IrOnTex: Using Ironable 3D Printed Objects to Fabricate and Prototype Customizable Interactive Textiles

JIAKUN YU, The University of Sydney, Australia
SUPUN KURUPPU, The University of Sydney, Australia and University of Moratuwa, Sri Lanka
BIYON FERNANDO, The University of Sydney, Australia and University of Moratuwa, Sri Lanka
PRANEETH BIMSARA PERERA, The University of Sydney, Australia
YUTA SUGIURA, Keio University, Japan
SRIRAM SUBRAMANIAN, University College London, United Kingdom
ANUSHA WITHANA, The University of Sydney, Australia

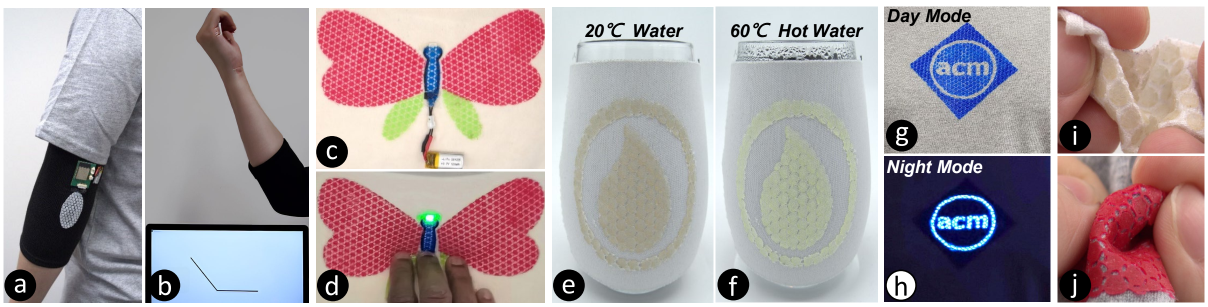

Fig. 1. Application examples for IrOnTex: (a)-(b) Elbow sleeve with bend sensor: (a) Side view and (b) Bend angle tracking, (c)-(d) Interactive plush toy responding to pressure, (e)-(f) Thermochromic cup sleeve indicating water temperature, (g)-(h) Glow-in-dark ACM logo appliqué. (i)-(j) Demonstration of textile-like properties achieved using tiling.

In this paper, we propose IrOnTex, an approach to design, fabricate, and prototype customizable interactive textiles by ironing 3D printed elements directly onto fabrics. Our method incorporates multiple filament types to demonstrate functionalities such as electrical conductivity, sensing, and thermo- and photo-sensitivity for interactive applications. Additionally, we integrate a tiling-like fragmented design to improve stretchability and flexibility to match the mechanical behavior of textiles in our 3D printed elements. We characterized the iron-on process through technical evaluations, which showed the durability and reversibility of the approach. We also suggested baseline parameters for prototyping and methods to enhance the functionality

Authors' Contact Information: Jiakun Yu, The University of Sydney, School of Computer Science, Australia, jiakun.yu@sydney.edu.au; Supun Kuruppu, The University of Sydney, School of Computer Science, Australia, kuruppumullage.kuruppu@sydney.edu.au and University of Moratuwa, ENTC, Sri Lanka, kuruppukdsd.19@uom.lk; Biyon Fernando, The University of Sydney, School of Computer Science, Australia, panthiyage.fernando@sydney.edu.au and University of Moratuwa, ENTC, Sri Lanka, fernandopbm.19@uom.lk; Praneeth Bimsara Perera, The University of Sydney, School of Computer Science, Australia, ppat0685@uni.sydney.edu.au; Yuta Sugiura, Keio University, Department of Information and Computer Science, Japan, sugiura@keio.jp; Sriram Subramanian, University College London, Department of Computer Science, United Kingdom, s.subramanian@ucl.ac.uk; Anusha Withana, The University of Sydney, School of Computer Science, Sydney Nano Institute, Australia, anusha.withana@sydney.edu.au.

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of certain materials. The empirical results from the studies were used to develop a design tool to assist the design process. A user study with 10 participants revealed the helpfulness of the tool. To demonstrate the capabilities of the approach, we show a set of example interactive applications. We envision the proposed approach will enable designers to rapidly prototype interactive textile applications.

CCS Concepts: • **Human-centered computing → Ubiquitous and mobile devices**; *User interface toolkits.*

Additional Key Words and Phrases: Interactive Textile; Fabrication; Design Tool; Customization; Iron-On Textile; 3D Printing

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1 INTRODUCTION

Smart textiles have explored ways to integrate functionalities such as sensing [73, 76, 92], actuating [54, 78, 113], and displaying information [12, 16] into our clothing. Smart textiles can respond to external stimuli such as pressure [41, 72], strain [86], light [12], heat [67], or moisture [102]. Similarly, these are also used as an output modality for haptic [11, 94] and visual feedback [79, 114]. Smart textiles enable many ubiquitous computing applications, including healthcare [19], sports [67], and fashion [108].

Recent research shows a need for customizability [49, 69], adaptability [63, 106], and easily prototypable methods [50, 55, 56] in wearable computing devices, especially in the context of clothing [51, 109]. Researchers have introduced various methods to integrate interactive and customizable elements into textiles. Fabrication methods, such as gluing [69, 81], weaving [15, 76], knitting [60, 86], embroidery [2, 35], and screen printing [1, 64], often make rapid and iterative design challenging. To address this, Klamka et al.[52] proposed a specialized handheld ironing device for fabricating interactive textiles. Similarly, hobbyists and DIY enthusiasts employ methods of applying heat-transfer vinyl to textiles[97]. However, these may not be ideal for iterative prototyping since removing these materials requires specific methods or solvents [52, 99]. Furthermore, many easily removable methods lack durability or stretchability due to hard materials used [3, 40, 85].

In this paper, we present IrOnTex, a fabrication approach for iteratively prototyping interactive textiles using an affordable 3D printer and a household iron. IrOnTex eliminates the need for specialized devices [52] in the fabrication. The method involves directly bonding 3D printed appliqué-like [103] elements onto textiles. The process follows two simple steps: 1) thin layers of decorative and functional elements are printed using a typical fused deposition modeling (FDM) 3D printer, and 2) they are transferred to textiles by directly ironing them onto the fabric using a household clothing iron.We leverage the working principle of thermoplastic filaments, where when they are heated, they become soft and adhesive. The approach also eliminates issues in direct 3D printing on textile [22, 27] such as, poor adhesion and warping [29, 65, 75], nozzle tangling with the fabric [82], and creep or filament popping issues [22, 82]. More importantly, the approach can be scaled to large clothing items and textile objects with uneven surfaces and texture (e.g., plush toys), that are difficult to fit on 3D print beds [82].

While explorations of similar adhesion approaches to textiles exist in hobbyist communities [42, 45], a comprehensive and systematic evaluation of material and application possibilities is missing. This paper investigates and studies the effects of ironing 3D prints onto textiles, including area spreading, durability, washability, and reversibility through technical evaluations. We explore a variety of polylactide (PLA) and thermoplastic polyurethane (TPU) materials, with different ironing settings, and fabrics to show the baseline parameters for prototyping. We further provide design approaches for certain filaments to improve their functionalities. More importantly, we evaluate the mechanical effects of integrating 3D printed layers onto clothing and introduce a tiling-inspired patterning approach to preserve the textile-like properties. Finally, based on our empirical evaluations, we develop and evaluate an interactive design tool that helps designers convert images into ironable appliqués. To demonstrate our approach's capabilities and relevance to ubiquitous computing, we show a series of example applications, including wearable sensing, interactive electronics, thermochromic, photochromic, and luminescent textiles. We believe this method offers significant benefits as a fabrication approach for prototyping interactive textiles for HCI and UbiComp applications. The key contributions of this paper are as follows:

- A simple fabrication process that combines 3D printing and ironing, IrOnTex, to iteratively prototype interactive textiles applications, including a tiling-inspired patterning technique to enhance the textile-like properties of 3D printed appliqués.
- Deriving a set of baseline parameters through a series of technical studies to evaluate plausible materials, fabrics, and fabrication conditions along with demonstration applications.
- Developing and evaluating a design tool that integrates empirical findings from our studies and encapsulates complex design requirements to assist users in the design process.

2 RELATED WORK

In this section, we explore the intersections of our work within the area of HCI, including different smart textile fabrication approaches, the integration of 3D printing with textiles, and design tools for customization.

2.1 Fabricating Smart Textiles

Fabricating smart textiles typically combines traditional methods and novel techniques to create fabrics that can react to the environment. These advanced techniques could be applied before, during, or after fabric production [17]. For example, Seyedin et al. [86] and Parzer et al. [72] used conductive yarns to allow the integration of interactive elements with fabrics. Typical methods such as knitting [60] or weaving [15, 76] converts various yarns into fabric. The textures or structures produced by knitting and weaving can also play an important role in customizing the functionalities [38, 115]. Honnet et al. [41] presented an in situ polymerization method to allow arbitrary textiles to detect pressure and deformation. Additionally, after the fabric is produced, the garment stage involves design and stitching and may also include the integration of interactive technologies. Methods such as screen printing with functional pigments are employed to create thinner layers. However, this method is intricate, time-consuming, and leaves hard-to-remove prints [1, 64, 93]. Other methods include embroidery [2, 35] or appliqué [103] for functionalities and aesthetics. This approach enhances the characteristics of the garment directly, thus saving effort and time for earlier steps. For example, Hamdan et al. [35] designed a method for transforming a sketch into an e-textile by an embroider machine; Klamka et al. [52] proposed a specialized hands-on tool for ironable fabric serving as an interactive textile; Wicaksono and Paradiso [103] implemented appliqué as a deformable musical interface. In particular, both embroidery and appliqué are the application of secondary material onto a base substrate, therefore requiring less integration with the structures of woven and knit fabrics [90]. It is also beneficial for iterative design because replacing a module is simpler than changing yarn or dyed fabric. In this work, we use an appliqué-like fabrication mechanism as the fundamental approach.

2.2 Integrating 3D Printing with Textiles

Researchers have explored directly printing textile-like structures. For instance, Takahashi et al.[95] and Forman et al.[20] developed techniques for creating 3D printed textile-like fiber structures. They aimed to mimic the feel of textiles with woven-like structures. However, the tensile strength and feel of the fabric are inherently limited by the 3D printed filament itself, indicating the need for further research and development in this area.

The combination of FDM 3D printing with textiles has drawn significant interest from both hobbyist and HCI communities. For example, PunchPrint utilizes TPU-based substrates to facilitate punch needle embroidery [13], while EscapeLoom employs PVA-based substrates to assist hand weavers in textile formation [15]. 3D prints that adhere to the fabric as an appliqué were introduced by Rivera et al. [82]. This approach is less reliant on traditional textile machines and requires less handcrafting. It has been further explored by hobbyists and researchers towards methods such as gluing [69, 81], direct printing [77, 80], ironing [20, 37, 45] and sewing [61, 81]. However, fabric glue, as an adhesive, poses challenges in changing its stickiness. It tends to be either too strong for easy removal [69, 81] or insufficiently durable for washing [3, 40, 85]. Moreover, sewing also poses challenges in prototype modifications and removal of 3D prints [61].

Previous studies have shown direct 3D printing on textiles using TPU [27] and PLA [22, 29, 65]. However, several limitations in this approach were identified in the literature. Due to the texture of fabrics and uneven surfaces, adhesion is not always guaranteed, and warping issues can easily arise in clothing [65, 75]. Grimmelsmann et al. [29] found that adhesion of direct 3D printing has limitations due to factors such as z-distance, temperature, and speed. Smaller z-distance and speed values may lead to the nozzle tangling with the fabric [82]. Direct 3D printing needs higher temperatures than filament standard (30°C to 60°C higher than typical ironing) [18] causing scorch marks on delicate fabrics like silk [25]. Increasing the printing temperature beyond recommendations [22, 82] could lead to heat creep or filament popping issues due to moisture within the filaments [66, 98]. Furthermore, direct 3D printing poses issues in fixing the textile and printing objects larger than the print bed [82]. Specially, the IrOnTex approach is ideal for integrating interactivity into existing cloths or fabric items (plush toys as shown in our application) with curved or uneven surfaces.

Hobbyists [37, 45] and Forman et al. [20] conducted some preliminary trials but did not report insights into how the method can be expanded to different materials and fabrics and to make the prints more textile-like. In our work, we found many generalizable strategies compared to previous work. For instance, we found using baking papers as transfer material [45] does not work for some functional filaments [29, 30, 65]. Instead, we employed a connected tiling structure as a metamaterial [44, 111] in the transfer substrate. We further expanded the materials to FDM filaments such as thermochromic PLA[1] (thermo PLA), photochromic PLA[1] (photo PLA), luminescent PLA[1] (lumi PLA), flexible TPU[2] (NinjaFlex), and conductive flexible TPU[2] (eTPU) to create functional 3D prints. This allows us to efficiently and iteratively fabricate interactive textile applications using current 3D printing techniques with existing filaments.

2.3 Design Tools for Customization

Design tools are often used in personal fabrication research to assist in the design process of interactive devices. They are particularly used to empower novice or non-skilled users to participate in design processes. Designers can benefit from design tools to explore design space in different ways [7, 105]. For instance, they often encapsulate complexities of underlying mechanisms such as sensing [26, 83, 84], mechanical [44, 58, 87], and fabrication [28] characteristics. They also help to automate parametric design processes [32]. More importantly, they help to facilitate the interface customization process without affecting functionality [58, 71]. In smart textiles, design tools have been shown to facilitate customization in terms of flexibility by enabling the selection of various knitting or weaving patterns [39, 95]. In IrOnTex, our objective is to facilitate customization and design processes through an easy-to-use design tool. We further aim to hide the complexities of the underlying mechanisms of the fabrication requirements from end users. We draw inspiration from previous work that developed design tools as plug-ins for 3D design software [28, 32]. We then adopted Grasshopper[3], a visual programming language plug-in for Rhino 3D, as the platform for our design tool.

[1] https://www.amolen.com (Accessed: [2023-11-30])
[2] https://www.ninjatek.com (Accessed: [2023-11-30])
[3] https://www.grasshopper3d.com (Accessed: [2023-11-30])

3 IrOnTex Concept

The IrOnTex concept follows a simple 3D printing and ironing approach to create interactive textiles. The design and fabrication pipeline can be divided into four distinct phases.

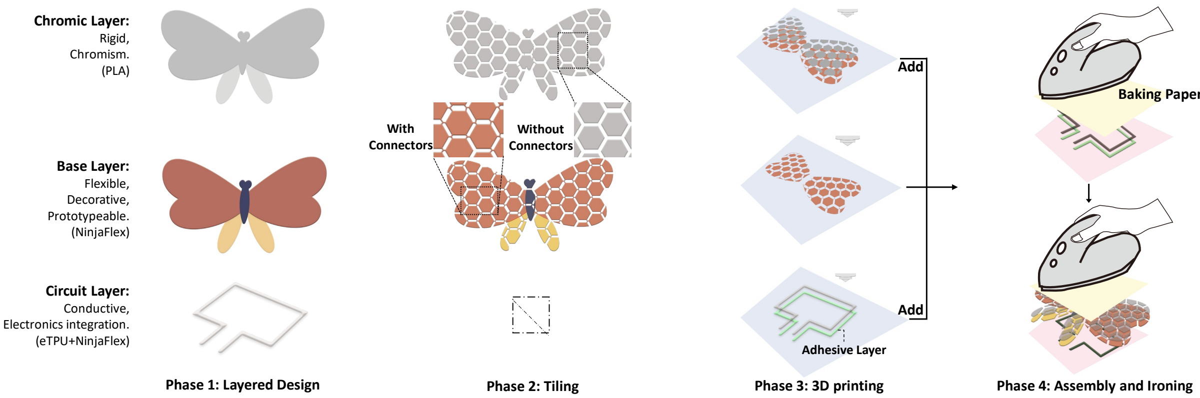


Fig. 2. The concept of IrOnTex depicted by the steps in 4 phases. Phase 1: Layered Design - Select and design the desired layer for printing. Phase 2: Tiling - Transform the solid surface into a tiling structure. Phase 3: 3D printing - 3D print the designed layers. Phase 4: Assembly and ironing - Combine and integrate 3D printing partitions together.

3.1 Phase 1: Layered Design

In interactive textiles, aesthetic design is as equally important as functional elements. Since we use FDM 3D printers to create interactive elements and different materials to create geometries, base colors, chromic and electrical functions, it is easier to represent a given design in terms of layers of printed materials in the design process. Therefore, we separate the aesthetic and functional characteristics of the application into different printable layers, which are the chromic layer, base layer, and circuit layer (See Fig. 2 - Phase 1). From this, the chromic layer and the circuit layer are functional layers.

We call the top layer the 'chromic layer' because it is ideal for visual objects. We use luminescent PLA, thermo PLA, and photo PLA filaments in the chromic layer to incorporate features such as phosphorescence, thermochromism, and photochromism. Since these materials are usually translucent or light-colored, they are best suited to be printed atop base layers to ensure visibility. However, the 'chromic layer' can be used for any other materials and functionalities (e.g., electrical) if needed.

The base layer serves as the base for colors, geometric features, and the chromic layer. For artwork-based designs, various colored regions need to be separated and grouped to represent printable layers using corresponding colored filaments. We primarily use colored and translucent NinjaFlex filaments for this layer, which are flexible TPU filaments. This supports flexibility and decorative functions. Additionally, due to the adhesive properties of NinjaFlex filaments, this layer provides adhesion for both the chromic layer and the textile. Our studies also show NinjaFlex has flexible adhesion which supports easy peelability.

The circuit layer embeds electrical functionalities into interactive textiles. We use eTPU to craft circuit wiring, connectors, sensors, and footprints for electrical components. Due to functional and electrical requirements, the circuit layer cannot follow the design of the base layer. We advise integrating the circuit layer along the edges and boundaries. Furthermore, considering the limited color options in eTPU, we embed the circuit layer beneath the base layer, unless specific components such as LEDs require visibility. We have observed challenges with adhesion between textiles and eTPU. To address this issue, we added a NinjaFlex adhesive layer between the circuit and the textile, with a matching design. The proposed method effectively improves the adhesion between eTPU and textiles, ensuring better overall performance.

The process involves identifying different regions in the artwork or design, separating color regions, integrating functional components, and extruding 3D printable geometries grouped by each filament type. We found that manually executing these steps was tedious and time-consuming. Moreover, design errors were frequent, resulting in wasted time and material. These challenges inspired the development of a design tool to assist the process.

3.2 Phase 2: Tiling

Given our focus on textile applications, it is important that the proposed appliqué resembles textile-like properties in terms of softness, stretchability, and bendability. Altering these properties can impact wearer comfort. Even though there are many flexible materials available for FDM 3D printers, compared to general textile properties, the flexibility of those materials is relatively low, even when printed as thin layers. Therefore, to emulate textile-like mechanical behavior, we propose a tiling approach inspired by kirigami patterns such as LASEC [32].

In our tiling approach, we employed hexagon shapes (Fig. 2 - Phase 2) due to their blunt corners, efficient space-filling, and organized printing path [34]. The tiling's flexibility and stretchability are influenced by the tile sizes and inter-tile gaps. While smaller tiles with large spacing create more flexibility, this reduces the aesthetic appeal of the base layer, which is also an important aspect of textiles. Therefore, a balance between these parameters needs to be established. Practically, the inherent constraints of FDM 3D printers, such as layer height, affect this tiling approach. It is important to note that we did not implement tiling in the circuit layer since it affects the conductivity. However, tiling made the handling and assembly of 3D printed layers hard. To address this, we integrated flexible connectors between the hexagonal tiles, as shown in Fig. 2 - Phase 2.

3.3 Phase 3: 3D Printing

FDM 3D printing served as our primary fabrication method for each layer. To represent different colors or functional properties, such as electrical functionalities, we created separate 3D geometries based on the materials and printed them individually. If a multi-material 3D printer supports printing these elements simultaneously, it would ease the process significantly. For instance, for better adhesion of eTPU materials, we combined the circuit and adhesive NinjaFlex layers, employing dual extrusion (Fig. 2 - Phase 3) to print together.

However, since we use a dual-nozzled 3D printer, which can only use two filaments per layer, multi-colored prints were difficult to print as a single object. Pausing and changing the materials layer by layer is an option, however, it can be time-consuming and cumbersome. Therefore, when more than two materials are necessary we export them as separate objects, that can be printed individually and attached together in the ironing process.

3.4 Phase 4: Assembly and Ironing

To assemble and integrate interactive elements with textiles, we leverage the thermoplasticity of PLA and TPU, which allows them to soften upon heating. The reversible Glass Transition Temperature (T_g) for PLA and TPU are approximately 60℃ and -40℃ respectively [33, 89]. The extruder temperature (T_m) for PLA and TPU is approximately 200°C and 220°C. Therefore, by heating PLA and TPU above their respective T_g without exceeding T_m [31, 48, 53], we can achieve a suitable adhesive state that integrates them together. Household irons operate within this range (110°C to 230°C) making it a suitable and accessible tool for our purposes.

In our approach, we simply put the iron on top of the prints and fabric, just as you would with regular ironing. All our ironing was conducted on an ironing board. When the iron presses the printed appliqués, the force is dispersed by the deformable ironing board and fabric. Since the appliqué is a thin layer ($\leq$ 0.4mm), this leads to an even pressure distribution during ironing [14, 110]. This helps when the fabrics are uneven or fluffy, such as on sofas or cushions. For instance, the proposed method can be used to transform existing furniture into interactive objects. Additionally, ironing offers other advantages over direct 3D printing by avoiding direct contact between the fabric and the print head preventing the fabric from shifting or stretching due to lateral forces [82]. This also reduces the risk of burns since the ironing temperatures are lower than those of the print heads.

Several different ironing approaches could achieve similar outcomes for IrOnTex; however, to make the process more intuitive for a broader range of users, we recommend the steps outlined below. In all the steps, we placed baking paper between the printed elements and the iron to prevent them from sticking. First, we recommend ironing the conductive/adhesive dual layer along with any electronic components and then ironing the chromic/base dual layers. This sequence also facilitates the placement of electronics and testing of the circuit before transferring other layers. We always ironed from the applique side. Ironing from the fabric side could potentially enhance adhesion. However, it is challenging to precisely align prints beneath the fabric, especially for multi-layered and electronic components. Additionally, the strength of the adhesion achieved by ironing from the top side is sufficient for most applications, especially to assure peelability.

4 TECHNICAL EVALUATION

To ensure the validity of the proposed fabrication approach, we conducted a series of technical evaluations. Specifically, we examined the impact of the ironing process on the geometries of the 3D prints, their adhesion to different textiles, washability, reversibility, and the effectiveness of the tiling process in enhancing flexibility and stretchability. Additionally, we explored the use of conductive filaments for sensing and integrating electronic components into the 3D prints. We also tested the responsiveness of the chromic layer to external stimuli. To the best of our knowledge, the combination of these experimental factors has not been studied in the literature and is essential to formulate the baseline parameters for the proposed fabrication method. All 3D printed samples for the studies were printed using a Makergear M3-ID 3D printer.

4.1 Area Dispersion After Ironing Printed Designs

Heat from the ironing softens the 3D prints into a pliable state that causes the filaments to spread and adhere to the textile surface. This spread or dispersion of the area, as depicted in Fig. 3(a), reduces the print resolution. This is undesirable when there are small features and details in the design. Many factors affect the level of dispersion, including filament properties, heating temperature, duration, pressure, and types of textiles [21]. We chose temperature and ironing time as easily controllable factors in a typical ironing setting and used them to study dispersion. We let the pressure be a random variable and used the iron as one would when ironing cloths.

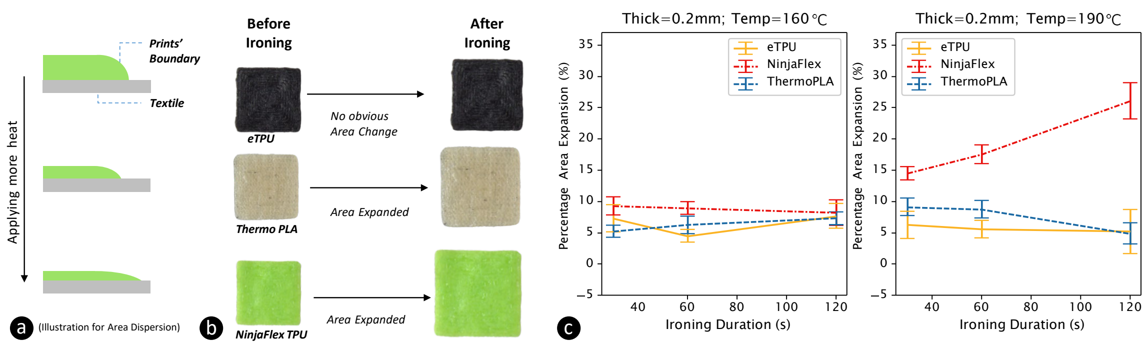


Fig. 3. (a) Side view: the effect of area dispersion after ironing. (b) Top view: the observed area dispersion of the samples. (c) Proportional changes in the area of the prints in relation to varying ironing times and ironing temperatures.

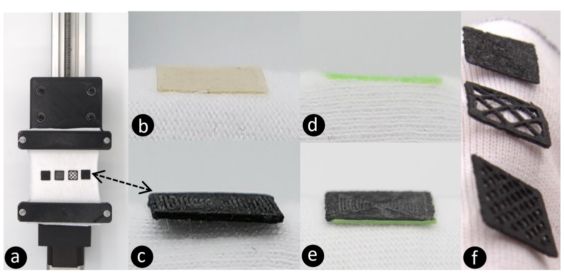
4.1.1 Procedure: We followed a factorial design with three independent variables: two ironing temperatures (set at commonly used household iron temperatures of 160℃ and 190℃), three durations of ironing (selected based on pilot studies: 30s, 60s, 120s), and three types of filaments: eTPU[2], thermo PLA[1], and NinjaFlex[2], representing circuit, chromic, and base layers, respectively. This resulted in $3 \times 2 \times 3 = 18$ factors.

We ironed square-shaped 3D prints (10mm x 10mm, 0.2mm thickness — i.e., the minimum thickness of the print) onto pieces of cotton undershirt fabric (100 mm x 80 mm). We repeated the process for all 18 factors, with 5 repetitions for each factor. For each square, we took pre- and post-ironing photos with a tripod-fixed camera (Fig. 3(b)), maintaining a consistent perspective and distance. A ruler was placed below the prints for pixel calibration and for calculating the percentage of area expansion before and after ironing. Images were scaled to the same millimetre-to-pixel ratio, cropped to isolate individual samples, and the area of each sample was calculated using pixel counts.

4.1.2 Results: Fig. 3(c) shows that at 160°C, the area expands by 5% to 10% for all three filament types, regardless of ironing time. Similarly, at 190°C, both eTPU and thermo PLA filaments exhibit a 5% to 10% area expansion across all durations. However, the NinjaFlex filament at 190°C shows expansions of approximately 15% at 40 seconds and 25% at 120 seconds. We also conducted two-way ANOVA tests for the area expansion of the three filaments. The results show that both temperature and duration have significant effects ($p < 0.001$) on NinjaFlex, but there is no statistical significance for eTPU and thermo PLA. Therefore, we conclude that controlling both temperature and duration is essential to preserve the geometric features of NinjaFlex.

4.2 Tensile Fatigue Test: Assessing Adhesion to Textiles Across Filaments

Fabrics undergo a number of strains and stretches when users perform daily activities. Therefore, the durability of adhesion is critical for real-world applications. To evaluate the adhesion against stretch, we conducted a stretch test for the same 18 factors (temperature-duration-filament) used for the area dispersion test (Sec. 4.1). Additionally, to evaluate the density of the 3D printed element, we included 2 different infills (25% infill, 50% infill) for each of the 18 factors.



Filament Type	Thickness (Infill) Variants	Ironing Temperature (Duration) Variants	Adhesion Following Multiple Stretch Cycles			
			10	100	500	1000
Thermo PLA	All	All	✓	✓	✓	✓
Ninjaflex	All	All	✓	✓	✓	✓
eTPU	All	All	✓	✗	✗	✗
eTPU-Ninjaflex Intergration	0.4mm (25% Infill)	160 °C (30s)	✓	✓	✓	✗
		Remaining	✓	✓	✓	✓
	Remaining	All	✓	✓	✓	✓

Fig. 4. (a) Top view of tensile fatigue test setup. (b)-(e) Side views after stretching for (b) Thermo PLA, (c) eTPU, (d) NinjaFlex, (e) eTPU-NinjaFlex integration. (f) Perspective view of eTPU after tensile test. (g) Adhesion results after 10, 100, 500, and 1000 stretch cycles for all variables.

4.2.1 Procedure: We used a linear actuator with a custom-designed 3D printed clipper to fix the textile, as shown in Fig. 4(a). The textile measured 100mm × 80mm, with a 60mm test area in between. We controlled the linear actuator to move from the 60mm position (0% elongation) to a 72mm position (20% elongation), which is the maximum elongation for typical t-shirts [10]. Following previous work, we visually observed the adhesion after 10, 100, 500, and 1000 cycles of stretching and recorded images (Fig. 4(b)-(f)) [74]. If any of the corners were detached (see Fig. 4(c) and (f) for eTPU), we categorized them as failed.

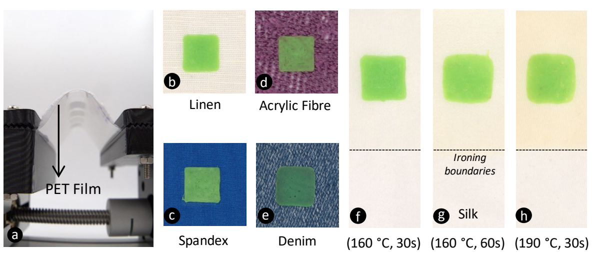
4.2.2 Results: The results depicted in Fig. 4(g) illustrate that both thermo PLA and NinjaFlex exhibit substantial adhesive strength under all tested conditions. However, all eTPU samples detached after 100 stretch cycles, making them unsuitable for daily use.

Since eTPU is essential for electrical conductivity, we explored alternative methods to enhance its adhesion. In our tests, we observed good adhesion strength in the tensile fatigue test for NinjaFlex. Thus, we used the 3D printer to print dual-layer objects, with NinjaFlex at the bottom and eTPU on top. With each layer at 0.2mm, the dual-layer 3D print was 0.4mm in thickness. To further evaluate this eTPU/NinjaFlex approach, we printed 3 (infill variants) × 6 (iron temperature/duration combination) = 18 samples of the same size and repeated the stretch test. Except for the 25% infill setting, all the eTPU/NinjaFlex samples survived the 1000 cycles. Therefore, for eTPU, we recommend the eTPU/NinjaFlex approach with higher infills.

Overall, both NinjaFlex and eTPU require a temperature of 160℃ for 60 seconds for durable adhesion. eTPU alone cannot adhere well to fabrics. However, when combined with NinjaFlex at 160℃ (60 s) or 190℃ (30 s), it achieved good adhesion. Additionally, slight adjustments may be necessary for optimal performance with specific filaments. For example, with thermo PLA, a duration of 120 seconds at 160℃ is suitable.

4.3 Bending Fatigue Test: Evaluating NinjaFlex Adhesion Across Fabrics

From the area dispersion test and adhesion evaluations, we observed that NinjaFlex shows good adhesion and can be used as an adhesive layer for other filaments. Therefore, to study the adhesion across different fabrics, we only used NinjaFlex as the filament type and expanded the fabric selection to linen, silk, spandex, acrylic, and denim (natural cotton blended with some elastane). These represent popular choices from natural (linen, silk), synthetic (spandex, acrylic), and combined natural/synthetic fibers (denim).



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Material	Ironing Temperature(°C)	Ironing Time (s)	Condition of Fabric After Ironing	Adhesion (1000 Bends)
Linen	All	All	✓	✓
Acrylic Fiber	All	All	✓	✓
Spandex	All	All	✓	✓
Denim	160	30	✓	✕
	190	120	✓	✓
Silk	160	30	Slightly Discolored	✕
	160	60	Discolored	✓
	190	30	Observably Discolored	✓

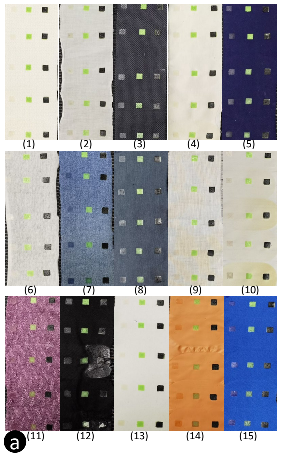
Fig. 5. (a) Side view of bending fatigue test setup. (b)-(e) Close-up views of linen, spandex, acrylic fiber, and denim. (f)-(h) Silk's post-ironing condition at varying temperatures and durations. (i) Results after the bending fatigue test.

4.3.1 Procedure: We chose a bending fatigue test for 1000 cycles instead of tensile fatigue tests because different fabrics have different elongation capabilities. Furthermore, bending gives good insights into softness, a key characteristic of fabrics. We used a similar setup as shown in Fig. 5(a) and placed a PET film underneath the fabric to bend and straighten the textile samples mechanically.

4.3.2 Results: The results show that NinjaFlex exhibits satisfactory adhesion to linen, acrylic fiber, and spandex after 1,000 cycles of bends. However, silk, due to its heat intolerance, begins to show discolorations at 160℃. Thus, managing the trade-off between adhesion and damage to the fabric becomes challenging (Fig. 5(f)-(h)). On Denim, only the 190℃ samples survived 1,000 cycles. In conclusion, we noted that different fabrics need different temperature settings to ensure durability.

4.4 Washing Machine Fatigue Test

Washability is a fundamental characteristic of textiles in their practical use. Moreover, washing subjects fabrics to a variety of strains that better represent real-world conditions than our controlled tests. To improve external validity, we conducted additional fatigue tests by washing our appliqués [91].



b

Fabric Type	Discolored or Burnt	Non-washable				Prototypeable (Washable & Peelable)		
		Peel@N	PLA	NF	eNF	PLA	NF	eNF
(1) 100% Cotton (Boxed Dobby Natte Weave)	IS5	1	None	IS 1	IS 1,2	None	IS 2,3	None
		3	None	None	IS 3			
(2) 100% Cotton (Voile Weave)	No changes	1	None	None	IS 1, 2	None	IS 1,2,3	IS3
(3) 100% Cotton (Leno Mesh Weave)	No changes	1	None	None	IS 1, 2	None	IS 1,2,3	IS 3,4
(4) 100% Cotton (Sateen Weave)	IS2,IS3,IS4,IS5	1	None	IS 1	IS 1, 2	IS 1	IS 2, 3	IS 3, 4
(5) 100% Cotton (Jersey Knit)	No changes	1	None	IS 1,2	IS 1, 2	IS 1, 2, 3, 4	IS 3	IS 3, 4
(6) 100% Cotton (Fine Jersey Knit)	No changes	1	None	IS 1	IS 1	None	IS 2, 3	IS 2, 3
(7) 80% Cotton/ 18% Polyester / 2% Elastane (Weave) (Denim)	IS4,IS5	1	None	IS 1	IS 1, 3	IS 1	IS 2, 3, 4	IS 4
		8	None	None	IS 2			
(8) 100% Wool (Merino Jersey Knit)	IS4,IS5	1	None	IS 1, 2	IS 1, 2	None		
(9) 100% Linen (Weave)	IS4,IS5	1	None	None	IS 1, 2	None	IS 1	IS 3
(10) 100% Silk (Satin Weave)	IS2,IS3,IS4,IS5(Burnt)	1	None	IS 1	IS 1	None	IS 2	IS 2
(11) 100% Acrylic Fiber (Knit)	No changes	1	None	IS 1	IS 1	None		
(12) 100% Polyamide (Jersey Knit)	IS3,IS4,IS5(Burnt)	1	None	IS 1	IS 1	None		
(13) Knitted Nylon-Laminated Neoprene	IS5	None				None	IS 1, 2, 3	IS 1, 2, 3
(14) 100% Nylon (Weave)	No changes	1	None	IS 1, 2	IS 1, 2	IS 1, 2, 3, 4, 5	IS 3, 4, 5	IS 3, 4, 5
(15) 82% Nylon/ 18% Spandex (Knit)	No changes	1	None	IS 1	IS 1	IS 1	IS 4	IS 2, 3
		5	None	IS 2	None			

The rest are washable and non-peelable, suitable for prolonged use.

** Note: Data points are abbreviated as follows: "PLA" = ThermoPLA, "NF" = NinjaFlex, "eNF" = eTPU/NinjaFlex; "Peel@N" = Sample peeled off during the Nth wash cycle (within cycles 1-10); "IS1" = 160 ℃/60s, "IS2" = 160 ℃/120s, "IS3" = 190 ℃/30s, "IS4" = 190 ℃/60s, "IS5" = 190 ℃/120s.*

Fig. 6. (a) Photos showing three types of filament ironed onto fifteen fabrics with five iron settings. (b) A detailed table of ironing outcomes for each fabric, including the status after washing and whether samples are peelable or not.

4.4.1 Procedure: We tested fifteen fabric types, including natural (types 1-6 & 8-10 as shown in Fig. 6(b)), synthetic (types 11-14), and blended fabrics (types 7 & 15), as well as varied constructions like knit and weave, to assess their impact on adhesion and ironing. We chose three print materials in combination with five different ironing settings (IS1 - IS5), as described in Fig. 6(b). For each fabric, we cut sections measuring 300 mm x 100 mm and ironed three filament samples (PLA, NinjaFlex, and eTPU/NinjaFlex), each measuring 10 mm x 10 mm, using five ironing settings (Fig. 6(a)). All these fabric samples with ironed appliqués underwent a 'Quick Mode' washing cycle (20 minutes rinse, 10 minutes spinning at 700rpm, 4 minutes draining) in a typical washing machine (Samsung WA65F5S2). The washing process was repeated 10 times. We recorded any sample that peeled or fell off after each wash cycle. All the samples were washed together to resemble a typical washing load.

4.4.2 Results: As shown in Fig. 6(b), we observed several key findings. Firstly, PLA samples exhibited superior adhesion, with none peeling off during the washing tests. NinjaFlex consistently adhered better than eTPU/NinjaFlex under the same ironing settings, indicating an adhesion hierarchy: PLA > NinjaFlex > eTPU/NinjaFlex.

Secondly, early detachments during the 1st wash cycle revealed that 160℃/60s for NinjaFlex and 160℃/(60s or 120s) for eTPU/NinjaFlex peeled off during washing. In contrast, from the 2nd to the 10th cycle, only 3 out of 188 samples detached, indicating a high likelihood of the remaining combinations being robust for prolonged use. Samples that stayed intact after 10 cycles, could still be able to be manually peeled off, which is useful for both prototyping and long-term use. 11 out of 15 Nylon samples survived after 10 washing cycles and all could be peeled off. Wool, acrylic fiber, and polyamide are the only non-peelable fabrics (except for IS1), showing stronger adhesion even after 10 cycles. They are not suitable for iterative prototyping, but ideal for long-term applications.

Additionally, we noticed some important effects on fabrics with different ironing settings. For instance, type-4, cotton, and silk, both featuring sateen or satin weaves, exhibited the lowest heat tolerance. Notably, silk and polyamide suffered burn damage at 190°C/120s. The standard T-shirt fabric, 100% cotton jersey knit, successfully combined durability with prototyping potential.

4.5 Peelability Test

Ability to implement iterative design changes is essential for prototyping. To evaluate whether the IrOnTex approach enables iterative changes, we conducted a study to see if appliqués can be easily peeled off and re-ironed without damaging the fabrics. We used square-shaped (10mm x 10mm X 0.2mm thickness) NinjaFlex samples as the appliqué. We chose this because all our designs have a Ninjaflex as the base layer (see Fig. 2).

In the study, five appliqués were iteratively ironed on the same location and peeled off (by hand) on 15 fabric samples shown in Fig. 6(a) using the ironing settings 160°C for 60 seconds (IS1). We visually observed any damages to fabric samples or residue left after peeling. No damages or residue was observed until the third iteration for all the fabrics. Silk and polyamide showed slight discoloration after the third attempt, while others showed no effect for all 5 trials. Despite the number of trials being limited, this indicated the process is repeatable except on sensitive fabrics. A shorter than 60 seconds but repeated ironing process may help in such instances.

4.6 Evaluating Tiling-inspired Structure

To assess how well the tiling emulates textile-like properties, especially when combined with hard filaments (e.g., Fig. 1(i)-(j) and Fig. 7(c)), we studied the stretchability of ironed on appliqués. The tested structure consists of two layers: 1) hexagonal NinjaFlex filament tiles connected by Y-shaped connectors on the bottom, and 2) matching hexagonal PLA tiles on the top layer. Both layers are 0.2mm thick. We opted for a dual-layer approach because NinjaFlex is flexible and adheres well to both PLA and textiles. The combined structure created a flexible and stretchable ensemble.

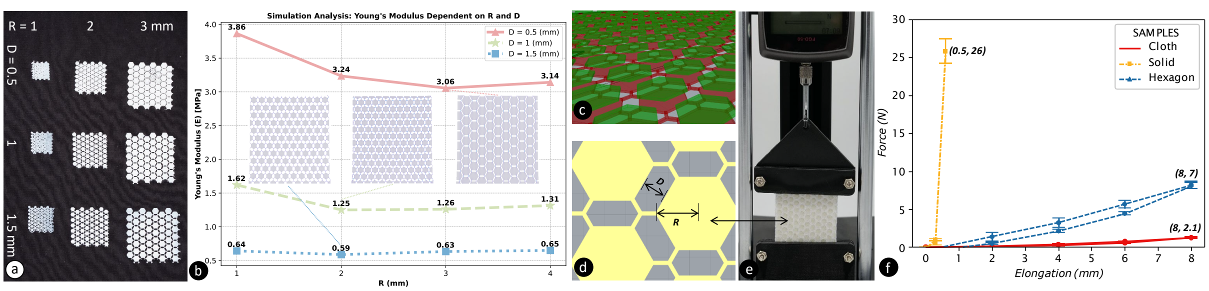


Fig. 7. (a) Samples with varying R and D. (b) FEA result of Young's Modulus vs. R and D. (c) Layer structure for thermo PLA-NinjaFlex integration. (d) Close-up picture for hexagon and connector. (e) Tensile test setup. (f) Results of tensile test.

4.6.1 *Effects of Tiling Dimensions:*

We analyzed the effects of the hexagon radius R and the inter-hexagonal distance D on stretchability, as illustrated in Fig. 7(d). First, we conducted a Finite Elements Analysis (FEA) using COMSOL Multiphysics to build the relationship between the two parameters (R and D) and the Young's Modulus of the composite. Simulation results in Fig. 7(b) show when area and R are kept constant, increasing D increases the structure's softness. However, when D is kept constant, the relationship between Young's Modulus with R is non-linear, resulting in a local maximum in softness. For example, the highest softness is achieved at $R = 2$ mm for $D = 0.5$ and 1 mm, whereas $R = 3$ mm is ideal for $D = 1.5$ mm. Stress distribution of the models from COMSOL Multiphysics for these three peak softness conditions are displayed in the middle of Fig. 7(b).

To empirically evaluate the effect, we printed 9 tiled structures using white NinjaFlex, with R ranging from 1mm to 3mm and D from 0.5mm to 1.5mm (See Fig. 7(a)). It revealed that smaller D values cause the patterns to merge due to heat. In contrast, larger D values make them appear porous. Additionally, with a reduced R, the patterns are not consistently reproducible, whereas an increased R diminishes the textile-like characteristics. To balance aesthetics and stretchable behavior, we selected $R = 2$ mm and $D = 1$ mm for our designs. This ensures graphic resolution and structural stretchability without pattern merging.

4.6.2 Stretchability of Tiled Structure: We compared the stretchability of the tiled structure to that of regular undershirt cotton fabric and a structure printed with PLA without tiling. Tensile tests were performed on solid PLA-fabric, PLA/NinjaFlex-fabric with tiling structures, and plain fabric, all with dimensions of 50mm×50mm. The thicknesses of the PLA, NinjaFlex, and fabric samples were approximately 0.2mm, 0.2mm, and 0.3mm, respectively. The samples experienced 2mm incremental strains. And the tensile forces were measured using a Starr FDG-50 digital force gauge.

4.6.3 Results: We aimed to compare Young's modulus across three factors. The results shown in Fig. 7(f) from the tensile test indicate that the tiling structure produced a composite material closer in properties to the plain fabric. Furthermore, we empirically calculated Young's modulus of the tiling structure to be approximately $1.25MPa$ (compared to PLA's $104MPa$ and the plain fabric's $0.87MPa$). This further demonstrates that the tiling structure brings the stretchability of the composite closer to that of the fabric.

4.7 Electrical Properties

In HCI applications, sensing external stimuli is an important interaction modality. Previous work has utilized eTPU as a resistive sensor for stretching [6, 70]. Therefore, we utilized eTPU to sense external mechanical stimuli, such as stretching and pressing, for interactive textile applications. To investigate the effectiveness of different eTPU sensor designs as stretch sensors, we conducted a series of evaluations. Initial investigations showed that the typically used horseshoe patterns resulted in low sensitivity. To enhance this sensitivity, we compared space-filling curves, such as simple U shapes (Fig. 8(a)), with the second-order Peano curve with 2 and 3 iterations (Fig. 8(b) and Fig. 8(c), respectively).

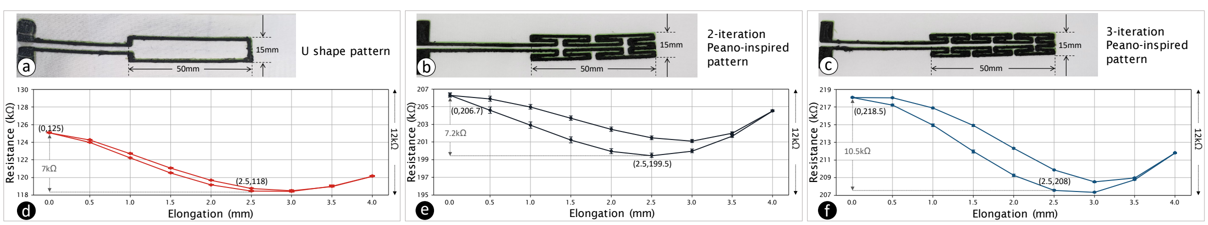


Fig. 8. Photos for (a) U-shape pattern, (b) 2-iteration Peano-inspired pattern, (c) 3-iteration Peano-inspired pattern. Resistance-elongation test results for (d) U-shape, (e) 2-iteration Peano, (f) 3-iteration Peano patterns.

4.7.1 Procedure: We conducted stretch versus electrical resistance tests on three designs: a U-shaped sensor, a 2-iteration Peano-inspired sensor (shortened as Peano-2), and a 3-iteration Peano-inspired sensor (Peano-3). All three stretch sensors were designed to have the same test area of 50 mm × 15 mm to minimize the impact of other sensor dimensions. Each design was subjected to 20 cycles of tensile testing with 8 steps of 0.5mm elongations (a total of 4mm). We recorded the resistance-elongation data over time.

4.7.2 Results: Fig. 8(d)-(f) displays the results as line graphs with standard deviation represented by error bars. We observed that the U-shaped curves exhibit less hysteresis compared to the other two designs. The absolute resistance changes for the U-curve, Peano-2, and Peano-3 are approximately 7kΩ, 7.2kΩ, and 10.5kΩ, respectively.

Their corresponding resistance change percentages are approximately 5.6%, 3.5%, and 4.8%. The U-curve's higher sensitivity, less noise, simple design, and low hysteresis made it the best choice for our applications.

4.8 Electronic Component Integration

The typical soldering temperature for electronics components is in the 300℃ to 350℃ range, which is well above our ironing temperatures [88]. An eTPU circuit incorporating current off-the-shelf electronic components could enable various interactive-textile applications [4, 104]. Therefore, we explored how effectively eTPU can be directly interfaced with electronic components through the ironing method.

4.8.1 Electrical continuity: We selected six electronic components for our test, as shown in Fig. 9(a)-(f). These components include SMD resistors (Footprints 0603, 0805, 1206), an SMD analog multiplexer/ demultiplexer (SOIC16), an SMD voltage regulator (SOT-89-3), and a through-hole Op-Amp (R-PDIP-T8). Although most of the components are Surface Mount Device (SMD) types, we also included a through-hole Op-Amp to explore the integration of through-hole components into our circuit designs. The pitch sizes of the electronic footprints are arranged from smaller to larger, starting from SOIC16 (1 mm) to 1206 (3.0 mm). The ironing method we used involves placing all components on the predesigned areas and then heating the entire surface together with the iron, similar to a reflow process. Due to the temperatures used, no fumes were generated from the fabric, filaments, or components. Components are positioned within designated open circuit areas as illustrated in the 'electronics integration' section (Sec. 5.3.2). These areas are designed to be like sinks or cases, where the base and sides are NinjaFlex and eTPU, respectively. The lengths of these open circuits are designed to be equal to or slightly smaller than the pitch size of the component. Therefore, the components can be firmly held in place during ironing and remain fully in contact with NinjaFlex to ensure adhesion and maintain connectivity with eTPU at both ends. For smaller components like SMD resistors and similar form factors, we completely cover the component with clear NinjaFlex as shown in Fig. 9(g) to strengthen the adhesion, while the components with larger form factors like through-hole Op-Amp and similar form factors, we only cover the connection pins as shown in Fig. 9(h). Performance tests were conducted on each component to verify electrical continuity using a multimeter and to visually inspect the adhesion.

4.8.2 Result: We verified the connection integrity between eTPU traces and the electronic component pins using a multimeter's continuity mode. All components exhibited electrical connections in the eTPU/NinjaFlex design, suggesting the potential to integrate different electronic components purely using the ironing method. A challenge with the Op-Amp (R-PDIP-T8) was its 4mm height, which made heat transfer harder. We resolved this by separately ironing its left and right legs.

4.8.3 Tensile and bending fatigue test: We selected an SMD (LED) and a through-hole (Op-Amp) component for 1000 cycles of tensile (10% strain) and bending fatigue tests, using the setup described in Sections 4.2 and 4.3 (Fig. 9(g)-(h)). The LED's functionality was monitored by powering it ON and checking the status, and the Op-Amp's continuity was assessed with an ohmmeter. There were no noticeable changes in functionality after 1000 cycles of fatigue test.

4.9 Thermochromic Properties

Thermochromic properties of materials such as thermo PLA have the potential to be used in interactive HCI applications. We investigated how a hybrid of thermo PLA and NinjaFlex can be used to alter the designs' thermal response. The aim is to create structures with varied sensitivities. The top layer consists of a thermo PLA, and we integrated hollow structures into the bottom NinjaFlex layer to trap air, thereby reducing the thermal conductivity.

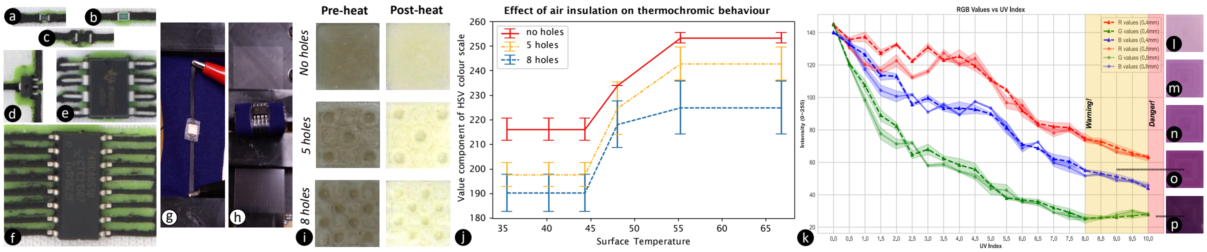


Fig. 9. Iron different footprint components onto circuit layer: (a) 0603, (b) 0805, (c) 1206, (d) SOT-89-3, (e) R-PDIP-T8, (f) SOIC-16. (g) Strain fatigue test for the integrated LED. (h) Bending fatigue test for the integrated Op-Amp. (i) Visual illustrations of Thermo PLA's color change. (j) Brightness vs Temperature. (k) RGB intensities of 0.4mm and 0.8mm samples after 5-second UV flashlight exposure. Photos (l)-(p) show color transitions for UVI 2, 4, 6, 8, and 10.

4.9.1 Procedure: We created three samples (10mm x 10 mm), one with no holes, one with 5 holes, and one with 8 holes (each hole is 1.5mm in diameter) in the NinjaFlex for the study (Fig. 9(i)). We used the heated printing bed of the 3D printer as a controllable heating source and captured photos of the samples while gradually adjusting the temperature. For each sample, we collected nine photos and extracted the HSV-value component to gauge the intensity of change, as it represents the brightness of the color as perceived by humans.

4.9.2 Results: As shown in Fig. 9(j), we observed that the brightness of the color decreased with the number of holes. This suggests that we can adjust the brightness level by altering the air insulation (number of holes), allowing for a more or less prominent color change in human perception.

4.10 Photochromic Properties

Similarly, photochromic PLA has the potential to create passive interactive textiles that indicate hazardous environmental conditions, such as excessive ultraviolet (UV) radiation. Off-the-shelf photo PLA[1] typically offers only a limited color range [43]. To identify the UV-induced colors that could potentially harm humans, we conducted a study that quantitatively analyzed the changes in color by UV lights.

4.10.1 Procedure: We used an intensity-controllable UV flashlight positioned directly above two samples with thicknesses of 0.4mm and 0.8mm, each measuring 30mm x 30mm. We employed the MS-98(3) UV detector to measure the UV Index (UVI) at the sample. After illuminating the sample with the light of a specific UVI, we took a still photograph. Using the Python-OpenCV library, we analyzed these images to calculate the sample color in relation to the measured UVI. We took an average of 10 measurements as the final color for the results. To mitigate the cumulative color effect, we chose to expose the original color samples to specific UVI light for only five seconds before capturing the photos.

4.10.2 Results: As shown in Fig. 9(k), the RGB values of the samples gradually decrease from (145,145,140) to (65, 30, 45), transitioning from a yellow-grey to a deep dark purple. The most noticeable color shift occurs between UVI 0 to 6.0. From 6.0 to 10.0, the color change slows and after UVI 10.0, the color becomes saturated, making it hard to distinguish with the naked eye. The thicker sample was initially darker (UVI 0.0 to 2.0) comparatively due to the thinner sample's initial transparency. But as the UVI increases, their light transmittance decreases, making the colors of the thick and thin samples converge. We marked UVI 8.0-10.0 as the 'Warning' zone (Fig. 9(o)) and indices above 10.0 as 'Dangerous' Fig. 9(p). According to research by Gies et al. [23], exposure should be limited to 40 minutes in the Warning zone and 20 minutes in the Danger zone.

5 Design Tool

The process of converting a given design into different geometries that need to be printed separately using different materials is challenging for novices. Particularly, integrating tiling with appropriate parameters, creating circuit and adhesive layers, and exporting them individually as printable models (e.g., STL) involves many details, which might be tedious. In our early prototyping stages, we experienced numerous instances where we made errors and the whole process needed to be repeated. To overcome these challenges and assist with the design process, we developed an interactive design tool and made it publicly available on GitHub[4]. The tool involves the results of our empirical studies. It is built as a Rhino 3D plugin using Grasshopper. This section describes the workflow and functionalities of the tool.

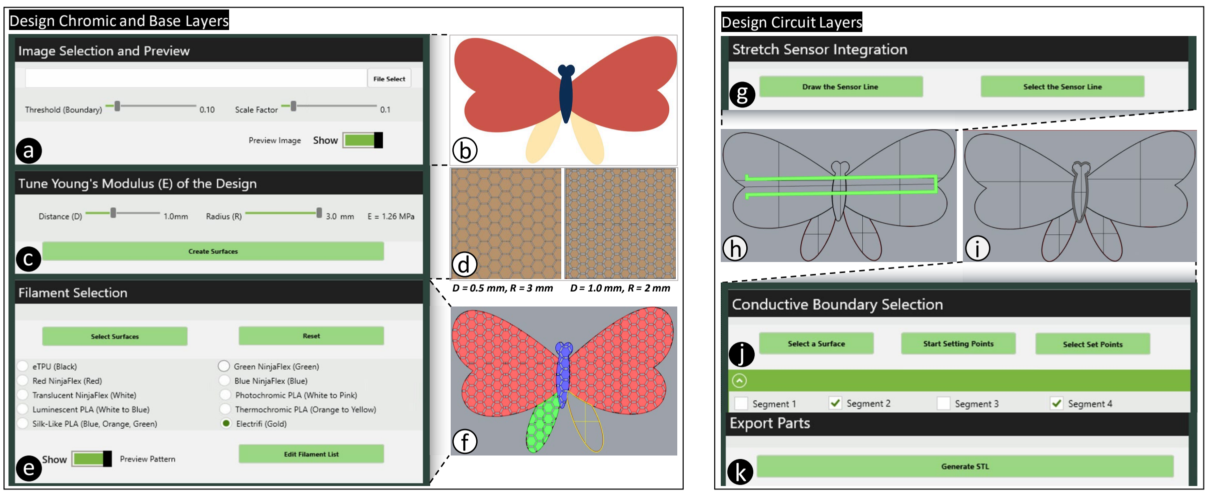


Fig. 10. (a)-(f) Design chromic and base layers: (a)-(b) Import, scale, and segment images; (c)-(d) Tune Young's Modulus using D and R; (e)-(f) Tile the segmentations and assign the filaments. (g)-(j) Design circuit layers: (g)-(h) Incorporate a stretch sensor into the design; (i)-(j) Convert a geometry boundary to a conductive eTPU element. (k) Export STL files.

5.1 Importing Artwork and Segmentation

In many cases, appliqués such as decorative patches on textiles begin with a 2D artwork or design. Similarly, our design tool allows users to start with 2D artwork by importing images in formats like BMP or PNG. The tool then converts these imports into a bitmap, creating the base for interactive element design. As shown in Fig. 10(a), the imported image can be scaled and cropped using the GUI to fit the intended size.

5.1.1 Segmentation. After uploading the artwork, the tool will automatically trace the outlines of different colored regions using the pixel-difference threshold values (Fig. 10(a)). We use the *BITMAP+* Grasshopper plugin to implement this function. Then, based on the regions, areas are partitioned, and different geometric objects are generated. Users can fine-tune the partition threshold to interactively change the identified regions.

5.2 Tiling and Material Assignment

5.2.1 Tiling. Tiling is required to mimic the mechanical behavior of the textile in 3D prints. Users can tune the parameters R and D to achieve given softness (Fig. 10(c)-(d)). The Young's modulus for different R and D

[4]https://github.com/aid-lab-org/IrOnTex-DesignTool

are derived from simulation results. The implementation of this function is achieved by filling a zone with unit shapes and merging it with the designated pattern. The merged result represents the desired tiling structure. The tool generates two STL files for each area: one with a hexagonal tiling top layer without connectors, and the other with a fully connected hexagonal tiling using Y-connectors. These Y-connectors not only connect things but also make it easier and more convenient to transfer or move the layers together. The layer containing connectors will be printed using NinjaFlex, while the other layer will be printed with a rigid filament, usually PLA.

5.2.2 Material Assignment. After creating separate geometric tiling areas based on the artwork, users can select the filaments to be used for each region (Fig. 10(e)-(f)). The tool will automatically combine the components that can be printed together as a single geometry based on material selection.

5.3 Circuit Layers

The circuit layer is designed using two functionalities enabled by the tool. They are (1) stretch sensor integration and (2) embedding electronics in the model. These two functionalities are achieved by integrating a U-shaped curve and generating conductive traces based on the image's outlines.

5.3.1 Stretch sensor integration. The tool enables users to draw a line within the design outline indicating the size of the stretch sensor. The tool will automatically place the optimal eTPU U-shape along this line within the design's boundaries, as shown in Fig. 10(g)-(h). Subsequently, the eTPU U-shape and its adhesive layer can be exported as two STL files. This feature aims to rapidly generate a U-shape curve within a particular design, enabling the quick integration of stretch or pressure sensor functionalities along a given direction. Furthermore, the tool will add connection pads to the U-shape at the edge of the design for external electronic connections.

5.3.2 Electronics integration. To enhance the convenience and usability of our tool, we have incorporated the ability to integrate common electronic components using the design interface. The tool enables to select boundaries made with *BITMAP+* to generate circuit traces as shown in Fig. 10(i)-(j). Within this circuit, users can choose the locations of the connection pads to place components such as LEDs, resistors, transistors, and batteries. When users choose their desired locations for the pads, the tool will create an open circuit and provide appropriate pitch sizes to ensure that the dimensions of the electronic components match the break lengths in the circuit design.

5.4 User Study for Design Tool

To evaluate the usability of the design tool [36] and how it assists users in creating customizable interactive textiles, we conducted a user study. The study received ethics clearance from the Human Research Ethics Committee (HREC) of the University of Sydney (Application number: 2019/553).

5.4.1 Procedure and Tasks: Participants were asked to use the design tool to design an appliqué to resemble the butterfly design shown in Figure 2. This includes four subtasks: 1) import an image of a butterfly and adjust parameters such as the threshold and scaling factors to isolate shapes, 2) adjust the softness by setting Young's modulus to 1.25 MPa by tuning parameters R and D, 3) assign different colors to various regions of the created surface, such as red for the wings, green for the tails, and blue for the body, and 4) integrate a bending sensor across the generated surface and adjust the locations afterward. The study began with a general introduction and demonstration of the design tool. Participants then needed to complete the tasks followed by a System Usability Scale (SUS) test [57] and a post-study interview. We encouraged participants to verbalize their thoughts and think aloud during the study. On average, a study took 40 minutes to complete. Each task was assessed as 'Success', 'Fail', or 'Success with Help'.

5.4.2 Pilot study: We initially recruited six participants for a pilot study. The results suggested that one participant needed help with Task 2, and two participants needed help with Task 3 and 4. Common comments included "some button names and locations are confusing" and "some features can be combined together." The average SUS score after interpreting was 60.83 (SD = 13.66), which is considered poor. We improved the layout of the user interface and order of steps, and removed redundant tasks.

5.4.3 Main User Study: After improving the interface, we recruited 10 participants (aged 22-33, with 4 females). Six of the participants had previous experience with Computer-aided design (CAD); two of them had previously used Rhino, and three had used CAD recently. The other four participants had rarely or not used CAD before.

Overall, most of the participants were able to complete the tasks independently except for Task 3 (Task 1 - 1/10, Task 2 - 0/10, Task 3 - 6/10, Task 4 - 3/10). In Task 3, the help provided was for Rhino functionalities that are not directly related to the tool. The success rate of Task 2 and Task 4 improved compared to the pilot study. We obtained an average interpreted SUS score of 80.75 (SD = 16.29), which is within the adjective rating of good and excellent [8]. The scores for participants with CAD experience (6 participants) and those without (4 participants) are 82.91 (SD = 14.78) and 77.5 (SD = 20.20), respectively. This shows that users with CAD experience found the tool to be more helpful than those without experience, even if it was their first time using it.

In the post-study interview, most participants found our design tool useful and straightforward for creating tiling structures and integrating stretch sensors. The CAD experts mention that "Can use Solidworks but it is not parametric" (P2), "Solidworks and Fusion [can be used]. [but] Thinks it will be very difficult" (P7) and "This application-specific design tool is useful" (P8). A few participants commented that Rhino functions, such as prompts, were not noticeable, and this is where they needed help to complete the task. P4 suggested we add explicit notifications in such situations. Additionally, P8 hoped for "more pattern options beyond just hexagons". These insights help us to improve the tool further.

6 EXAMPLE APPLICATIONS

To demonstrate the capabilities of various functionalities of the IrOnTex approach and our design tool, we developed a series of application examples.

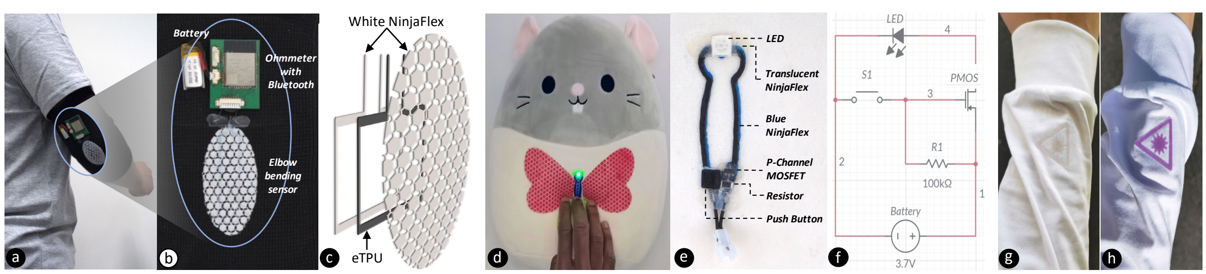


Fig. 11. (a) A man wearing the elbow bend sensor. (b) Close-up view of the elbow bend sensor. (c) Layered structure of the sensor. (d) A demonstration of interactive butterfly with light up. (e) Integrating electronic components to circuit layer. (f) Circuit diagram of (e). (g)-(h) UV indicators on a sleeve: (g) Under shadow conditions, (h) Direct exposure from sunshine.

6.1 Arm Movement Tracker

To demonstrate the sensing capabilities and the ability to integrate the layered structure onto clothing, we created a wearable arm movement tracker with IrOnTex. As depicted in Fig. 11(a), we ironed a sensing part and electronics onto a stretchable arm sleeve. The bend sensor comprises a stretch sensor in the circuit layer and an elbow patch design on the base layer (Fig. 11(c)). As shown in Fig. 11(b), the base layer effectively conceals the sensor beneath it. The sensor interfaces with a PCB, connecting it to a voltage divider circuit that functions as an ohmmeter. A microcontroller (ESP32 Wroom 32E) measures the changes in resistance and transmits them to a computer via Bluetooth. Upon first wearing the elbow sleeve, there will be a five-second per-user on-the-fly calibration using the full flexion and extension of the elbow, yielding the minimum and maximum sensor values [24]. These values are then normalized to a [-1, 1] range. All subsequent measurements are calibrated against this normalized data and translated into the elbow's bend angle for visual representation, as depicted in Fig. 1(b).

6.2 Interactive Plush Toy

To demonstrate the circuit design and the electronics integration capabilities of the IrOnTex method, we created an interactive plush toy appliqué that responds to user touch as shown in Fig. 11(d)-(f). The circuit for this application (Fig. 11(f)) triggers an LED when pressure is applied to the sensing area. This circuit was generated using the 'Electronics Integration' feature of our design tool. We designed the butterfly's body to contain all circuit traces, carefully placing breaks between traces to match the pitch of the corresponding electronic components. Fig. 11(e) depicts the complete circuit on the butterfly's body with all the components ironed on. Besides using blue NinjaFlex for the base, we put an overlay on small components using translucent NinjaFlex before ironing them onto the conductive traces to ensure adhesion and stability. The butterfly-shaped decorative layer is then ironed on top of the circuit layer, effectively masking the electronics except for the LED. Fig. 1(c) shows the complete butterfly ironed on the plush toy, while Fig. 1(d) and Fig. 11(d) highlight the interactions by pushing.

6.3 Temperature Sensitive Cup Display

To demonstrate the thermo PLA in an interactive application, we created a neoprene sleeve for a cup with a thermochromic display indicating internal temperature as shown in Fig. 1(e)-(f). We imported an image of a flaming fire into our design tool and specified its dual-layered structure with thermo PLA and translucent NinjaFlex on the bottom. The translucent NinjaFlex effectively makes the adhesion layer and connector less noticeable, thus reducing their perceptibility. Once ironed onto the neoprene sleeve, it offers users a visual cue of the beverage's temperature. At room temperature (20°C), the display is dark yellow (cream) color (Fig. 1(e)). However, at 60°C, near the optimal 57.8°C for hot drinks as noted by Brown and Diller [9], it turns light yellow (Fig. 1(f)), allowing users to easily discern their drink's temperature. We integrated holes in the bottom layer to trap air to balance the temperature and color.

6.4 UV Warning Indicator

Our fourth application aims to demonstrate the UV-sensitive PLA in a personal safety application. As shown in Fig. 11(g)-(h), we fabricated a UV indicator on clothing, enabling wearers to visually gauge UV index (UVI) levels through color transitions. As UV light intensity increases, the photochromic filament changes color, providing a visual alert (refer to Fig. 11(g)-(h)). Based on Gies et al. [23] and UV guidelines, we have indicated color ranges for UVI levels from 0 to 10+. For UVI 0-2 (Fig. 9(j)), sunglasses are recommended; for 3-5 (Fig. 9(k)), sunscreen is suggested; for 6-7 (Fig. 9(l)), it is advised to limit midday sun exposure; for 8-10 (Fig.9(m)), take extra precautions and avoid the midday sun; and finally, for 10+ (Fig. 9(n)), maximize protection with full body coverage and minimize outdoor activity around noon. Notably, high UVI levels can occur on both hot and cold days.

6.5 Luminescent Display

Our final application, as depicted in Fig. 1(g)-(h), showcases a luminescent PLA material. An ACM logo is crafted using a combination of luminescent filament and base layer. The logo's blue background is crafted from blue NinjaFlex, while its characters and circle are dual-layered with luminescent PLA and translucent NinjaFlex. This design makes the logo appear as a reflective display when the environment is light (Fig. 1(g)). However, when it is dark, it converts to an emissive display, where luminescent PLA glows (Fig. 1(h)). This can create displays that change the information based on the context, for instance between day and night. It can be used for applications such as parties, to display surprise messages when the lights are off. It could also be used in safety suits for emergency guidance under low-light conditions.

7 DISCUSSION AND LIMITATIONS

In this section, we discuss our reflections on the proposed approach, key limitations, and possible future directions.

7.1 Discussion

Our technical evaluation and the application examples collectively show the potential of the proposed approach as a fabrication method for interactive textile applications. We believe that the HCI and UbiComp communities will benefit from it as an approach to prototyping artifacts [107].

We also observed that by varying ironing settings, filaments such as NinjaFlex, eTPU/NinjaFlex, and thermo PLA can be tailored for different purposes. For example, in our tests with most fabrics, we found that 160℃/60s was suitable for reversibility; 190℃/30s achieved good washability and reversibility, making it quite prototypeable; and 190℃/120s ensured superior adhesion that lasted over 10 washing cycles. Good reversibility means that appliqués can be easily peeled off without damaging the fabrics, allowing for design replacement.

The fatigue test provided us with distinct results on the types of fabrics with which the method can be used. In particular, polyamide, sateen weave cotton, and satin weave silk proved unsuitable for high ironing temperatures or durations due to their propensity to burn. Notably, both sateen and satin patterns, with their similar shiny weaving patterns, demonstrated lower heat tolerance compared to other weaves. This is likely because their more exposed yarns on the surface are more prone to heat damage [25], unlike interlocking yarns in plain weaves. In contrast, wool and acrylic fiber showed high adhesion and did not support peeling off, indicating their unsuitability for prototyping.

Furthermore, lower-density fabrics have a more porous structure. This provides a greater surface area for melted filament adherence, resulting in stronger bonding after curing. In contrast, higher-density fabrics do not bond as strongly. This insight refines our understanding of fabric selection for an effective IrOnTex fabric range. However, it is important to note that these findings for fabric density are preliminary, given the limited scope of the study, and require further systematic investigation for comprehensive validation.

The features of the tool, including automatic layer creation and Y-shape connectors, helped significantly to simplify the design process and handling. This streamlined the alignment of layers, transferring prints onto textiles, and adjusting softness. The design tool further helped customization by importing artwork images, selecting filament, and tuning hexagonal structure and circuit design. While some filaments, such as eTPU, did not provide color choices, the tool helped to align these along borders and edges without affecting the artwork. The layer selection offered further customization. For example, the circuit layer is only necessary if there is a need for electrical characteristics and the base layer can operate independently without a chromic layer. Furthermore, users can tailor functionality using available filaments, such as adjusting eTPU dimensions for sensitivity or modifying air traps to alter thermochromic features.

We believe that the integration of some unique 3D printing functionalities with textiles through IrOnTex could expand research possibilities. This includes aesthetic innovations [59, 96], complex circuit designs [6], invisible information [46], and customizable thermochromic [112] or photochromic applications [47]. Additionally, automated filament inking [59] could enhance IrOnTex by offering a wider color selection, like the specific color printing in EcoPatches [62], thus providing color references. Moreover, the potential for actuation [68, 69] and shape-changing functions, including metamaterials [44, 111] and morph structures [100, 101], could further provide direction to improve the pliability and adaptability of textiles. For wider adaptation, we could make pre-printed, modular, and functional IrOnTex appliqués available on the market for users.

7.2 Limitations and Future Work

While IrOnTex shows promising results, we observed several limitations and considerations that need to be addressed in the future.

7.2.1 Complex Designs: The design tool was beneficial in simplifying the process. However, if the design is complicated with overlapping and multi-colored regions (above 5), it can become cumbersome to assign materials and settings. We used a 3D printer with two extruders, which constrained our ability to create multi-color designs. As a workaround, we framed the design outline and printed each partition separately before assembling and ironing them together. However, for complex designs, it can be tedious to print them independently and assemble them. In the future, with the use of printers equipped with more than two extruders, performance can be improved. Currently, our design tool does not support varying softness across regions. Other hexagonal Euclidean tilings [5] or morph structures [101] can help achieve adaptive softness from region to region.

7.2.2 Filaments: IrOnTex's performance is closely linked to the properties of the filaments used. For instance, eTPU exhibits relatively high resistance, limiting its possible circuitry uses. We used balanced circuits that leverage limited currents to overcome this limitation. While some copper-based filaments with high conductivity were available, they were too fragile to use in textile applications. When higher current is needed, we used thicker, wider, and shorter traces. Additionally, some chromic properties like luminescence have shorter persistence (~5 minutes). This limitation affects the duration of visible effects in practical applications. We believe that future advancements in material sciences will overcome these limitations. Additionally, we anticipate that the range of FDM materials available in the future will further enhance the versatility of the IrOnTex approach.

7.2.3 Fatigue Test for Tiling Structure: Our studies did not conduct a formal fatigue test on the tiling structure. We observed that the flexibility and softness of the tiled structures demonstrated higher resilience to fatigue compared to solid fills. However, it is important to note that in real-life scenarios, tiling may be susceptible to tangling and latching. These issues could lead to the appliqué being peeled off over time. Therefore, while our observations indicate a certain level of resilience, the actual durability of tiling structures under varied and repeated use still requires further investigation.

7.2.4 Evaluation of the Effect of Pressure on the Iron Settings: Due to the thin ($\leq$ 0.4mm) nature of our designs, we could assume an even pressure distribution (Sec. 3.4). However, we have not quantitatively assessed the effect of the pressure on the fabrication approach. Considering the variability in the weight, the contact area, and the force used by different people when ironing, this is an important aspect to evaluate in the future.

8 CONCLUSION

This paper presents an approach for fabricating and prototyping customizable interactive textiles by combining FDM 3D printing and ironing. We employed a tiling-like fragmented design to enhance stretchability and flexibility, simulating fabric-like behaviors in interactive appliqué. We demonstrated that the approach enables the use of a wide variety of printing materials with different functionalities, such as electrical, thermochromic, and photochromic, which are suitable for different applications. Our technical studies and fatigue tests highlight the durability, washability, and peelability of the appliqués. The method enables iterative and reversible design changes without causing damage to the textile. The results of our evaluations informed the development of a user-friendly design tool, which facilitates the creation of interactive textile applications. We envision that our contributions pave the way for designers and makers to fast prototype interactive textile applications.

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