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ABSTRACT

As electronic textiles have become more advanced in sensing, actuating, and manufacturing, incorporating smartness into fabrics has become of special interest to ubiquitous computing and interaction researchers and designers. However, innovating smart textile interfaces for numerous input and output modalities usually requires expert-level knowledge of specific materials, fabrication, and protocols. This paper presents EmTex, a construction kit based on embroidered textiles, patterned with dedicated sensing, actuating, and connecting components to facilitate the design and prototyping of smart textile interfaces. With machine embroidery, EmTex is compatible with a wide range of threads and underlay fabrics, proficient in various stitches to control the electric parameters, and capable of integrating versatile and reliable interaction functionalities with aesthetic patterns and precise designs. EmTex consists of 28 textile-based sensors, actuators, connectors, and displays, presented with standardized visual and tactile effects. Along with a visual programming tool, EmTex enables the prototyping of everyday textile interfaces for diverse life-living scenarios, that embody their touch input, and visual and haptic output properties. With EmTex, we conducted a workshop and invited 25 designers and makers to create freeform textile interfaces. Our findings revealed that EmTex helped the participants explore novel interaction opportunities with various smart textile prototypes. We also identified challenges EmTex shall face for practical use in promoting the design innovation of smart textiles.

CCS CONCEPTS

• **Human-centered computing**; • **Human computer interaction (HCI)**; • **Interactive systems and tools**; • **User interface toolkits**;

KEYWORDS

Smart textile, Wearable construction kit, Modular toolkit, Visual programming tool, Prototyping.

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1 INTRODUCTION

Incorporating smartness into apparel and everyday fabrics has been a prominent trend, thanks to the enormous advancement in electronic textiles (e-textiles) in the disciplines of integrated sensing fibers [39, 60], woven display [47] and soft actuating mechanism [3], etc. The improved capability in integrating electronic components into fibers and textile structures brings special interest to ubiquitous computing and interaction researchers to build advanced textile interfaces [45], yet how to integrate diverse functions of textiles in variable living scenarios remains under active exploration. However, understanding modified textiles with numerous input and output modalities usually requires expert-level knowledge of specific materials, fabrication, electronics, and protocols.

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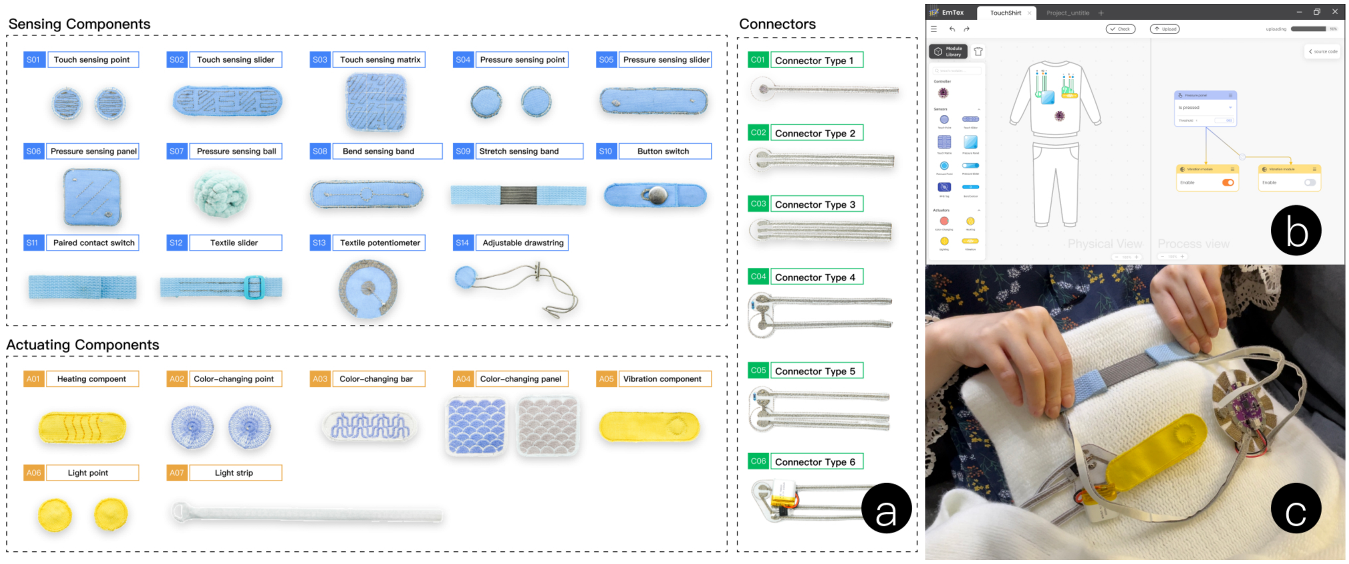

Figure 1: EmTex consists of components in an e-textile construction kit and a visual programming platform to support designers and makers in creating e-textile prototypes of diverse applications in daily life. (a) 28 sensing, actuating, connecting and controlling components in the toolkit; (b) visual programming platform; (c) a project created during the workshop study.

To tackle the challenges, this paper presents EmTex, a modular embroidered e-textile construction toolkit that enables designers to compose smart textile prototypes of diverse applications, high quality, and high-level textile-integration. EmTex is developed upon the success of previous textile toolkits (see Figure 2) while complementing these efforts, in increasing the diversity of components in functions, and maintaining the unity of textile style. It achieves so by adopting machine embroidery which brings consistent, reconfiguration, precise and rapid functional integration within the textile structure, and provides more freedom of routing the textile wiring with varied threads, e.g., stainless conductive threads, thermochromic threads, enameled copper wire, etc [11, 12, 40]. As a result, EmTex is compatible with a wide range of threads and underlay fabrics, proficient in various stitches to control the electric parameters, and capable of integrating versatile and reliable interaction functionalities with aesthetic patterns and precise designs.

EmTex consists of 28 stick-and-play sensing, actuating, displaying, connecting textile components, and controlling modules. It supports users' touch, press, slide, bend, and stretch actions, and provides color, thermal and vibration outputs, as shown in Figure 1. The components are patterned with embroidered conductive, thermochromic, and/or normal threads on regular-shaped woven canvas. All the components can be used in a stick-and-play manner because of the dedicated design of connectors, that work similarly to hook-and-loop fasteners. Meanwhile, form factors of the connectors are kept consistent with traditional buttons, stickers, and belts in everyday garments. Lastly but not least, EmTex optimizes the design and prototyping process via a visual programming tool, with circuits building guidance, and functions and connections of the textile components coded automatically.

To validate the value of EmTex (e.g., the potential of creating versatile e-textile interfaces for daily applications) and to see how EmTex, as a construction kit is perceived by users and could be improved for practical use, we conducted a workshop with 25 participants from a local design college and a maker community. Eleven (11) demo textile interfaces that embraced the form factor features and sensing, actuating, and connecting capabilities of EmTex were prototyped and presented. The demos ranged widely in life scenario applications, including social interaction, home living, health and wellbeing, VR, and public safety, etc. The observation and the participants' feedback indicated that the rich functions integrated into diverse textile components, as well as the programming tool helped to inspire smart textile interfaces that shift our way to interact with environments and others. It showed that EmTex was a valid construction kit that can be effectively understood, learned, and used by the participants.

The paper made the following contributions: i) EmTex as a modular embroidered e-textile construction toolkit for smart textile prototypes of diverse applications, high quality, and high-level textile integration; ii) design schema and fabrication of 28 textile sensing, actuating, and connecting modules based on machine embroidery; iii) a visual programming tool to assist users without e-textile or programming background to compose rich design and prototypes of interactive textile interfaces; iv) validation of the usefulness of EmTex in helping users design and build diverse textile interfaces via a design workshop.

2 RELATED WORK

2.1 Smart Textile Interfaces

Researchers and practitioners are witnessing profound changes in the e-textile field [39], which has steady streams of breakthroughs from multiple disciplines, including material science, computer science, and engineering [46]. Numerous advanced e-textile interfaces have enriched ubiquitous interaction by incorporating interactive fibers, threads, and fabrics capable of gestural and environmental sensing in daily life scenarios [58]. Previous work has investigated conductive, resistive, and capacitive ways to enable textile-based touch[1, 25, 33, 50] bend[10], pressure[2, 24], strecth[55],twist[32], pinch[32], and mid-air gesture input [13, 34], etc.

On the other hand, e-textile displays and actuators are often explored and leveraged to output information to users, including light, sound, shape or color changes, vibration, etc [46]. For example, I/O Braid could provide dynamic color feedback by embedding fiber optic lines[31]. SkinLace fabricated by freestanding lace could be equipped with LEDs to make displays on human skin [14]. Based on the thermochromic principle, Wang et al. designed a color-changing cheongsam [56], and Endow et al. developed liquid crystal textile displays [8]. KnitSkin integrated actuators into knitted fabrics for directional locomotion [20]. Sonoflex [41] proposed textile speakers by embroidering enameled wires. While these works demonstrate the new capabilities of smart textiles, the integration of textile natural forms into living environments is still a topic of current research. Inspired by these previous work, EmTex was developed to include the common textile sensing and actuating functions with dedicated components.

2.2 Fabrication Techniques for E-Textiles

The fibers or textile structure itself is now capable of providing intelligent functions, allowing them to be seamlessly integrated as soft interfaces in recent years. It has been possible to significantly change the appearance of textiles and develop smart textile interfaces through various fabrication techniques. For example, sewing, weaving, knitting, hot-pressing, and embroidery are highly automated and getting familiar to researchers and designers [49]. Fabric electronics can be created at scale using conductive and non-conductive threads during the weaving and knitting stages of textile production. For instance, Project Jacquard [39]pioneered manufacturing touch-sensitive textiles utilizing highly conductive thread and machinery for textile weaving, while it is more suitable for large textile surfaces with flat structures and only capable of touch sensing. Sun et al. explored a series of on-skin textile interfaces through hand weaving which required huge manual work [50]. KnitUI demonstrated resistive pressure sensors by machine knitting [24], and Mcdonald et al. proposed knitted capacitive touch sensors [26]. However, it is challenging to create a multi-layer structure by integrating pre-cut materials via machine knitting, generating small-size textile components through the same fabrication procedure and achieving textile patterns with minimal graininess. Besides, they all require extra manual work to build the conductive connection traces.

Post et al. first proposed using embroidery as a means of creating computationally active textiles in 2000 [38]. Machine embroidery brings the advantages of great flexibility, versatility, and adaptability, and has recently gained popularity in textile-based interaction design for various applications [27]. For instance, machine-embroidered textiles have been designed and explored to build various types of capacitive and piezoelectric sensors [1, 51], textile speakers [41], textile electrodes [20], wireless power transfer [21], motion monitoring stretch sensors [22], and other high-fidelity textile prototypes [11]. On one hand, machine embroidery is compatible with a wide range of threads and underlay fabrics including knitted, woven, and non-woven fabrics. On the other hand, it is capable of creating arbitrary patterns and precise designs for functional or aesthetic purposes. In this work, we envisioned that functional textile components by embroidery have great potential to integrate with daily textile-based artifacts and embroidery enabled us to fabricate the functional textile areas and build the toolkit components with accurate form factors and standardized fabric patterns through the same process.

EmTex was inspired by these works and took an approach of machine embroidery-based design and fabrication, that constructs a rich set of sensing, actuating, and connecting components with unified appearance and aesthetic patterns, and high textile-integration.

2.3 Contruction Kits for Wearables and E-Textile

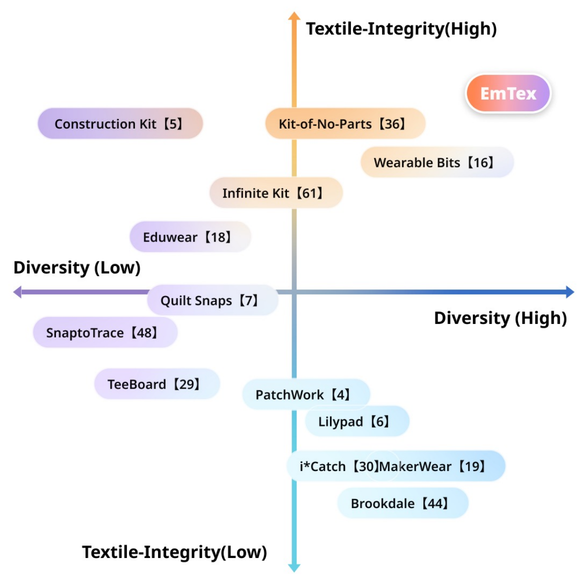

Figure 2: Quadrant map of the related kits from the textile-integration and diversity perspectives.

Construction kits are considered an effective way to help individuals to compose and evaluate design solutions without worrying about technical barriers. Nanda et al. [28] first proposed e-textile toolkits in 2004, and a variety of tools and kits [37] in the domain of e-textile have been proposed in the subsequent years. E-textiles, also known as smart textiles, refers to the integration of electronic components or intelligent materials with textiles [37]. While, the **textile-integration level**, namely the role of the "textile" in smart textiles has evolved significantly over the past two decades, **moving from a substrate stage to an embedded and entirely textile-based level** [43]. There are increasing demands for new E-Textile toolkits to encourage the explorations of applying textile interfaces in daily surroundings. As Posch et al. [37] reviewed available e-textile toolkits in 2019 and pointed out future directions, *"how to diversify and professionalise the field and its community of practice."*

As shown in Figure. 2, to clarify the motivation for design and implementation of EmTex and position the new toolkit clearly, we positioned the previous e-textile construction kits in a new taxonomy that consists of two axes, namely the two challenges that motivated our system's development. Challenge 1 refers to **textile-integration** (how the electronics are integrated with textiles). Challenge 2 refers to **diversity** (diversity of the modules and richness of the applications). A further statement of these two challenges was presented as followings.

2.3.1 ***High Textile-Integration through Fully Textile-based Modules.*** The LilyPad [6] Arduino kit is the first widely accessible e-textile toolkit, as popular wearable mainboards with a set of sewable components and has a wide range of wearable applications. They have been used as the basis for extensive explorations, such as TeeBoard [29] which demonstrated a snappable t-shirt breadboard platform and Patchwork [4] which incorporated sewing snaps. For reducing the high entry barrier of programming and electronics, MakerWear [19] proposed a set of plug-and-play wearable components, and i*CATch [30] created customized wearable components and a programming environment. Recently, Seyed et al. proposed Brookale[44] which is a wearable toolkit for fashion designers and it consists of modular plug-and-play hardware and software. These previous works demonstrate toolkits play important roles in empowering new audiences to e-textile community. However, they are all in the stage of mounting or embedding the hard electronics components on textiles by sewable connections, snaps, or as accessories. It is desirable to explore how the textile-based components that have a capacity of sensing and actuating could be integrated into their daily surroundings unobtrusively and maintain the characteristics of the textile-based artifact.

Towards the direction of achieving the capacity of sensing and actuating through the textile structure itself, a number of works contributed to construction kits by incorporating textile components with conductive characteristics. As a pioneer work, Buechley et al. [5, 7] proposed a series of refined textile components with electronics mounted and conductive fabrics as connection pins so that the components can be sewed by conductive threads. SnapToTrace [48] created a snappable mat as a learning environment and three hand-crafted textile input components and the possibility to add their own. EduWear [18] emphasized the soft feature of e-textile toolkits instead of technical-looking characters, the kit included several sensing inputs also involved textile sensors, and they highlighted the conductive threads as data busses. Similarly, Wearic [57], and Zhang et al. [61] extended textile input and output components that can be snapped together. Towards textile scaffolding for wearable projects, Wearable bits [16] embedded electronic components in a square shape as the basic component, and users can assemble various forms of smart clothing with the square fabrics for different functions. Noteworthily, the Kit-of-No-Parts [36] emphasized the textile characteristics and demonstrated an approach for individuals to develop customized textile components as previous groundbreaking work, and their website [54] has been a constantly updated library with continuous inspiring explorations.

These previous works proposed pioneering explorations in textile-based modules and demonstrated the features and ability of soft materials, while they are in different levels of textile integration and still present challenges for seamless interaction into everyday objects. Projects in high levels textile-integration, for instance, Kit-of-No-Parts encouraged personalization of interfaces which has a high barrier to begin, it requires specialized materials and a certain level of expertise. EmTex also builds upon these previous works, sensing mechanisms and patterns inspired by individual soft modules Kit-of-No-Parts, etc. While EmTex argues the high-integration level and modular solution as a systematic way of constructing fully textile-based e-textile prototypes.

2.3.2 ***High Diversity by Incorporating Various Modules and Versatile Scenarios.*** The motivation to offer abundant modules is to achieve high flexibility and broaden the design space, to facilitate applications not only for wearables but also for environments. Previous studies mainly emphasized on-body scenarios, for example, WearableBits [16] focused on co-design wearable projects through scaffolding tools, TeeBoard [29] and SnapToTrace [48]proposed on-body textile platform. While Kit-Of-No-Parts [36] was more like a swatch book library and the modules have potential in various domains, Zhang [61] explored e-textile toolkits to support textile designers with professional expertise. In addition, Education has been quite an important target area for previous toolkits, for example, MakerWear [19], i*Catch [30], and EduWear [18] conducted workshops to enable children to ideate and create wearable applications. Different application scenarios require varied textile experiences supported by suitable interactive textile technologies.

Instead of a specific application area, rich sensing, and actuating capabilities are preferred to support as many textile-based scenarios as possible. As the basis of innovation, the proposed prototyping tool should fully stimulate designers' creativity, make the prototyping process easier, and allow designers to freely express their creativity. The touch-based or pressure-based textile sensors are among the most popular ones in the e-textile field. Previous research has explored the diverse sensing capabilities of e-textiles, including touch, bend, twist, pinch, pressure, and fabric electrodes for vital parameter monitoring. Compared to e-textile sensing, it's more challenging to create textile actuators based on the textile structure itself. Previously more studies were focused on novel thermochromic displays and shape-changing interfaces [56]. While the above-mentioned textile-based e-textile toolkits have a limited number of modular sensing and actuating modules.

To this end, EmTex consists of plentiful touch, pressure, bend, stretch, and manipulation sensors with abundant effort in the pattern and appearance design for both functionality and form factor. In addition, the prototype tool should also lower the level of difficulty in building the circuits and coding. Dexterous connection methods allow agile and reconfigurable prototyping.

3 COMPONENTS AND IMPLEMENTATION OF EMTEX

EmTex is built upon the advantages of machine embroidery and provides a set of textile components that enables plentiful sensing, displaying, and actuating interfaces in daily scenarios, by which,

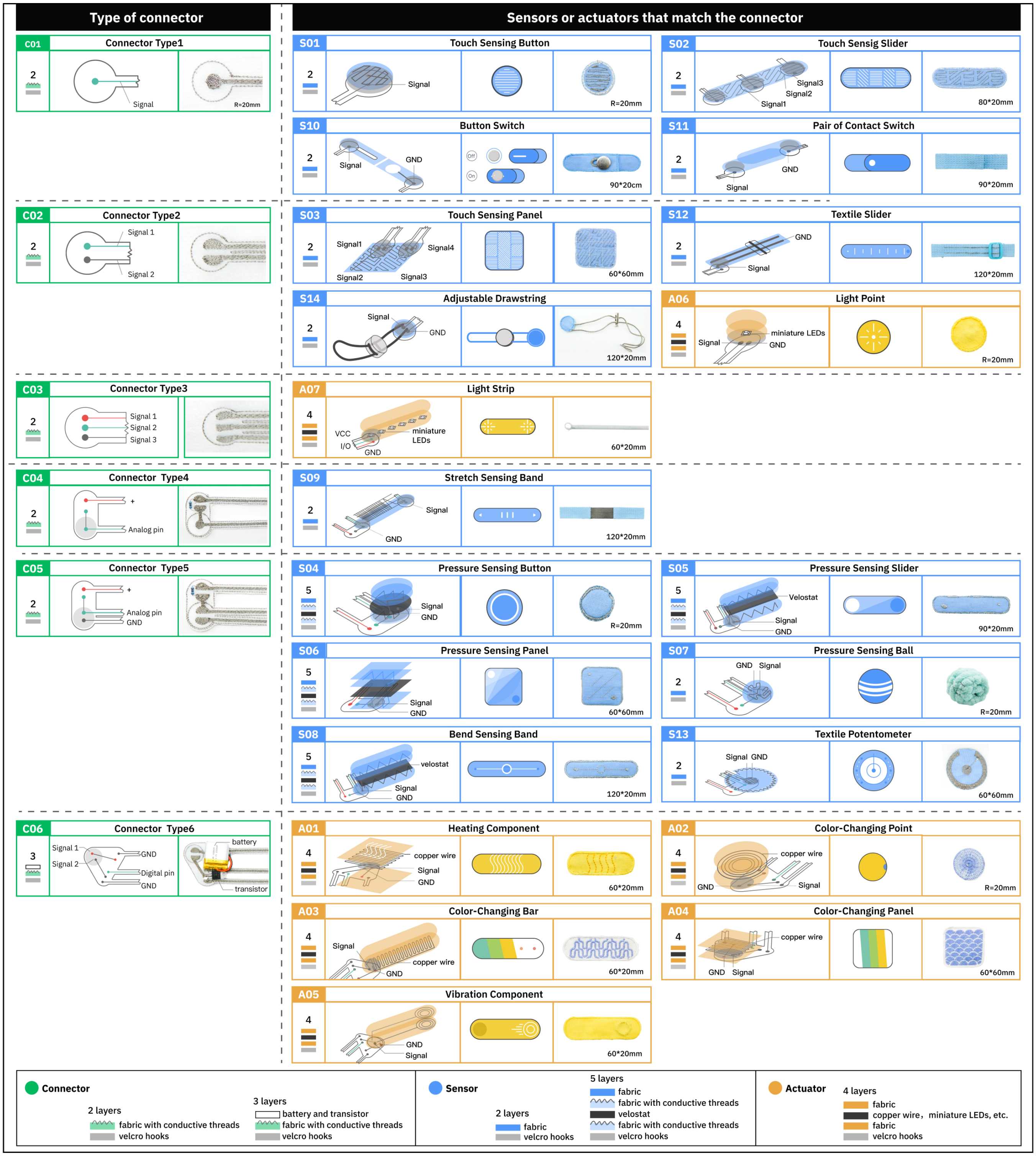

Figure 3: Overview of EmTex components: the components include sensors, actuators, and connectors, that use 2, 4, or 5 layer strucutre. Different brand colours were used to improve the recognition of the components.

EmTex extends the diversity and the ability of textile-integration of the prototyping toolkit.

3.1 Functional Textiles through Machine Embroidery

Various structural and embroidery patterns are defined for functional and aesthetic purposes with flexible combinations of threads. The functions of the embroidery pattern for the components can be categorized as sensing, electric conduction, color/shape changing, and decorative. The type of threads and parameters used for embroidery differ depending on the functions of the patterns. With machine embroidery, a stitch is formed when the needle carrying the top thread passes down through the needle hole in the needle plate and connects with the bobbin thread. It is possible to use the conductive top thread and the regular bobbin thread, which is suitable for fabricating patterned sensing units on the components. It is also possible to use conductive top and bobbin thread, which will decrease the resistance and is suitable to be used as connectors. Besides, various functional threads can be applied, such as using thermochromic top thread in conjunction with conductive bobbin thread to make color-changing components. Finally, the surface pattern of the components can use regular thread and serve no sensing function, but to provide an aesthetic appearance and indicate the function of the component.

EmTex also focuses on textile interfaces with extensive application potential, but in a way that is suitable for fast and flexible prototyping by machine embroidery with various underlay fabrics. Instead of proposing novel threads or threads with better characteristics from a material property perspective, EmTex adopts off-the-shelf threads with good reliability and universality. The idea is to support the designers and makers to excavate textile-based electronic components, to enable a wide range of applications and interaction possibilities. As shown in Figure 3, the EmTex toolkit includes 14 sensing components, 7 actuating components, 6 connectors and 1 microprocessor. The components and connectors are constructed completely or mainly in textile forms.

Overall, the components include three main structures. Two-layered components like touch sensing components (S01, S02, S03), textile slider (S12), and textile potentiometer (S13) comprise a sensing layer based on embroidered conductive pattern, and a thin connection layer (Velcro hooks). Four-layered components like heating component (A01), and color-changing components (A02, A03, A04) comprise an actuation layer (e.g., thermochromic threads), a functional layer (e.g., heating material, miniature LED), a base layer, and a connection layer. Five-layered components like pressure sensing components (S04, S05, S06, S08) have a sandwich structure for pressure sensing, a top layer for aesthetic appearance to indicate the function of the component, and a connection layer. Additionally, a few components have different structures, e.g., control widgets, and will be described in the following subsections.

3.2 Sensing Components

The EmTex kit provides 14 sensing components that can sense touch and pressure, bend and stretch, on-off manipulation, etc. (Figure 3).

3.2.1 ***Touch Sensing Components.*** The touch sensing button (S01), slider (S02), and panel (S03) detect the touch behaviours of tapping and sliding. Previous work like Gilliland et al. [9] proposed embroidered textile touch sensing via measuring the change in capacitance of conductive electrodes . We developed upon this principle and achieved multi-touch sensing through interdigitated stitches (see stitch patterns of S02 and S03 in Figure 3) to save the number of signal ports required. The touch sensing slider (S02) and panel (S03) can distinguish 5 and 9 touch areas through 3 and 4 signal ports, respectively.

3.2.2 ***Pressure, Bending, and Stretch Sensing Components.*** We used resistive sensing to detect users' pressing, bending, and stretching input.

Contact Pressure and Bending Component. The contact pressure sensing button (S04), slider (S05), and panel (S06) detect pressing and sliding actions with pressures, respectively. The bending component (S08) identifies users' bending actions. Inspired by Kobakant [54], these two types of components are composed of a middle layer of piezoresistive material (i.e., Velostat) in conjunction with the top and bottom conductive layers. When the components are pressed or bent, their resistance values change accordingly.To help users distinguish the two types of components, we used different embroidery patterns on the surface as visual indicators. Figure 4a-d show the performance test of the contact pressure sensing panel, and the bending sensing components using a regular digital multimeter.

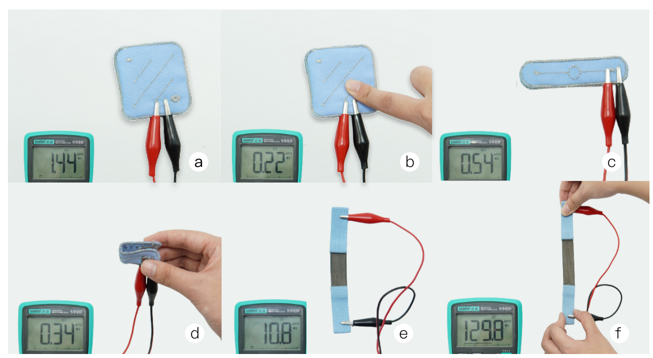

Figure 4: Performance test of pressure sensing panel (a-b), bending sensing component(c-d) and stretch sensing component(e-f).

Stretch Sensing Component. The stretch sensing component (S09) detects users' stretching behaviors based on resistive textile strain sensing. To ensure the stable performance of the component, conductive elastic webbing was used. As shown in Figure 4e-f, the resistance of the component showed a large range of variation during the stretching.

3.2.3 ***Control Widgets.*** Control widgets include on-off switches (e.g., button switch, paired contact switch) and simulation manipulation (e.g., textile slider, adjustable drawstring, textile potentiometer), the resistance of which reacts to the users' actions. These components consist of various resistive materials and removable conductive accessories.

Button Switch and Paired Contact Switch. The button switch (S10) and paired contact switch (S11) are to detect the closure and interruption events by sensing the mutual contact or separation of conductive parts. The Swatch exchange sample made by Ricardo O'Nascimento [42] and the paper contact switch in Kobakant [53] inspired the design. S10 consists of conductive buttonholes and metal buttons (Figure 5a). For S11, in contrast to the previous work, we used paired metal magnetic buttons rather than aluminum foil as the two electrodes of the paired contact switch (Figure 5b). Besides, metal magnetic buttons were easier to buckle and had better conductivity.

Textile Slider. The textile slider (S12) consists of two parallel conductive tracks and a conductive buckle. The conductive threads were placed firmly on the fabric using the embroidery. The buckle was made of plastic and coated with the conductive silver paste (Figure 5c). Compared with the conductive fabric used in previous work [54], conductive silver paste provides better conductivity and stability between the buckle and the tracks.

Textile potentiometer. The textile potentiometer (S13) was made of base fabric with conductive areas and a mental needle. It was inspired by the work from Perner-Wilson and Buechley, etc. [36], and got adapted to the embroidery technique to create the conductive areas of the textile potentiometer.

Adjustable drawstring. The adjustable drawstring (S14) was inspired by the string on a hoodie in daily life. The resistive material and the conductive accessory of the adjustable drawstring were a folded piece of conductive string and a metal clasp, respectively.

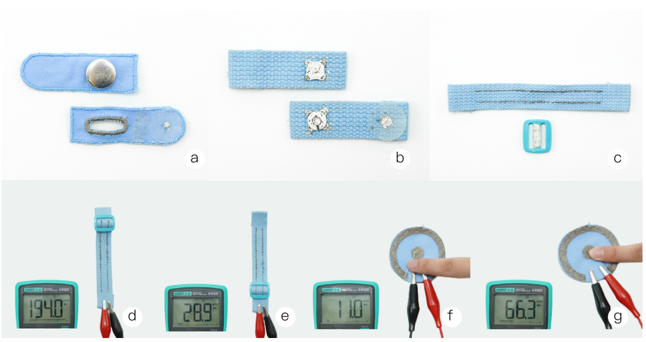

Figure 5: Details of button switch (a) and paired contact switch (b) and textile slider (c), and performance test of textile slider (d-e) and textile potentiometer (f-g).

3.3 Actuating and Displaying Components

The actuating and displaying components in the toolkit provide visual, thermal, and haptic feedback.

3.3.1 ***Heating and Color-changing Components.*** The heating component (A01) and color-changing components (A02, A03, A04) leveraged the electrothermal effect principle.

Heating Component. The heating component (A01) consists of the heating element (i.e., enamelled copper wire) in the middle layer and regular textiles on the top and bottom layers. Compared with other conductive wires, the enamelled copper wire has a relatively low resistance and heats up more quickly. Moreover, the surface of the enamelled copper wire is insulated so that it does not short-circuit when being wound. We chose 0.2mm diameter enamelled copper wire and wrapped it in multiple circles as the heating material (Figure 6a).

Color-changing Components. We applied a thermochromic thread that could change its color when the temperature exceeds 31 degrees. Components in this set have a sandwich structure: the color-changing layer on the top, the heating material (same as A01) in the middle, and the base layer on the bottom. Figure 6b shows the color change effect before and after being heated. EmTex provides several patterns in different sizes, shapes, and colors to suit a broader range of applications.

3.3.2 ***Vibration Components.*** The vibration component (A05) is based on a similar principle (i.e., electromagnetic induction) to that of Kobakant [52], where the two thread layers get separated when power is applied. It can thus achieve a vibration effect when switching on/off the power frequently. The component consists of an inductive coil and a permanent magnet on both sides of the textile (Figure 6c).

3.3.3 ***Light-emitting Component.*** The top and bottom layers of the component are both regular textiles. The middle layer is based on miniature LEDs and conductive traces. We embedded the positive and negative ends of miniature LEDs into the two embroidered conductive paths (Figure 6d).

Figure 6: Details of the heating component (a); color-changing component before/after the change (b); internal details of vibration component (c) and light point (d).

3.4 Connectors

Components need to be connected to the ports (VCC, GND, and I/O) of the control board for signal input and output. In this work, we proposed Velcro as connectors to connect the components (soft textile materials) and the control board (electronic component) in a stick-and-play manner.

3.4.1 ***Hook-and-loop Fasteners.*** Previous connection methods in e-textiles included sewing, metal snap fasteners, metal zips, magnets, conductive hooks, loops (Velcro), etc. For example, Karrer et al. [17] used sewn conductive threads to connect a T-shirt sleeve and a microcontroller board . The stitched connection brings good comfort and aesthetics to e-textiles but is inflexible and unsuitable for repeated usage. Lui et al. [23] used sewn conductive threads to create conductive trails and metal hooks to connect different parts. Boone et al. [4] and Lee Jones [15] used concealed metal fasteners to construct basic circuits. Although metal connectors offer good conductivity and stability, their rigid construction decreases the comfort and aesthetics of the textile. Pearce et al. [35] put conductive textiles on the conductive Velcro to complete the circuit. Inspired by this, we chose the style of hook-and-loop fasteners to connect the component and the control board to pursue softness, flexibility, and reuse.

3.4.2 ***Types of Connectors.*** Different components are connected to the control board via different ports. We summarized the connection options and designed the following 6 types of connectors (Figure 3). The connectors are available in 120mm, 200mm, and 300mm lengths to suit different application scenarios.

The connection between components like touch sensing (S01-03), button switch (S10) and the control board only requires good conductivity. We divided the port types of these components into five categories (i.e., I/O ports, I/O ports and pin (GND), two I/O ports, three I/O ports, pin (VCC, GND) and I/O ports), and designed connectors of type 1, type 2, and type 3, with a corresponding number of ports. Components like touch sensing button (S01), button switch (S10), and paired contact switch (S11) can connect to the Connector-Type-1. Connector-Type-2 has two ports and it supports two cases. Frist, it connects to I/O ports and pin (GND) of the textile slider (S12), textile potentiometer (S13), and adjustable drawstring (S14). Second, it connects to two I/O ports of the touch sensing panel (S03). Connector-Type-3 with 3 ports can be used simultaneously as I/O ports for the touch sensing slider (S02) or as pin (VCC, GND) and I/O ports for the light strip (A07).

For resistance-based pressure (S04-07), stretching (S09), and bending components (S08), the resistance measurement requires a resistor to be connected in series, which is complex for novice users. We therefore designed Connectors-Type-4 and 5 that fixed the series resistor to the connector. Only one I/O port is connected to the component on Connector-Type-4, while two ports of Connector-Type-5 are connected to the component (I/O ports and pin (GND)).

The heating (A01), color-changing (A02, A03, A04), and vibration components (A05) require a higher driving current. Therefore, these components need an external power supply to provide sufficient current and control the energization and de-energization through a triode. The circuit for current amplification is relatively complex. To make the connection easy, we designed Connector-Type-6 that fixed the external power supply and the triode to the connector.

3.4.3 ***Formfactor Design of Connectors.*** To connect the components with the connectors, it is easier to make conductive traces on the loop part of the Velcro than on the hook. Therefore, we chose the loop part of the regular thin Velcro (non-conducting) as the base material for the connector and the hook part as the back layer of the component. We made the conductive track of the connector by embroidery, which offered good firmness between the conductive thread and the base material. Figure 7a-c show the resistance of connectors with different lengths. The round conductive points (radius 2-3 mm) at the back of the component were made with conductive silver paste (Figure 7-d).

We selected the Lilypad Arduino as the control board because of its sewable pins. However, there are instances where a single port

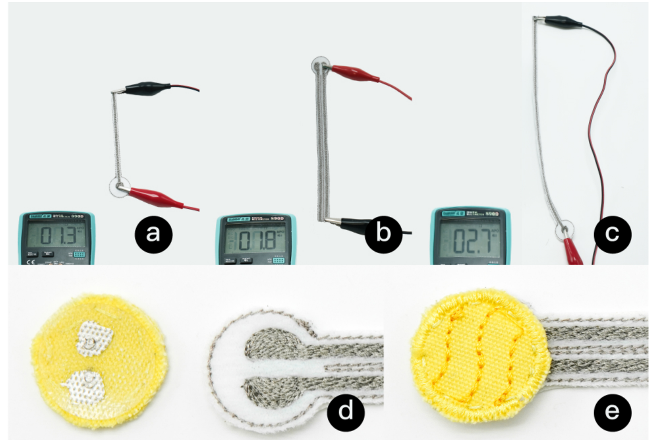

Figure 7: The resistance of (a) the 120mm connector; (b) 200mm connector; (c)300mm connector, and (d-e) connection details between component and connector.

on Lilypad is required to connect to multiple ports, particularly the negative terminal. To address this, we utilized conductive Velcro as an extension area for the board. The conductive Velcro's loop and hook parts were sewn onto the connector and the Lilypad, respectively (see Figure 8a-b). Each port on the Lilypad's extension area can connect 4-5 connectors simultaneously.

Figure 8: (a-b) Connection details between main control board and connector; (c) the resistance of an extension area on main control board and (d) resistance between extension area on main control board and the end of connector.

4 TEXTILEATION PROCESS BASED ON EMBROIDERY

The textileation process based on embroidery (Figure 9) involved four phases, including pattern design, embroidery, tailoring, and encapsulation. Specifically, the fabrication process of multi-layer components involves fabricating every single layer, stacking them on the base fabric, embroidering them along the borders, and finally cutting out the additional parts. Manual alignment is employed during this process. A general fabrication process takes around 10-13 mins and varies depending on different components, with roughly 30% manual effort spent on tailoring and encapsulation.

4.1 Design the Embroidery Patterns

Based on Wilcom Embroidery Software [59], we designed the shape of patterns involving stitch type and stitch values for each component. However, different design considerations of embroidery

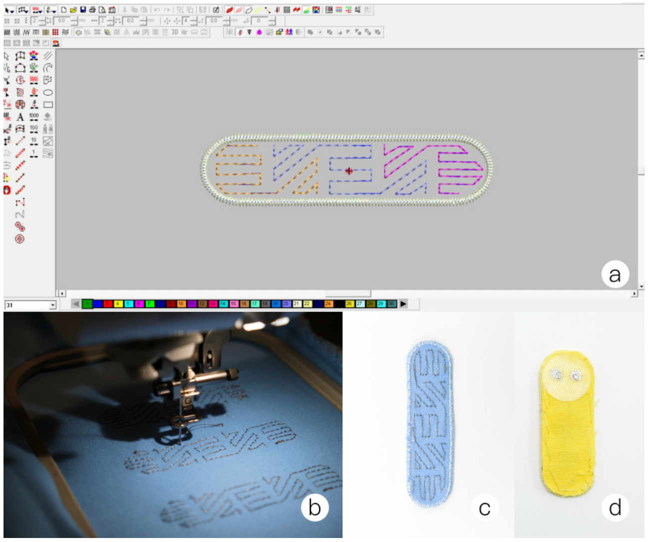

Figure 9: Textileation process based on embroidery: (a) designing the embroidery pattern, (b) embroidery, (c) tailoring, and (d) encapsulation.

patterns were made for sensing/actuating components and connectors.

For sensing/actuating components, the non-conductive thread was used to increase the aesthetics and also discrimination of different component types, and the embroidery patterns had little effect on the sensing/actuating function. For example, as shown in Figure 1, the touch sensing components (S01, S02, and S03) had different pattern design compared with the pressure sensing components (S04, S05, and S06).

In the case of connectors, the conductive thread was used and the embroidery patterns were responsible for electric conduction. One small challenge here was to ensure the overall resistance of each connector was not too high after the conductive thread was embroidered. To reduce the resistance, conductive material was used for both upper and bobbin threads, which showed a lower resistance characteristic than applying conductive thread only for the upper or bobbin. Furthermore, it was found that thicker stitches and smaller spacing resulted in lower resistance, and we chose the circumferential stitch type with 0.4 mm spacing.

4.2 Embroidery

The substrate textile for embroidery was the rough, non-stretch woven canvas (weight: 380g/m). The embroidery machine used in this work was the Brother Domestic Embroidery NV180. The size of the needle hole limits the thickness of the conductive thread, and the 200D silver conductive thread (0.15mm thread diameter, 3 ohms/cm resistance) was the conductive thread that could go through the needle hole with the smallest resistance we could access. We used different types of threads and parameters, and the substrate of the embroidery machine was a non-stretch woven canvas with a weight of 380g/m. We applied specific tension settings for different yarns, e.g., using a 3/5 tension rate for regular yarns, 2.5/5 for conductive yarns, and 3.5/5 for thermochromic yarns.

4.3 Tailoring & Encapsulation

To make all components consistent and delicate, we designed embroidered border patterns for the components based on woven canvas. For the touch sensing slider (S02), matrix (S03), and connectors, it is also essential to keep conductive wires away from each other to avoid signal interference. Cutting is done manually using scissors. As the borders of the components are embroidered (Figure 9a), making dense stitches of a specific thickness (Figure 9c), it is convenient for us to cut along the borders manually.

A section of conductive thread left by the embroidery process needs to be made into a uniform connecting port. The encapsulation process inncludes sticking the hook part of the regular Velcro on the back of the component, making the conductive thread pass through the hook part of Velcro through a needle, and pasting the conductive silver to the conductive thread and forming a circular conductive contact point with a radius of 2-3 mm. In practice, connectors are placed crosswise to each other, and the back of them is a conductive track. To prevent different ports from contacting each other, we pasted a layer of insulating paper to the back of the connectors.

4.4 Durability and Washability

We performed durability tests with two typical components: S09-stretch sensing and S01-pressure sensing. They were stretched and pressed 100 times using dedicated tensile and pressing platforms and measured the resistance before and after. To provide accurate load for stretching and pressing the samples, a precise stepper motor was used to induce reciprocal movement of a vertical slider at a deforming speed of 22.5mm/s, and a force sensor with high sensitivity for measuring compressing forces in the range of 1N to 10N was placed on a vertically motorized platform. The sensor resistance value was recorded for both the tests. The results indicated both components showed consistent sensitivities and sensing ranges (Figure 10). We also conducted washability tests on S09, S01, and A02 by moistening the components and then getting them flat-dried. The results showed that this process did not impact the sensors' properties.

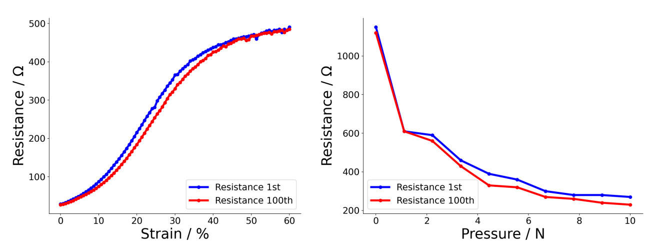

Figure 10: Sensor resistance values at different strains and pressures before and after the durability tests.

5 VISUAL PROGRAMMING TOOL

The visual programming tool supports users in composing the functionality and interaction logic of e-textile prototypes and assists them to build the prototypes following connecting instructions.

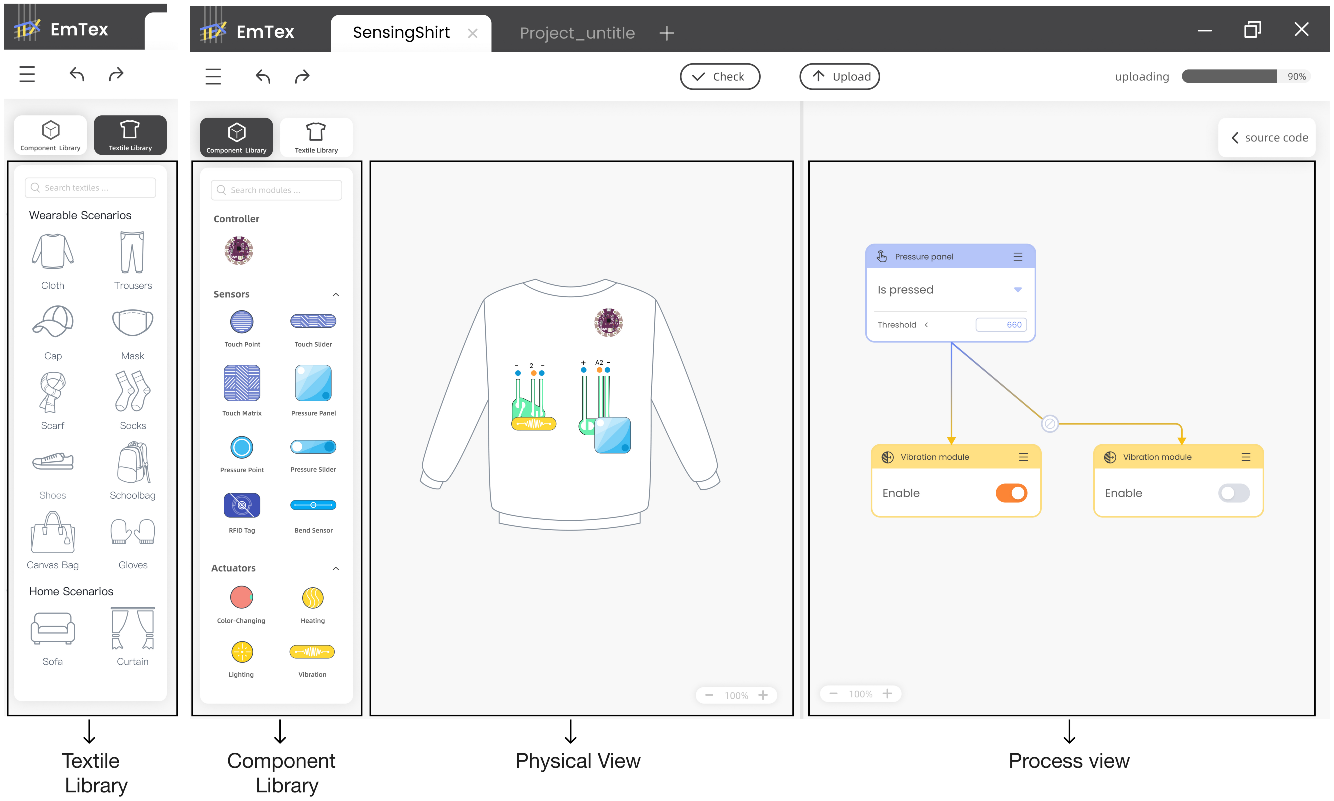

Figure 11: Layout of the visual programming tool. Textile Library: Users could choose different textile forms that fit various scenarios, including cloth, trousers, etc. Component Library, where users could choose the components from EmTex. Physical View: Users could arrange and adjust the positions of different components. Process View: a visualized interface that supports editing the interaction flow of components.

5.1 Layout and Implementation

As shown in Figure 11, , we divide the entire page into four main sections based on the functional architecture of the visual programming tool: ***1 - Components Library*** that contains icons of all components in the toolkit, ***2 - Textiles Library*** that contains various background textiles to be used in scenarios, such as clothes, trousers, hats, scarves, etc., ***3 - Physical View*** for placement and layout of desired components, and ***4 - Process View*** that supports editing the interaction flow of components. The source code window allows users with programming backgrounds to review code.

The visual programming tool uses a Node-Based visual language, and the textile components are designed as an extensible program module and stored in the database. The data model includes type, size, icon, feature and other parameters of the textile component, which can be added to new textile components easily in the future. The tool offers clear visualization of the operation process and flexible editing. It consists of a front-end for user interaction, a middle platform for logic and program statement library, and a back-end for communication with Arduino and hardware. The front-end provides modular prototype construction tools and interactive process editors. The middle platform generates real-time program code based on the user's interface edits, while the back-end handles data parsing and program communication with the Arduino platform.

5.2 Prototyping Workflow

We take the example of using the pressure panel (S06) to trigger the vibration component (A05) on a T-shirt to describe the prototyping workflow (Figure 12).

(a) Connect the control board. When the Lilypad Arduino is successfully connected to the PC, the interface shows the model number of the Arduino.

(b) Simulate the design. Users select the textile of T-shirt from the textile library, and then drag and drop the desired components (S06 and A05) from the component library to the physical view . Users adjust the position of the components to make them look neat and appropriate.

(c) Assign the functions. Users right-click the mouse in the process view to add the single-touch and vibration modules. Then users select parameters from the drop-down list to define the component's functions, e.g., "is pressed" panel for the pressure panel and two "on/off switch" panels for the vibration module.

(d) Edit the interactions. Interaction logic between the components is established by connecting them with a line. Here users

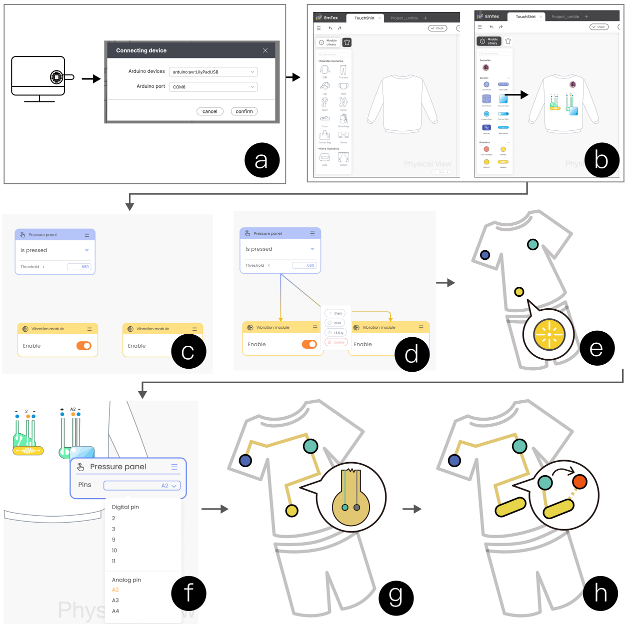

Figure 12: Prototyping workflow. a) Connect the control board, b) Simulate the design, c) Assign the functions, d) Edit the interactions, e) Place components and connectors, f) Set wiring pins, g) Connect the circuit, h) Test and iterate.

intend to activate vibration (A05) by touching the pressure panel (S06). Therefore, users set the threshold value of pressure to 660, and enable the vibration if the condition get satisfied, and disable the vibration otherwise. Users click the "Upload" button to upload the code to the board.

(e) Place components and connectors. Users start working with the EmTex toolkit, and place the pressure panel (S06) and the vibration component (A05) onto the T-shirt.

(f) Set wiring pins. After dragging the pressure panel (S06) into the physical view, the interface automatically displays the connector type 5 (C05) that matches the component and the default pin (+, A2, -). Users can select another digital pin, such as A3 or A4, from the drop-down list or use the default pin (A2). The "+" and "-" icons on the connector indicate the positive and negative pins, respectively.

(g) Connect the circuit. Users select matched connectors and follow the wiring instructions to connect modules to the connector and connect the connector to the control board.

(h) Test and iterate. Users run and test the prototype by trials and errors, and iterate the process until the prototype works successfully.

6 WORKSHOP AS EVALUATION

To evaluate the effectiveness and utility of EmTex in creating e-textile prototypes of diverse application scenarios in daily life, we conducted a workshop with 25 participants. Through this workshop, we investigated how EmTex can support the design and prototyping of E-textile projects. Furthermore, this investigation provided us with valuable insights into the vast potential of e-textile interfaces in various daily-life scenarios.

6.1 Participants, Appearance, and Procedure

6.1.1 ***Participants.*** In total 25 participants (Figure 13) who had interests in e-textile (15 female), aged 19 to 32 (M = 24.04, SD = 3.08) were recruited from a local design college and a maker community. The participants had diverse backgrounds in design, software engineering, material science, and education technology. Before the study, the participants were asked to complete a questionnaire about their experiences in programming, hardware, electronics, sewing, and crafting. All the participants provided their informed consent and were split into seven groups at random.

6.1.2 ***Set up.*** The workshop took place in a spacious and comfortable area, equipped with several large working tables. Figure 14 shows the workshop setup. Each group was provided with a set of materials, including EmTex, a computer (with the visual programming platform installed), fabrics-based items such as T-shirts, scarves, and bags, a prototyping flowchart and a digital camera.

Group	ID	Age	Gender	Background	Programming Exp	Hardware Exp	Electronics Exp	Sewing Exp
G1	G1-1	19	F	Interaction design	●●○○○	●●●○○	●●○○○	○○○○○
	G1-2	19	M	Industrial design	●●●○○	●●●○○	●●○○○	○○○○○
	G1-3	21	F	Industrial design	○○○○○	●●○○○	○○○○○	○○○○○
	G1-4	20	F	Industrial design	○○○○○	○○○○○	●●○○○	●●●○○
	G1-5	21	F	Education technology	●●○○○	●●○○○	●●○○○	○○○○○
G2	G2-1	25	F	Interaction design	●●○○○	○○○○○	○○○○○	●●○○○
	G2-2	21	F	Industrial design	●●●○○	●●○○○	●○○○○	○○○○○
	G2-3	22	F	Industrial design	●●●○○	●●○○○	●○○○○	○○○○○
G3	G3-1	23	M	Interaction design	●○○○○	●●●○○	●○○○○	○○○○○
	G3-2	26	F	Software engineering	●●●●○	●●○○○	●●○○○	○○○○○
	G3-3	27	M	Vehicle engineering+Interaction design	●●○○○	●●○○○	●●●○○	○○○○○
G4	G4-1	21	M	Industrial design	●●○○○	●●●○○	●○○○○	○○○○○
	G4-2	23	F	Software engineering+Interaction design	●●●●○	○○○○○	○○○○○	○○○○○
	G4-3	24	F	High polymer materials	○○○○○	○○○○○	○○○○○	○○○○○
	G4-4	24	F	Textile design	○○○○○	●○○○○	○○○○○	○○○○○
G5	G5-1	25	M	Interaction design	●●●●○	●●●●○	●●●○○	○○○○○
	G5-2	26	F	Interaction design	●●●○○	●●●○○	●●○○○	○○○○○
	G5-3	27	M	Software engineering	○○○○○	●●●○○	●●●○○	○○○○○
G6	G6-1	26	M	Interaction design (VR design)	●●●○○	●●○○○	●●○○○	○○○○○
	G6-2	26	F	Interaction design	●●○○○	●●○○○	●●○○○	●●○○○
	G6-3	32	M	Software engineering	○○○○○	●●●○○	●●●○○	○○○○○
G7	G7-1	29	F	Transportation Design	●○○○○	●○○○○	●○○○○	●●○○○
	G7-2	24	M	Interaction design	●●●●○	●●●○○	●●●○○	●○○○○
	G7-3	24	F	Industrial design	●○○○○	●●○○○	●○○○○	●●●○○
	G7-4	26	M	Interaction design, traffic engineering	●●●○○	●●○○○	●●●○○	○○○○○

Figure 13: Demographics of the participants.

6.1.3 ***Procedure.*** The workshop was composed of five stages that progressed in sequence: introduction, brainstorming, demonstration, prototyping, and interview. The duration of the entire process was around four hours, and it was facilitated by a team of five researchers. One researcher was responsible for introduction, another for recording, and the remaining three researchers provided technical support and conducted interviews. The specific tasks associated with each stage were as follows:

Introduction, grouping and pre-questionnaire (0.5h). Firstly, the researcher introduced the fundamental concepts and demonstrated a number of renowned e-textiles projects to help the participants quickly get to know about the field of e-textiles. Following by the introduction of design challenges and unique features of the toolkit EmTex. Then, each participant shared their background and interests, and made groups.

Brainstorming with EmTex (1h). Once the teams were formed, the participants were encouraged to discus and brainstorm, and

Figure 14: Workshop environment and the items provided for the participants.

propose their e-textiles design ideas and concepts in versatile daily life scenarios.

Demonstration of how to use EmTex (15min). The researchers built 2 example prototypes with EmTex (including an introduction to connector types, module connection methods, the visual programming platform, the connection of circuits, etc.) to assist participants in quickly getting familiar with the EmTex toolkit.

Prototyping with EmTex (1.5h). The group members collaborated to prototype their design using the toolkit. The researchers observed the participants' behaviors during the process, which helped the researcher to gain insights into how the participants understood e-textile interfaces, learned, and used the toolkit.

Post-study questionnaire and interview (25min). Both quantitative and qualitative data were collected. A semi-structured interview was conducted for each group. This allowed for a better understanding of participant evaluations of the EmTex-built prototypes, reflections on e-textile interface prototyping with EmTex, as well as any difficulties encountered while utilizing the toolkit. We adopted System Usability Scale (SUS) for measuring the perceived usability of the programming tool. It consisted of 10 items, with a five-point Likert scale for responses ranging from Strongly Agree to Strongly Disagree.

6.1.4 ***Data Analysis.*** The following data were collected: 1) questionnaires, 2) interview recordings, and 3) workshop videos. Research analysis for qualitative data was conducted using deductive thematic analysis of the transcriptions. We also performed quantitative analysis on the questionnaire results.

6.2 Results and Findings

6.2.1 ***Overview of the eleven presented prototypes.*** The participants showed great interest and actively participated in the brainstorming, concept ideation, and prototyping. Finally, seven groups came up with various e-textile interfaces with the EmTex toolkit, which covered a variety of application scenarios in daily life. These ideas resulted in the creation of 11 prototypes, as shown in Figure 15, and we classified these projects into 5 themes.

Health and wellness applications. Group 3 proposed a smart bed sheet with a vibration component (A05) for people with mild obstructive sleep apnea (OSA), which aimed at alerting OSA patients of their wrong sleeping position (Project 2, Figure15b). Group 4 targeted at new interactions for pregnant women with e-textiles. A smart belt with stretch sensing band (S09) and vibration (A05) and light strip (A07) was designed to monitor their breathing condition (Project 4, Figure15d).

Coronavirus pandemic solutions. Due to the need to reduce the risk of infection exposure, Group 1 came up with the concept of people greeting each other by touching elbows, with emotional feedback such as light and vibration (S06, A05, A06, Project 1, Figure 15a). Meanwhile, Group 2 created two smart masks using EmTex. One of them reminded the user to change their mask in time by emitting lights (S04, A06, Project 3, Figure 15c), and the other featured a color-changing bar (A03) designed as a more convenient alternative to health codes on mobile phones (Project 6, Figure 15f).

Smart household scenarios. In addition to health issues, the participants also explored potential e-textile interfaces for home environments. For instance, Group 5 designed a smart collar incorporating a touch-sensing slider (S02) to regulate the air conditioning system (Project 5, Figure15e). A smart curtain was designed to control the room lights with the button switch (S10) (Project 9, Figure15i). Furthermore, Group 6 envisioned turning the couch in one's home into a controller for VR systems (Project 10, Figure15j).

Intelligent cockpit experience. Group 7 proposed a pressure sensing slider (S02) as an intuitive surface for controlling the sunroof (Project 7, Figure15g), and they also proposed a smart safety belt that could change color pattern (A04) according to the interactions between passengers. (Project 8, Figure15h).

Human-robot interaction. Group 5 incorporated the touch sensing sliders (S02) onto a robot, such that when individuals interacted with the robot (e.g. stroking the surface), it would display a smiley face to enhance emotional communication (Project 11, Figure15k).

6.2.2 ***EmTex Components Enable Diverse Scenarios.*** The participants found that EmTex was highly supportive in generating various e-textile interface concepts from different perspectives.

a). Versatile components and features enabled the implementation of various functions. The EmTex toolkit's diverse range of components and features proved to be instrumental in the participants' exploration of new e-textile interfaces. A total of 7 types of sensing modules, 5 types of actuating modules, and 6 types of connectors were utilized in the final 11 projects. The S06 pressure-sensitive panel (n = 4) and S02 touch sensing slider (n = 4) were the most commonly used sensors, while the A05 vibration module (n = 4) was the most frequently employed actuator. Connector C01 was most used (n = 8). During the workshop, once the participants had any concept, they tended to find components in EmTex to determine whether the toolkit could support their ideas. As G7-1 said: *"... I liked the richness of the components when we made brainstorming on e-textile interfaces in automobile, and we found EmTex components could support many of our ideas, not just one."*. 20 participants

Figure 15: Final 11 project prototypes in different themes were built during the workshop. Specifically, health and wellness applications: b & d, coronavirus pandemic solutions: a, c, & f, smart household: e, i, & j, intelligent cockpit: g & h, and human-robot interaction: k.

acknowledged the versatility and richness of the EmTex toolkit was supportive for a wide range of e-textile design possibilities. As mentioned by G1-4: *"With rich components in EmTex, especially the interactions implied by these different components, it is easy for me to relate EmTex and e-textile interfaces to common interactions in daily life scenarios, and some relatively new and uncommon fabric interactions have inspired us in many ways."*. Besides, two groups mentioned that the textile carrier and component library in the programming tool provided some default choices, which helped them form the initial ideas.

b). Diverse shapes and sizes allowed the prototypes to adapt to wide scenarios. Project 5 is as a notable example where the participants initially placed a touch sensing point (S01) on the collar that proved to be imprecise due to its small size, then they quickly replaced it with a larger touch-sensing slider (S02) for a more intuitive and efficient interaction. As noted by G5-1, "Finding the functional components or modules we needed was quite convenient and made the brainstorming and prototyping efficient. We felt encouraged and it saved time for generating more exciting ideas.". Also, G5-2 added, *"It is quite motivating to get 'yes' responses from EmTex when looking for components to support our ideas."*.

These impressions and comments from the participants convinced us that the diversity of the EmTex components showed great support in facilitating the prototyping of e-textile interfaces.

6.2.3 *High-level Textile-Integration Encouraged Creation*.

In conjunction with the analysis of the 11 final prototypes, our observations and interviews revealed that EmTex's textile-integration capability had a positive influence on the participants' motivation to generate ideas and make prototypes.

a). EmTex helps understanding and envisioning the creation of natural and senseless interactive experiences. The participants reported that through the workshop they clearly understood how an E-textile product might look like in the future. Take G6-1's quote as an example: *"I can imagine the seamless integration of smart material into regular textile products with concealed input and output."*.

b). High-fidelity components are supportive in illustrating the appearance and demonstrating the concepts. It enables designers to create products that are not only functional but also aesthetically pleasing. During the interviews, G4-2 emphasized that the soft and suitable nature of EmTex modules and connectors were ideal for designing textile-based products, *"Heavy or hard components were not ideal for designing textile-based products for pregnant individuals in our case."*. Additionally, G4-3 said: *"The embroidery pattern is both indicative for gestures and aesthetics as decoration."*. In general, the textile integration feature of EmTex facilitated the participants' consideration of the appearance and comfort of their e-textile prototypes.

c). Textile integration and modular solutions facilitate rapid validation of ideas. For example, Group 4 designed a smart belt for pregnant individuals that can monitor their breathing, and it took them approximately 87 minutes to create a prototype from scratch. After quick testing of different sensors, the participants chose the stretch sensing band (S09) from the toolkit, which was fixed to a regular belt, to detect changes in the user's abdominal rise and fall. Additionally, the six types of connectors in the toolkit, which can suit all connection situations, enable quick and stable connections compared to traditional sewing or using crocodile wires.

6.2.4 Support from the Visual Programming Tool.

The SUS scale statistics indicated that the visual programming platform had good usability (M=81.9, SD = 4.5). Based on the observation and interview, the visible circuit information and simulation provided by the programming tool facilitated the participants to evaluate their ideas and lower the barriers of building prototypes, which could support them in defining the functionality, designing the logic of e-textile prototypes and connecting the circuit. For example, in Project 1, the participants spent 82 mins building the "greeting through textile" prototype. During the process, they showed nice collaboration with each other. Among them, G1-3 was responsible for creating interaction flow in the visual programming platform, and the other team members placed the EmTex components and textiles to assist her to evaluate the prototype functionalities. Although none of them had adept experience in connecting circuits, they did a great job of connecting different components. As G1-5 said: *"What we did not expect was that the platform could directly show us the right pin ports, which saved us a lot of time, and it is quite annoying to check the circuits once and once again."*. Also, we found the connectors EmTex provided were positively perceived. As this G1-2 said in the interview: *"I used to use Arduino and did not expect the pin ports were clearly provided, and also, the connectors and pin ports provided by the programming tool had corresponding relationships."*.

7 DISCUSSION

With the rich set of embroidered sensors, actuators, connectors and the programming tool, EmTex is developed to enable designers to compose and implement smart textile interfaces that are of high diversity and high-level textile integration. According to the final projects presented in the workshop, we made reflections on how EmTex helped the participants compose the ideas and build the prototypes. We also gained insights into how the participants perceive the toolkit and possible e-textile interfaces in daily life from the observation and interviews. Furthermore, we present the current limitation and the future work.

Textile Interfaces in Daily Environment. Researchers keep developing novel textile interfaces that weave computing capability into the fabric of everyday surroundings. Toolkits play important roles in empowering and enabling new audiences to experiment as toolkits can lower the barriers and reduce the effort. However, comprehending customized fabric-based artifacts with a variety of input and output modalities typically calls for expert-level expertise in a particular field. By providing EmTex, we achieved the aim of encouraging the integration of textile natural forms into the daily environment. The participants could propose creative ideas and construct working prototypes. From the workshop, we found all the participants showed great interest in proposing new e-textiles interfaces in daily life and intended to turn more textiles in life scenarios into smart ones. With their passion, the workshop went well and EmTex was well evaluated. A lot of creativity and ideas came out during the workshop, but due to the time limitation, only 11 projects were finally built with EmTex.

However, one limitation was that no professional designers (like fashion designers) were involved in this evaluation study, and it was not clear how they would view EmTex. We will open-source the toolkit and programming tool, we hope to attract more designers and makers to the field. In the next step, we will invite professional users in a specific domain, for instance, fashion design and household design, to explore how EmTex may support textile-based professionalized concepts.

Besides, the design concepts were varied with different emphases on health, education, entertainment, etc., and the toolkit had a trade-off between modularity and personalisation. The participants were eager for more components, especially the actuators and textile sensing modules in customized shapes. As a result, it is encouraged to achieve customization by developing software that can create conductive paths on different module shapes, allowing users to have more customized modules in the EmTex toolkit.

Two New Features Specified by EmTex. For the development of a toolkit encouraging e-textile interfaces, we identified two main challenges that motivated the development of EmTex. One of the points was the designers' expectation of a high level of textile-integration. To echo this design consideration, we used embroidery techniques, and EmTex was equipped with fully textile-based components. As a result, almost every component in EmTex showed softness, good quality, and low unobtrusiveness in textile-based artifacts due to the embroidery techniques. It may be the case that EmTex itself carries the intention of softness and dexterity due to the design and fabrication, and as a result, when the participants explored possible e-textile interfaces with EmTex, they would prefer to bring the e-textile into daily life scenarios. As a promising trend, e-textile interfaces will probably be presented with less electronic hardware and more closely resemble the form and characteristics of the textiles and fabrics that people use in daily life.

In response to the other core design requirement, we deliberately considered the diversity of the components for supporting various preliminary design concepts that were proposed for different scenarios. The 28 textile-based components provided common sensing and actuating components that are not unfamiliar or hard to understand to the participants, while maintaining the diversity for rich design possibilities. From the workshop, it can be seen that the diversity of the toolkit was well perceived and exploited by the participants, enabling design concepts in many diverse domains. The connectors also have different types in various lengths, compared to each component with a connector itself, this modular solution may support various scenarios with different requirements. From this aspect, diversity shall be emphasized for future e-textile toolkit research and critical for e-textile interface design and deployment. The diversity of the components can be easily achieved, also thanks to the embroidery technique, which provides standard fabrication pipelines and allows us to focus on the pattern and sensing/actuating mechanism design.

However, there is still additional work that could be done in future iterations to make EmTex better in these two features. In order to achieve high textile-integration and modularity, only the components that conform to the fabrication process of machine embroidery are included. As a result, some frequently used components in wearable technology that rely on hard components, like accelerometers, are absent in the current version. We envision adding more modules that require chips on board with the rapid development of flexible electronics and crafting fabrication technology, such as textile accelerometers. Besides, Lilypad as the rigid component and central microprocessor restricted the compliant feature of EmTex, the direction of soft microprocessors or wireless communication to replace or remove the module is especially worthy of exploration. Furthermore, some participants mentioned that the components' colors and fabrics were relatively homogeneous and did not support customization. To address this, it is suggested that the kit should offer a greater range of color options and an online pattern customization tool to designers to improve the personalization capabilities of the components.

Embroidery based toolkit. Machine embroidery brings the advantages of great flexibility, versatility, and adaptability. As the technique becomes mature and ready for daily use, users need not worry about the fabrication challenges, but purely focus on the pattern and function design. The commercially available software that was used to design and transform the patterns the machine executable codes is easy to learn and use. As shown, the embroidery supports well the development of EmTex, including the sensing, actuating and connecting components. In the same way, textile components with more functions can be investigated in the future. Besides, embroidery provides a feasible way to add decorating patterns to the textile, which is already familiar to designers. This helps EmTex to maintain constant and aesthetic appearance, turning to be well perceived and preferred by the participants. Furthermore, embroidery allows patching the sensing, actuating and connecting threads directly onto existing fabrics and clothes, providing the potential for the further development of textile interface that are truly ubiquitous and non-intrusive.

Visual programming tool. The visual programming tool plays an important role in the toolkit. It is known that lacking of programming and hardware skills becomes a major barrier for designers to work on textile interfaces. The visual programming tool helps tackle the challenge, which is confirmed in our work. Through the workshop, we found most participants relied on the tool to design the interface and more importantly, to build the prototypes. The very important information provided for the participants was the guidance for cable connections. Thus, it is necessary to improve the visual programming tool and provide more detailed tutorials, e.g., step-by-step ones, to guide the users and let them learn from it. Regarding precise patch placement, the tool may add a function that users can derive a design drawing with marked positions of the components, users can print the drawing on an equal scale and use it when prototyping to achieve accurate patch placement. Furthermore, auto-suggestion and auto-connection functions would be valuable to improve the usability of the tool.

8 CONCLUSION

In this paper, we present an e-textile construction kit called EmTex, which consists of a set of modular textile sensing, actuating, and connecting components and a visual programming tool for designers and makers who are interested in implementing e-textile projects. EmTex is built upon the advantages of machine embroidery and provides a set of fully-textile based modular components with standardised patterns and appearance design. We first analyzed the E-textile construction kits and proposed the challenges of high diversity and textile integration. We demonstrated the mechanisms, functions, and implementations of EmTex. Based on the evaluation of the workshop with 25 participants, EmTex can enable individuals to build e-textile prototypes for daily scenarios. EmTex has good potential to help designers and makers develop interactive apparel concepts and prototypes and can help promoting innovative applications of e-textiles in the future.

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