-Parametric CAD Softwares	Parametric CAD Softwares
P1	1	1	1	1	1
P2	1	3	2	3	2
P3	5	1	1	1	1
P4	1	2	3	3	1
P5	3	1	1	1	1
P6	2	1	4	2	1
P7	2	2	4	1	1

Table 6.1: Participants' backgrounds and expertise in textile crafts, 3D Printing, Digital vector illustrations, Non-parametric CAD and parametric CAD (1 being No experience and 5 being expert).

Day 1: Participants spend one hour learning to punch needle on PunchPrint's 3D-printed fabrics (Figure 6.3a). Then, participants had to option to select fabrics with pre-made designs or free-style their designs. Most participants selected a pre-made design. Afterward, participants were encouraged to design a 3D ornament made of two intersecting geometries. Lastly, participants spend the reminder time using the Punch-

Print design tool to create their final project design (Figure 6.3b).

Day 2: Participants spent most of the second day finishing their final punch needle project and engaged in discussion. Participants had to option to engage deeper in their design by manually decorating their artifacts with beads, creating keychains, and hanging ornaments (Figure 6.4).

6.5 Evaluation

During the session, PunchPrint's design software and fabric separately were assessed. Recognizing the difficulties and constraints of teaching Rhino and Grasshopper in just two days, the majority of this evaluation emphasizes the 3D-printed fabric. We developed the following criteria to evaluate the design software:

Usability: Were crafters motivated to learn the design tool? What was the crafter's assessment of the parametric design tools? To what degree did craftspeople experience the general benefits of parametric design including exploration of design variations and rapid iteration?

Process: Are crafters limited or motivated to use pre-existing designs? Can users easily modify designs to suit their specific needs?

The following criteria were used to evaluate the fabric produced using the PunchPrint parametric tool:

Usability: What was the crafter's assessment of the fabric? Are crafters interested and engaged with the fabric? Did the crafters like the feel and look of the fabric?

Compatibility with manual practice: How did crafters punch-needling experience with the fabric differ from traditional fabric? What suggestions or feedback did crafters have for improving the usability of the fabric to aid punch needle?

Aptitudes: Does punchprint encourages crafters to think about the integration of

3D printing and textile crafts? Does punchprint affect how crafters plan punch needle projects?

We gathered data in each study by recording discussions, administering surveys, and documenting participant artworks. The surveys that was conducted included attitudinal questions that related to our evaluation criteria, which used 5-point Likert scales with 5 indicating the optimal response. We then analyzed the survey results, discussion transcripts, and artwork in relation to our evaluation criteria.

6.6 Limitations

We recognize the limitations of teaching Rhino and Grasshopper in under six hours to participants with none to little experience in computer-aided design (CAD) or programming. We compensated in our study by providing pre-made designs for crafters to select from instead of creating their own designs in Rhino or using any other vector illustration software. This constraint impacts the creative expression of the participants. Nonetheless, we offered assistance to any participant with the desire of customizing their design outside of the parameters we established in Rhino. Additionally, we provided a wide variety of additional crafting materials to inspire crafters in creating several types of functional objects. Furthermore, we recognize the challenge of evaluating the compatibility of our fabric with traditional punch needle from our audience since most participants had no previous experience with punch needle. Another crucial limitation is the restriction of the project only 3D ornament made of two intersecting geometries. The system did not enable any other type of project not input from manual drawing. Lastly, participants could not interact with the fabrication process, abstracting the idea of fabricating their own textiles.

6.7 Workshop Results

”Loved learning a new technique and combining it with 3D printing.” Participant 4.

”I enjoyed doing punch needle so much that I didn’t want to stop once I started.” Participant 5.

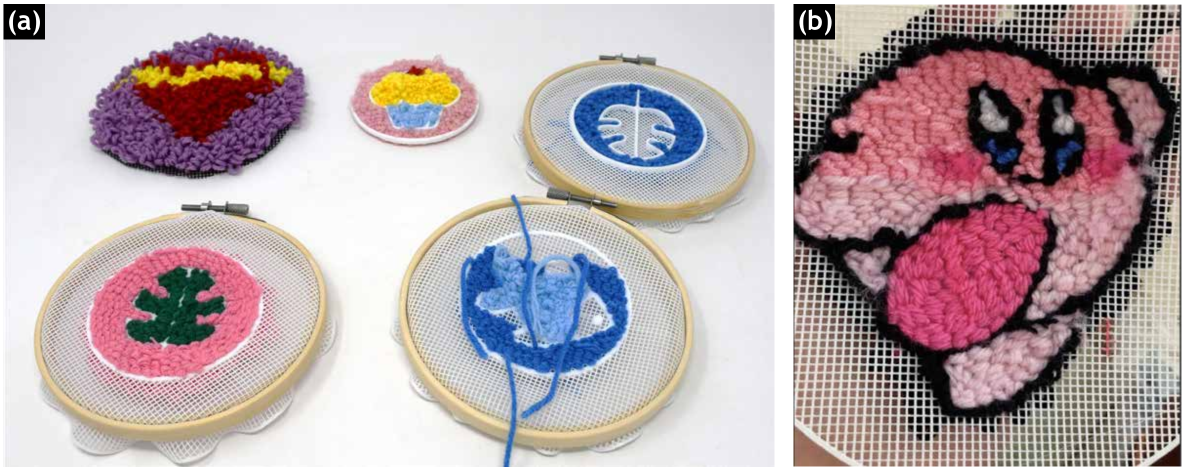

Figure 6.2: Participants learned to punch needle on PunchPrint fabric, (a) most participants selected a fabric with a pre-made design. (b) One participant took an empty fabric after the second day of the workshop and created a design that was more aligned with their interest.

In general, the findings suggest that the participants are interested in incorporating new technologies into their textile crafts and in using 3D printing to create unique fabric designs for crafting purposes. In the following section, we detail the results based on each evaluation criteria, starting with the software evaluation.

Usability: In general participants were excited to learn the basics of Rhino and Grasshopper, however, they also highlighted that it was challenging and wished for more time to interact with the software. Participants also recommended more in-depth examples and guidance on navigating and using the fabric design tool. Likewise, participants

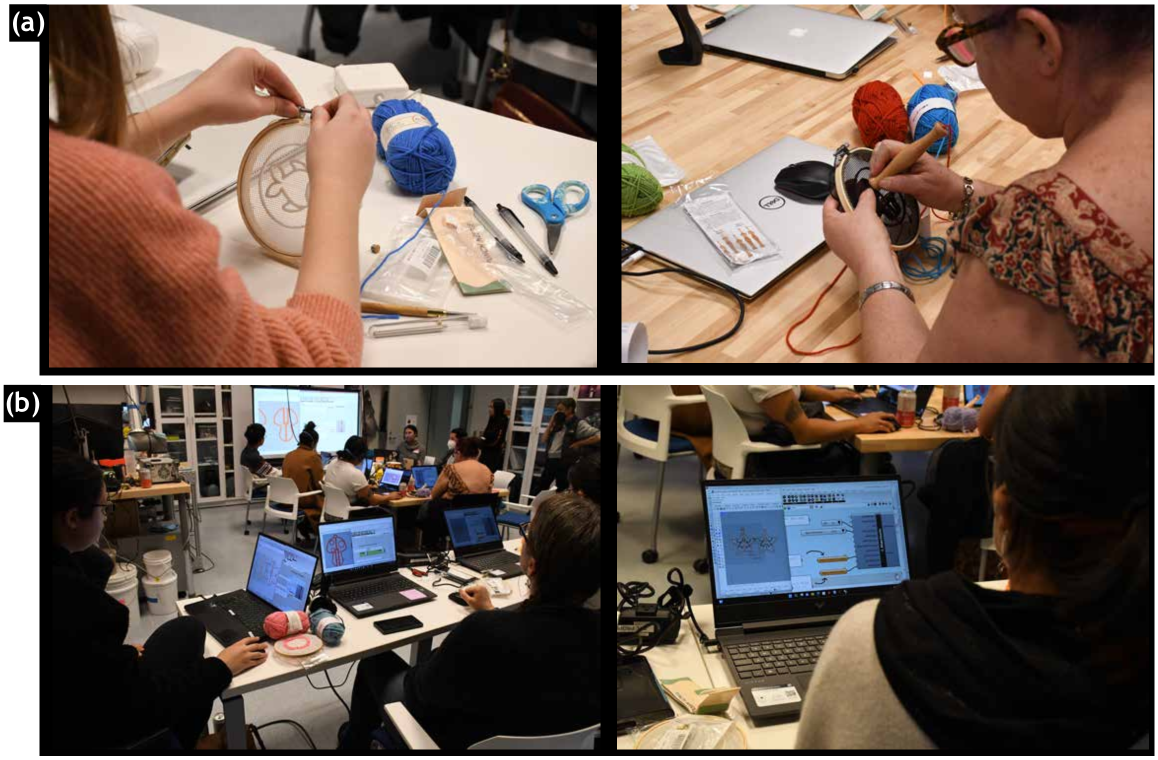

Figure 6.3: (a) Participants spend the first portion of the workshop learning to punch needle on a pre-made PunchPrint fabric. (b) They spent the reminder time designing their final project.

suggested more emphasis on the vocabulary and interface of the software, for instance, a participant express confusion about the term ”curve”. The data shows that participants had the most trouble when learning and interacting with the software, which is an understandable and expected challenge due to the nature of the workshop.

Process: The results shows that participants were intrigued by the new design possibilities the tool provides moreover, they critiqued the use of pre-made and selected designs, saying it constrained the design of the fabric to resize an existing designs. In general, the result shows that participants wanted to be able to have more control in the design process.

The following are the results regarding the 3D-printed fabric:

Usability: The participants expressed a positive response towards the fabric's overall

Figure 6.4: (a) Participants spend the first portion of the workshop learning to punch needle on a pre-made PunchPrint fabric. (b) They spent the reminder time designing their final project.

appearance, texture, and features; they also appreciated its versatility in being able to be paired with other crafting materials. Moreover, participants found the clear visible grid structure of the fabric helpful to create straight lines. Additionally, a participant believed the rigidity of the fabric ease the process of punch needling while contrasting their experience when learning another fiber craft using traditional fabric, in which they describe the malleability of traditional fabric made it hard to control and handle.

Compatibility with manual practice: Participants shared key aspects of the stitching technique and fabric behavior that were challenging or deferred from traditional practices. Results demonstrate that participants noted how the stitching technique varied due to the 3D-printed features of the fabric. For instance, participants reported experiencing difficulty in placing stitches at the edges of 3D solid elements or design guides on the fabric where cells were obstructed. The guides and 3D solid geometries also alter the stitch pathway, increasing the instances where the yarn needed to be cut it. Furthermore, participants pointed out how the grid structure of the fabric made difficult curved pathways. Additionally, participants noted key behaviors of the PunchPrint's fabric that differ from traditional manual practices. A participant experienced a mismatch in the EPI and the needle size, which led to an increase in the force required to pierce the fabric. This additional force caused the participant's hands to hurt. The participant commented on the contrast of force required in traditional punch needle. Results were mixed regarding the ability to punch needling our fabric without a hoop. While some participants indicated they do not feel a difference when punching the practice fabric (with a hoop) and the final artifact (without a hoop), other participants mentioned that punch needling without the hoop was challenging since the place where the needle needed to pass through was the place were they were holding the needle. Nevertheless, participants did not report any injuries or instances in which they actually pierced their hands.

Aptitudes: The data shows that participants enjoyed learning to punch needle and using our fabric. Additionally, participants agreed that software enables textile crafters to iterate on designs faster and it can open opportunities to work with new machines and expand creative spaces within crafts. Likewise, a participant showed interest in using PunchPrint to add fiber to their graphic art practice. Additionally, participants mentioned how the tool could support the making of unique and innovative garments. Participants with skills in drawing software tools expressed an interest in creating their own designs in tools like Illustrator and then using the system to generate a printable outcome.

Figure 6.5: For the final project of the workshop participants designed and punch needle a threedimensional ornament made of two intersecting geometries. Not all participants were able to complete their final project. Participants who finished added additional craft elements like keychain hooks, ribbons, and beads.

6.8 Discussion

This workshop provided important insights into the integration of punch needle embroidery with the PunchPrint design tool and fabric.

6.8.1 Targeting Specific Audiences

The PunchPrint system offers exciting opportunities to engage experienced and beginner textile craftspeople with computational design and additive fabrication. There are several advantages of inviting textile craft novices to try out our system, for instance, is easier to find participants without specific levels of expertise, they can be more receptive to new workflows, and may be more flexible to incorporate new tools and affordances. On the other hand, participants with experience in textile crafts, particularly fabric-based needlecrafts, can relate better to the challenges that PunchPrint addresses. Participants with experience may present a bigger interest in fully exploring new types of projects since they are aware of the projects that are challenging to do within the craft. However, participants with a higher level of experience may also show resistance to new tools, new workflows, and affordance.

In our audience, we only had one participant (P6) with previous experience with punch needle. Overall, P6 dislikes the look and feel of the fabric, as well as digitally designing the fabric. On the other hand, the rest of the participants (no experience with punch needle) shared positive feedback. These different responses lead me to believe that these two audiences should not follow the same workflow. Even though I recognize that one participant with punch needle embroidery is not Representative of punch needle practitioners, I still believe two different workflows should be developed to better suit different levels of expertise in the craft.

As P6 suggested, I think that participants with experiences in fabric-based needlecraft should have more time to engage with the design tools and have more control over the fabric. The experience of P6 raises new questions about the use of PunchPrint by expert punch needlers: what would punch needle crafters see as control over the design of their fabrics? What projects are participants with punch needle experiences excited to create?

6.8.2 Re-evaluating PunchPrint's Workflow

The current workflow has many limitations due to the short period participants engaged in the workflow. This may indicate that six hours is not feasible for the interactions intended since participants express they wanted more time designing, learning to punch needle, and creating their final project. Additionally, it points to possible changes in the workflow and first interactions with the PunchPrint fabric and design tool.

I can visualize a workflow (for both punch needle beginners and practitioners) that focuses on exploring and getting used to the affordances of PunchPrint. In my effort to demonstrate to the participants the unique projects PunchPrint could achieve I lost sight of the limitations imposed by only being able to create a 3D ornament. When reflecting on a moment where a participant asked for an extra piece of fabric to create a unique Kirby design which they transfer by drawn by handon the fabric (Figure **??**) I realized that a simple fabric may have sufficed to showcase one of the most exciting things PunchPrint fabric offers compared to traditional fabrics. The fact that PunchPrint fabric does not unravel hence there is no post-processing to secure any edges, means that the fabric can be cut manually to have any shape without any extra step. Therefore, I believe that for both types of audience (punch needle beginners and practitioners) the first interaction with PunchPrint should be with a plain piece of 3D-printed fabric that they can draw on top of freestyle when they punch.

Even though having fabrics with pre-made designs offer a sense of personalization, it did not build a level of understanding of all the challenges PunchPrint can support in the crafts, starting with the simplest challenges like creating a robust fabric with any size and shape may support a better understanding of PunchPrint features. The workflow designed for this workshop focused more on showcasing all the system features rather than guiding the craftsperson to understand the fundamental design opportunities the system offers. Future workflows should start by creating the simplest project the system can achieve, which still holds incredible value compared to a traditional approach.

6.8.3 Re-thinking Teaching Approach of Computational Tools

Teaching anyone a computational design tool is challenging in itself, and reducing that teaching to approximately an hour seems even impossible. I found myself in a position in which I had to make a compromise on what things should I teach and what should participants should just follow blindly. I learned that is crucial to either abstract the design environment, for instance creating an interface they can engage instead, or teach basics commands to move around the environment (zoom in, scroll, etc.). For this workshop, the best course of action may have been to create a user interface. Participants' first struggles were navigating between Rhino to see the pre-made designs and Grasshopper to edit their designs. This type of workflow of Rhino and Grasshopper is challenging for people with experience, so naturally, it posed a challenge for the participants. Additional to the technical skills, each design software also uses specific jargon or terms not common to people outside of design or engineering fields. For example, participant 6 shared:

> *"I found the software really difficult. I'm still not sure what a curve is."*

This highlights the need to re-think the teaching approach of the design tool and even fabric. Furthermore, shades light on conceptual learning challenges that might hinder the experience for textile crafters when engaging for the first time with computational design tools.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

I began this thesis with the interest of giving 3D-printed fabrics the desirable soft and colorful attributes commonly found in traditional fabrics. Drawing upon my expertise in needlecraft, I actively pursued the chance to incorporate yarn into 3D-printed fabrics through these techniques. This innovative integration not only offers a solution to overcome the limitations of 3D-printed fabrics but also facilitates the exploration of how needlecrafts can leverage computational design and digital fabrication to their advantage.

After a thorough exploration, punch needle embroidery exhibited promising qualities that make it suitable for integration with 3D-printed fabrics. Punch needle stitches do not need to be secure and can be done and undone with ease. Moreover, is a craft highly restricted by its foundation fabric. With these benefits and limitations in mind, I sought to develop methods to create a 3D-printed fabric that could support punch needle embroidery. This goal led me to the development of PunchPrint.

PunchPrint is a technique to design and fabricate robust, flexible, and programable 3D-printed fabric that can serve as foundation fabric for punch needle embroidery and potentially other fabric-based needlecrafts. Ultimately the goal of the system is to support textile crafters in designing and fabricating a custom 3D-printed fabric and give life to new types of textile projects. I did a short evaluation of the possible challenges and opportunities this integration presented.

I conducted a two-day workshop with textile crafters (most without experience in punch needle, programming, or computational design). Through the workshop participants engaged with the PunchPrint design tools and PunchPrint fabric. By the end of the workshop, participants had created two punch needle projects, a coaster, and a 3D ornament. Through a series of discussions and surveys, participants shed light on ways in which the system could improve to support textile crafters.

7.2 Future Directions

Many research questions remain to be addressed within the intersection of needlecrafts and 3D-printed fabrics. The PunchPrint system can support a wide range of textile projects not possible through traditional means. During 5.4, I showcase just a handful of possible projects PunchPrint can support. To extend the system's capabilities, I need to address the current design limitations. A straightforward approach to reduce challenges related to the level of technical skills required to use the tools is creating a user interface within Grasshopper. This will shift the interaction from Grasshopper and possibly Rhino to an interface design with crafters in mind. Another possible direction is to create a system that can generate G-code without requiring complex CAD skills and ideally following closely the design workflow of textile crafters.

PunchPrint bridges digital fabrication with textiles, making it possible to transform common 3D-printing projects into ”fluffy” textiles projects. In 5.4.3, I explore how we can make punch needle automata, enabling a new interaction with punch needle artifacts.

Additional explorations in this area may [provide insights into other areas explored in HCI, for example, soft interfaces, soft sensors, or soft robotics.

Furthermore, considering the deep-rooted presence of manual textile production across various societies and cultures, I am intrigued by the potential of PunchPrint to facilitate cultural representation. Additionally, I am interested in exploring how PunchPrint can enable collaborative design among designers, artisans, and craftspeople from diverse cultural backgrounds.

So far, only people with access to the Grasshopper software can use the PunchPrint system. Even so, the system is not ready to be shared. A potential goal is to share the system with the Grasshopper community. I visualize using several sharing platforms like Instructables or Github to disseminate the system while promoting crafters and makers to share their projects and possibly contribute to making the system better. Lastly, I would like to explore how PunchPrint can be of interest in a more artistic light. I would like to present my work in art exhibitions, museums, festivals, or symposiums.

Appendix A

Additional PunchPrint Craft Artifacts

PunchPrint offers a vast realm for creative expression within the realm of punch needle embroidery. In this section, I present additional PunchPrint artifacts that were not previously showcased in the preceding chapters but provide useful insights for comprehending the potential of PunchPrint. While PunchPrint extends the boundaries of traditional punch needle craft, it also introduces new possibilities and limitations for engaging with 3D-printed fabrics and textile artifacts. These explorations have deepened my understanding of PunchPrint artifacts and possible uses.

Figure A.1: Since the PunchPrint fabric does not unravel when cut, the leftovers of the fabric can be repurposed to create new PunchPrint craft artifacts. These earrings were made using the excess fabric of a practice fabric used in the workshop 6.2

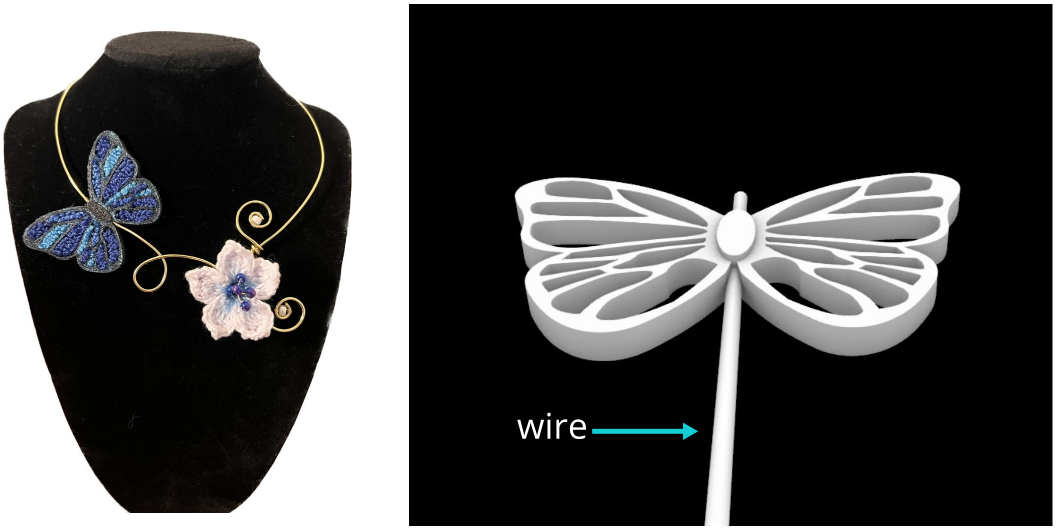

Figure A.2: PunchPrint artifacts can be merged with other craft practices and materials. This necklace integrates a wire bending technique with a crochet flower and a PunchPrint butterfly. The butterfly has a channel in the middle to allow the wire to pass through.

Figure A.3: 3D solid geometry can be used to add complex details to the fabric that would otherwise be challenging to create with punch needle 5.9. This detachable collar uses this feature to create a detailed design while maintaining the flexibility needed for garments and wearable.

Figure A.4: This series of cellphone case designs is done with embroidery floss to compare its durability to 5.14. Even though the embroidery floss gives it a bright and colorful aspect, these designs demonstrated to be less robust than the initial phone case done using cotton yarn.

Figure A.5: Coasters are common punch needle projects for beginners. PunchPrint enables the creation of intricate and personalized coaster's designs.

Figure A.6: By incorporating additional fabric around the coaster design, the designer gains the freedom to extend the design beyond its defined edges. This extra fabric when cut does not result in a smooth finish.

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