Sketch&Stitch: Interactive Embroidery for E-Textiles

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Figure 1. Sketch&Stitch workflow: 1. The user sketches an artwork directly on the fabric, 2. she uses *Circuitry Stickers* to plan the circuit layout, 3. she draws circuit traces to connect the stickers, 4. the system takes a picture of the sketch, converts it to embroidery patterns, and sends them to an embroidery machine for stitching using conductive and non-conductive threads, 5. the user replaces Circuitry Stickers with real electrical components and attaches them to the fabric.

ABSTRACT

E-Textiles are fabrics that integrate electronic circuits and components. Makers use them to create interactive clothing, furniture, and toys. However, this requires significant manual labor and skills, and using technology-centric design tools. We introduce *Sketch&Stitch*, an interactive embroidery system to create e-textiles using a traditional crafting approach: Users draw their art and circuit directly on fabric using colored pens. The system takes a picture of the sketch, converts it to embroidery patterns, and sends them to an embroidery machine. Alternating between sketching and stitching, users build and test their design incrementally. Sketch&Stitch features *Circuitry Stickers* representing circuit boards, components, and custom stitch patterns for wire crossings to insulate, and various textile touch sensors such as pushbuttons, sliders, and 2D touchpads. Circuitry Stickers serve as placeholders during design. Using computer vision, they are recognized and replaced later in the appropriate embroidery phases. We close with technical considerations and application examples.

ACM Classification Keywords

H.5.2 User Interfaces

Author Keywords

E-textile; Embroidery; Interactive Fabrication; Physical Sketching

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INTRODUCTION

Electronic textile technology enables people to create expressive, interactive, and functional textile artifacts for both playful and serious applications. It combines the visual and haptic expressiveness of textiles with the interactivity and utility of electronic components such as LEDs, vibration motors, speakers, GPS receivers, and touch sensors. At the intersection of technology, art, and fashion (see, e.g., CuteCircuit.com), e-textiles have attracted artists, designers, hobbyists, and makers applying this technology in creative and artistic ways [2, 9]. This has motivated HCI research to investigate techniques that enable a wider audience to integrate fabrics and electronics into interactive textiles [6, 41, 42].

In e-textiles, conductive threads, inks, polymers, or textiles are attached directly to a base fabric, creating *fabric circuits*. These circuits connect traditional electronic components, usually on printed circuit boards, but they can also directly include functional parts such as fabric-based resistors, capacitors, touch sensors, or antennas. Creating e-textiles typically involves 1. designing or choosing an artwork, 2. planning the layout of electrical components and traces, 3. creating the artwork and fabric circuit on the base fabric, 4. insulating circuit traces where necessary, and 5. attaching electronic components [32]. The techniques for implementing e-textiles are based on traditional methods such as printing [24], weaving [20], knitting [15], and embroidery [42].

As users rely predominantly on manual fabrication of e-textiles [22], executing a design becomes labor-intensive and requires high skill levels as the number and density of electrical components and connections increase. Debugging e-textiles is only possible after investing considerable time in building them. Insulating circuit traces is an extra step requiring special tools and materials [6]. Observing participants in our e-textile workshops, and analyzing over 70 e-textile projects documented online, we found that this laborious multi-step process often forced them into trade-offs between the visual and functional aspects of their design, impeding improvisation and exploration. The lack of a design workflow and digital support for e-textile fabrication can thus limit the creative and iterative design of interactive textiles.

In this paper, we present *Sketch&Stitch,* an interactive embroidery system that enables users to create e-textiles by sketching on fabric (Fig. 1). It uses a computerized embroidery machine as a digital fabrication tool to handle the two most laborious steps when creating e-textiles, stitching and insulation. Yet, it maintains the physical and direct interaction between the user and the work piece during the creative tasks, designing and planning the visual and functional patterns. Sketch&Stitch features *Circuitry Stickers*, printed adhesives representing elements users can embed into their design, from circuit boards and components, to wire crossings to insulate, to various textile touch sensors. These stickers guide the user while drawing circuit traces to ensure reliable electrical connections, and are recognized using computer vision, automatically generating stitch patterns for wire crossings, insulations, and sensors.

In the remainder of this paper, after reviewing related work, we first briefly introduce the particular features of computerized embroidery machines that are relevant for this work. We present the Sketch&Stitch system and workflow. We illustrate the extensions we added to Sketch&Stitch beyond the basic system that enable a wider range of practical applications, and walk the reader through a concrete example. After an evaluation of technical stitches for fabric circuits, we describe the software implementation. Finally, we present several example artifacts created by an artist using our system, and close by discussing the current limitations of the system and opportunities for future research.

In summary, this paper makes the following contributions:

- Sketch&Stitch, a new approach and system prototype to create e-textiles by drawing directly on the fabric;
- Interaction techniques and embroidery patterns that let users include circuit boards, components, insulation, wire crossings, and a variety of fabric sensors using Circuitry Stickers;
- Technical evaluations of stitches for embroidering fabric circuits with digital embroidery machines.

RELATED WORK

This paper builds on research in e-textile fabrication techniques and interactive personal fabrication.

Fabrication Techniques for E-Textiles

E-textile research investigates combining electronics with textiles to create soft flexible interfaces in ubiquitous objects such as clothing, furniture, and toys [6]. A key challenge in this area is creating fabric circuits. These circuits are made of conductive traces integrated into fabric to interconnect electrical elements to form a functional system. Ultimately, these electrical elements, such as sensors, actuators, transistors, power sources, etc., may become textile-based themselves. Research into the creation of transistors and other components directly on fibers, toward fully integrated fabric circuits, is ongoing [48]. To enable the creation of e-textiles today, researchers have focused on developing techniques for creating fabric circuits that connect off-the-shelf hardware, usually mounted on printed circuit boards (PCBs).

The primary e-textile fabrication techniques are coating, weaving, knitting, and embroidery. Coating techniques include silk screening and sputtering [24], inkjet-printing [50] and others [10]. Most of these require special tools and processes such as a vacuum chamber, regulated temperatures, or chemical etching agents. Moreover, coating inks, polymers and solutions alter fabric flexibility [14]. Printed conductive lines are prone to cracking when bent, impeding conductivity. Research into making printed conductive traces more tolerant to bending, washing, and dry cleaning is ongoing.

Weaving [3, 11, 12] and knitting [15] integrate conductive yarn during fabric production. Weaving is the most common technique for e-textile manufacturing [35]. It is cost effective, quick, and can be used for large areas A Jaqcuard weaving machine can read a circuit design and create complicated woven patterns on fabric with high precision in an automated manner [43]. Weaving applies only low forces to the yarn, and a much wider range of yarns can be used successfully in a Jacquard loom than in an embroidery machine. However, Jacquard looms are much less accessible for end users than embroidery machines, and setting them up to create circuit patterns requires significant skills and labor [29]. While knitting has not been used to produce fabric circuits at scale, researchers have created knitted circuit elements such as resistors, inductors, and capacitors [52] as well as stretch sensors [38] using conductive and piezoresistive yarns.

Embroidery is a textile embellishment technique in which strands of thread are stitched onto a fabric surface. Embroidery can be manual or numeric. An advantage of embroidery machines is that they can create nearly arbitrary patterns on woven, non-woven, and knitted fabrics, including tailored textiles and garments. Embroidery machines require less machine preparation than weaving looms. One can potentially use an embroidery machine to create a PCB on fabric. Post and Orth [42] pioneered stitching and embroidering conductive thread to create resistors, capacitors, data and power buses, and capacitive keypads. Other researchers demonstrated the embroidery of touch sensors [18, 45, 54], stretch sensors [51], and antennas [4]. Gowrishankar et al. [17] created a repository of embroidery pattern motifs with different resistance values that can be easily incorporated into embroidery projects and in place of hardware resistors. Swiss company Forster Rohner[1] developed a commercial manufacturing method for embroidering circuit traces and attaching LEDs to fabric. We use an embroidery machine to enable end users to create fabric circuits and embed embroidery patterns of touch sensors and circuit trace shielding.

Buechley et al. [6] have led the efforts of developing e-textile fabrication techniques that are accessible to a broader audience. Their goal is to diversify technology by including artists, designers, crafters and makers, and to use e-textiles as a plat-

[1] www.frti.ch/en/technologie-2/tab-1496914209772-3-3

form for motivating STEM education. The authors use a laser cutter on conductive fabric with iron-on backing to create fabric PCBs. However, the resulting circuits are not durable enough for washing and extended use. They also describe techniques to insulate conductive threads and fabrics. Perner-Wilson and Satomi [41] explore different crafting techniques such as knitting to make sensors from soft conductive threads and fabrics. Peng et al. [40] use an adapted laser cutter to create 3D textiles with embedded conductive fabric.

Once a fabric circuit has been created, the second key challenge is attaching electronic components and PCBs to it. Physical connection options include ribbon cable connectors [26], gripper snaps [42], and electronic sequins and socket buttons [6]. Reflow soldering can attach surface-mounted LEDs to a solderable conductive yarn [1, 33]. Applying pressure can displace a non-conductive adhesive from between component leads and the textile conductor [30], and embroidery has also been used to connect flexible electronics modules with conductive yarn [28]. Arduino LilyPad [5] and Adafruit Flora are commercial wearable electronics kits that include common electrical components attached to small PCBs with connector holes suitable for needlework and exposed conductive pads on the top and bottom of the PCB. We use embroidery to create the contact areas for electronics on fabric, and describe techniques for attaching parts from the LilyPad kit as an example.

Wearable construction kits such as Quilt Snap [8], EduWear [21], TeeBoard [36], i*Catch [37], and Makerwear [23] abstract from low-level electronics and provide plug-and-play electronic modules and graphical programming environments to lower the barriers to e-textile creation. They provide custom solutions for creating fabric circuits and attaching electronics. These kits mainly target children and young adults.

Interactive Personal Fabrication

Interactive fabrication is a method of integrating design and digital fabrication into a single process to recapture the creative possibilities of direct making [53]. Interactive systems replace computer screens and design software with direct physical interactions with the workpiece. They track users' gestures, digitize them, and transfer them to digital fabrication tools in 'almost real time'. Several systems have been developed for milling [27], 3D printing, and laser cutting user defined objects based on tangible input. For example, Shaper [53] lets users create foam sculptures using gestures on a transparent touch screen on top of the foam and milling machine. With Tactum [16], users sketch with their finger on their forearm to model printable 3D arm casts. Constructables [34] uses constraint-based tools to sketch over the transparent enclosing window of a laser cutter to create precise artifacts. Makers' Marks [46] lets users create complex physical objects with hinges, parting lines, and electronics stickers to annotate sculpting material. Sketch&Stitch takes inspiration from this line of research, using Circuit Stickers to annotate special circuit elements

EMBROIDERY MACHINES IN PERSONAL FABRICATION

Computerized embroidery machines have become a tool frequently found in schools, maker spaces, and small businesses [31], and are part of the MIT recommended Fab Lab inventory, for example. They use a hoop system to hold the fabric taut under the needle and move it automatically along the x and y axes during stitching. A presser foot, a metallic attachment that surrounds the needle, holds the fabric flat to prevent it from rising and falling with the needle. A control panel and embedded display provide basic functionality to, e.g., start/stop the machine, control thread tension, change stitching speed, view embroidery patterns and make minor adjustments such as re-positioning, scaling, rotating, mirroring, and re-ordering. Home embroidery machines can stitch up to 1000 stitch/min.

Embroidery machines come with proprietary software that runs on the user's computer. The software transforms color images into embroidery patterns and generates a tool path for the machine. The path dictates how an embroidery hoop moves under the needle. It includes stitch patterns, thread color changes, and jump stitches when traveling between different stitch objects. To optimize tool path generation, embroidery software separates design objects into multiple layers based on color. That way, the machine has to stop and prompt the user to manually change thread color less often. Jump stitches need to be trimmed automatically or manually. To reduce these jumps, professional embroidery designers often re-program patterns, manually sequencing stitch objects and individual stitches. An embroidery machine reads a digitized embroidery pattern from a memory card or a computer connection, recognizes color layers, and stitches them sequentially.

The internal algorithms that generate a concrete stitching pattern and tool path from a design encode advanced expertise in the mechanical properties of fabrics and threads, not unlike the slicing software turning 3D models into print head tool paths for 3D printers. This complexity is usually kept from the user, but embroidery software still has a relatively steep learning curve, offering a large number of visual design options and specialized tools for manipulating stitch patterns, such as a parametric stitch designer and pull compensation options. Its user interface assumes a nontrivial amount of expertise in threads, fabrics, embroidery, and the workings of the machine.

SKETCH&STITCH

Sketch&Stitch (S&S) supports a new workflow for creating artistic e-textiles with embroidery machines. It lets users convert an idea sketched on fabric into an interactive system. Users draw both artwork and electrical connections in free artistic shapes directly on fabric, without having to interact with CAD/CAM tools on a computer screen. S&S captures the sketch and converts it into embroidery patterns. S&S is designed with artists and makers in mind, enabling improvisational design and quick, low-threshold prototyping.

The system comprises a smartphone on a mount above the work surface, a computer, a commercial embroidery machine, and a wireless button (Fig. 2). The smartphone runs our S&S mobile app to capture a picture of the user's sketch and upload it to cloud storage. The computer runs our S&S PC app and a proprietary embroidery software. Our S&S PC app digitizes the sketch, sends it to the embroidery software for conversion into embroidery patterns, and finally sends the patterns to the embroidery machine to be stitched.

Users communicate with the system by sketching their art and circuit using colored pens and Circuitry Stickers on fabric. To execute a design, the user places the fabric under the smartphone mount and presses the wireless button to capture a picture of her sketch. The S&S PC app lets the user verify the digitized sketch and tune color detection using a simple slider-based user interface. The user sees the converted embroidery patterns on the embroidery machine's touch display. Optionally, the user may use the touch display to manipulate, e.g., scale, mirror, translate, or delete patterns. To start stitching, the user threads the machine's needle with the appropriate thread, and presses the start button on the machine.

Circuitry Stickers are symbolic images printed on adhesive paper. They are adhered to fabric to represent elements to be added to the circuit during and after embroidery. S&S offers two types: *Component Stickers* and *Embroidery Stickers*. Component Stickers serve as placeholders for electronic components such as LEDs, motors and speakers, usually on PCBs. Users replace these stickers with their hardware counterparts after embroidery is complete, using one of three attachment techniques we describe further below. Embroidery Stickers represent multi-layer custom embroidery patterns required for wire crossings and our textile touch sensors. Users remove these stickers from fabric after capturing their design, and our system inserts the required patterns in place automatically during the embroidery process.

Circuitry Stickers were developed for two reasons: First, the presser foot in embroidery machines only has a clearance of about 1 mm above the fabric, too low to travel above even thin populated PCBs. For comparison, LilyPad PCBs are 0.8 mm thick but in total more than 2 mm high due to the SMD components. Second, we wanted to save the user having to hand-draw the multi-layer patterns our textile sensors etc. require. Both kinds of stickers help users plan and sketch a circuit with ease and precision. Their adhesive backing allows experimenting with different layouts and holds them in place.

The resulting end-to-end workflow is to 1. sketch an artwork directly on fabric with textile pens, 2. place Circuitry Stickers and draw connections between them, 3. capture the design via a camera, 4. remove any Embroidery Stickers and stitch the design on the embroidery machine, and finally 5. attach the electronics, replacing any Component Stickers. We look at these steps and our solutions for advanced features below.

Sketching on Fabric

Physical sketching enables users to express themselves freely without the constraints of design applications [25, 39, 49], and provides a continuous representation of the evolving work piece [53]. Drawing on fabric is an established art form. It is also used to design patterns for manual embroidery and mark the placement of pockets, buttons, and other design elements.

At the beginning of S&S workflow, the user assigns her color palette—colors of the fabric pens that she will use in her sketch. Our system supports a palette of six colors: a *trace color* for drawing electrical traces, an optional *insulation color* for drawing insulated traces, and up to four *art colors* for drawing the artwork. The system reserves the *sticker colors*

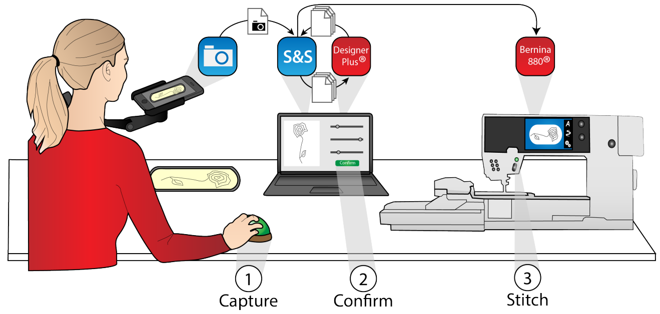


Figure 2. Sketch&Stitch comprises a smartphone, a wireless button, a PC, and an embroidery machine. It runs two custom softwares for capturing and digitizing sketches and a proprietary embroidery tool for converting images to stitches. Users capture a design with the button, verify it on the PC screen and stitch it in the embroidery machine.

white and black for Circuitry Stickers. To assign the color palette, she uses our printable color template, which consists of six slits, each marked by a name: trace, insulation, or art, and an AR marker for optical detection. She places the template on the fabric and draws a stroke in each slit using water-soluble marking pens. The markings of these pens can be washed out easily when desired. She then captures the template by pressing a wireless button. The S&S PC app provides feedback on the results of color assignment on the computer screen. After color assignment, the user secures the fabric flat and taut in an embroidery hoop of the desired size. The hoop has AR markers to localize the sketch. She now sketches her art and circuit.

S&S uses colors instead of symbolic sketch annotations for user–system communication to avoid imposing design constraints on freehand sketches, and to keep the design uncluttered. Pen colors are used to encode stitch types and enforce the sequence of pattern stitching. For example, in a simple design, the system sequences all objects in *trace color*, followed by objects in each *art color*. This reduces the number of thread changes that the user has to do and enables her to debug her circuit before stitching the artwork. The number and color of threads for stitching the artwork can be chosen during the embroidery process, independently of the color palette. The user may pause the embroidery machine, re-thread the needle with a new thread, and resume stitching.

The user can draw her art and circuit in any order. To *undo* any markings, she erases pen strokes by patting on the fabric with a damp cloth. She can undo stitched lines using a seam ripper. A design does not need to be complete to be stitched. At any point, the user can hit the button to take a photo, secure the hoop in the embroidery machine, and start the stitching process. This lets her evaluate and test her design early on, supporting *incremental design*. For multiple iterations, the user should capture another photo of the embroidered fabric before making any new changes to avoid color confusion with stitched artwork (which can be of any thread color).

Adding Electronics

Component Stickers have the same shape, size, and name as their physical counterparts. Fig. 3 shows a simple hand-sketched circuit that uses Component Stickers for the LilyPad kit. The grooves near the pin holes are added to guide the user

Figure 3. 1. Component Stickers represent electrical components in a hand-sketch circuit. Pin grooves designed to enlarge component contact area. 2. Stickers replaced with hardware counterparts after embroidery.

and ensure that the connecting traces extend under the component and create sufficient contact surface for the attached board. The user prints Circuitry Stickers from the S&S mobile app on adhesive paper using any printer. Stickers are tinted with *sticker colors*. To use a sticker, she peels off its backing and adheres it to the fabric. Using the *trace color* pen, she then draws circuit traces to connect the stickers. Component Stickers can be created for any PCB or off-the-shelf components. The only constraint is that they must have a pitch of at least 2.5 mm between their leads (see Technical Stitching). The stickers can be reused in later projects.

Attaching Electronics

After embroidery is complete, the user replaces all Component Stickers with their corresponding hardware components and attaches them to the fabric. We describe three techniques for attaching electronics to fabric. The first uses 3M Electrically Conductive Tape 97033 (Z-tape), a double-sided adhesive that conducts in the z dimension only when compressed. A piece of Z-tape is applied to the back of a component, the component is aligned to the stitched contact surface on the fabric and pressed down to create a connection. This technique is especially suitable for testing and prototyping a circuit, since it allows for easy removal, but can also be used for final attachment for e-textiles that are not handled much during use.

The second technique uses the embroidery machine. We developed the *LilyStitch*, a custom stitch to attach components with 3 mm diameter pin holes. The stitch is a Single Running stitch in an M shape. This shape strengthens the attachment and forces the tie knots, which require more space than 3 mm, to be stitched outside the pin hole. The length of the LilyStitch accounts for (a) the distance between the center of a pin hole and outer edge of the PCB (~4 mm), and (b) the distance between needle point and the outer edge of the presser foot (~5 mm). Figure 4 shows a custom embroidery pattern for attaching a board. LilyStitches were sequence-ordered manually to prevent the presser foot from traveling over the board during embroidery. This technique is very reliable and efficient for attaching sewable electronics. However, it requires accurate alignment between the physical component on fabric and the embroidery pattern. If an embroidery machine does not support such accuracy, users can stitch part of this pattern on fabric, align the component based on the stitches, then restart the embroidery. The physical component should be adhered to the fabric temporarily to keep it from moving. S&S stores embroidery patterns for stitching LilyPad components

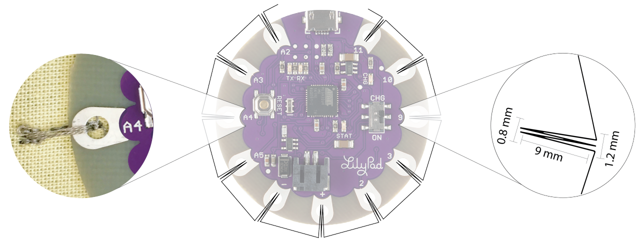


Figure 4. A custom embroidery pattern of LilyStitchs for attaching sewable electronics on fabric using an embroidery machine.

on the embroidery machine. They can be accessed from the machine's touch display.

The last technique uses the Button Sewing presser foot in sewing machines. The user has to manually align each pin hole under the presser foot. While this requires some skill, it becomes efficient with practice. Of course, the user can also manually sew into the holes using conductive thread as usual [7]. The results of a sewing machine and manual sewing can be as reliable as using the embroidery machine, but they require more manual labor and time.

Insulating Circuit Traces

Insulating circuit traces, especially in wearable e-textiles, is paramount for their functionality. Exposed traces may come in contact with each other as fabric folds or bends, creating shorts or undesired signals. Buechley et al. [6] proposed couching—stitching one thread over another—as a natural insulation technique for fabric circuit traces. However, they noted that sewing machines may leave gaps in the couching stitch, making it an unreliable cover for the underlying conductive thread. Computer-controlled embroidery machines are much better at maintaining a consistent couching stitch, making them a perfect fit for this technique.

The user insulates a trace in S&S by drawing it using the *insulation color* pen. The system detects objects in this color and creates an *insulation stack*—a grid layer and an insulation layer. Each layer contains a copy of the objects and is converted to an embroidery pattern. The machine stitches the patterns in sequence using the corresponding stitch type.

While couching circuit traces has functional advantages, it has two pitfalls: It can have a pronounced visual impact on the design due to its thickness, and the build-up of stitches can reduce the flexibility of the base fabric. In textile touch sensors, couching can reduce the sensor's sensitivity.

Handling Crossing Traces

As the number of circuit elements increases in a design, the need for circuit traces crossing each other becomes inevitable. Dunne et al. [13] manipulated the tension of the embroidery threads to allow two conductive threads to cross without touching. However, from our experience, this technique does not provide fail-safe insulation, especially when pressure is applied at the intersection point. Thread tension is determined by the fabric material, and changing it impairs the strength and appearance of stitches. It may also lead to "thread birdnesting", which causes the thread to tangle and the machine to

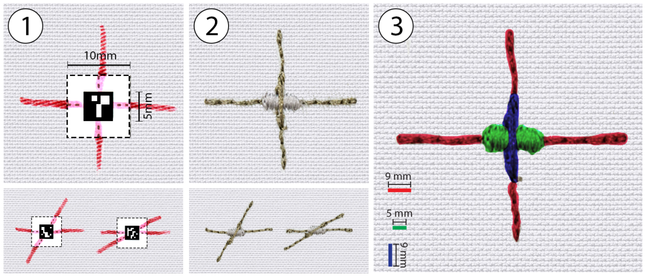


Figure 5. 1. Shield Stickers mark crossing traces (at 90°, 60°, 30°) on fabric. 2. Stitched shields. 3. Shield stack and pattern.

stop. S&S provides users with *Shield Stickers*, Embroidery Stickers to mark trace crossings to insulate on fabric.

To shield an intersection between two traces, the user places a sticker over the intersection point and draws connections between the traces on the sticker and her circuit traces using the *trace color* pen (Fig. 5.1). Embroidery Stickers have AR markers for optical detection. When the system detects the sticker, it creates a *shield stack* in place. The stack is composed of a grid layer, an insulation layer, and a bridge layer. The grid layer contains a line segment to connect one of the user's traces. The insulation layer contains a line segment to couch the bottom segment. The bridge layer contains a line segment that bridges the user's second trace over the intersection. Objects in the *bridge layer* are stitched using the *bridge stitch* which connects two separate traces (up to 9 mm apart) without stitching between them. The layers are converted to embroidery patterns (Fig. 5.) and stitched in sequence using the corresponding stitch type.

Adding Interactivity

Besides hardware electronics, users can use *Sensor Stickers*, Embroidery Stickers to add touch sensors made from conductive thread directly onto the fabric. S&S supports three sensor types: a pushbutton, a slider, and a touchpad.

Figure 6 shows hand-sketched pushbuttons and sliders. A capacitive pushbutton is created by connecting any segment of conductive thread to a capacitive sensing circuit. The circuit can sense when the user's finger or body is in contact with the thread (touch) or not (no touch). A resistive pushbutton can be created with two conductive traces 3–4 mm apart that the user bridges when touching. A slider can be implemented by placing several pushbuttons next to each other. A capacitive circuit can interpolate the position of a finger on a slider based on the amount of surface area it covers, allowing for high input resolution with limited wiring. Using these simple techniques, users can create physical widgets of custom shapes and convert parts of their artwork to touch-enabled surfaces, by using the *trace color* to draw those parts.

A matrix of pushbuttons, with each button connected to one IO pin, can be used as a 2D touchpad [19, 42]. However, a 4×4 touchpad would require 16 pins and traces. This complicates the wiring and may require additional hardware. Instead, using a layout of grid lines with time-multiplexing, as used in capacitive touchscreens, provides a sensor surface area capable of detecting individual touches, simple gestures, and sub-sensor point detection. It requires fewer pins and less

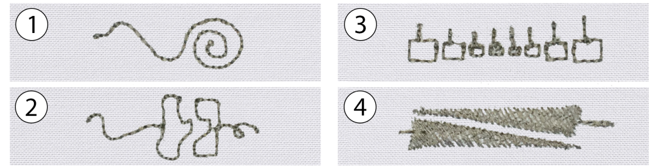


Figure 6. Hand-sketched sensors stitched with conductive thread. 1. Capacitive pushbutton. 2. Resistive pushbutton. 3. and 4. Sliders.

power than scanning individual buttons. We applied the concept of a Shield Sticker to a grid layout and created the Sensor Sticker. The sticker enables 1D and 2D touch sensors to be automatically stitched on a single fabric layer. Figure 7 illustrates how users can add a touchpad sensor to fabric. The sticker can be cut in any convex shape and connected to a touch sensing Component Sticker via a *trace color* pen. The system replaces each grid point in the Sensor Sticker with a *shield stack* and stitches the sensor.

To evaluate our touchpad sensor, we overlaid two pieces of fabric over two 4×4 sensors of 7 mm and 9 mm pitch. The fabrics were pre-marked with 9 touch locations each. We measured the error in distance between the touch location on the upper fabric and the measured location on the lower fabric (we used TI's MSP430G2553 MCU). We collected a total of 126 readings. The average error in both dimensions for the 7 mm sensors was ($M = 3.7mm, SD = 1.5mm$) and for the 9 mm sensor ($M = 2.2mm, SD = 0.7mm$). Highest accuracy was achieved when the touch location was on top of a grid point. A 9 mm sensor can interpolate one touch point. Embroidering a 4×4 sensor of 9 mm pitch requires less than 10 minutes.

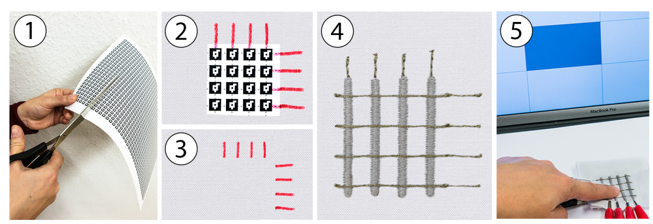


Figure 7. Sensor Sticker process: 1. The user cuts the sticker, 2. adheres it to fabric, and draws connecting traces with *trace color* pen, 3. captures the design and removes the sticker, 4. the system stitches the sensor.

Circuit Integration Strategies

Our system offers five strategies to integrate circuit traces and hardware components in a design: the first is drawing circuit traces to be part of the artwork. The second is drawing circuit traces close to art outlines, which makes traces less obvious. The third is camouflaging traces by insulating them with a thread color that matches the color of the base fabric [6]. The fourth hides hardware components by attaching them to their contact area from the back side of fabric using one of the suggested thread-based attachment techniques. The fifth hides fabric circuits completely. It uses two layers of fabric: a top layer for the artwork, and a bottom layer for traces and Circuitry Stickers. The two fabrics are sketched and embroidered individually. At the end of embroidery, the user attaches components to the bottom fabric and manually layers the fabrics on top of each other. Capacitive touch sensors will work through a thin top fabric. For components that need to be visible on the surface, such as light sensors and LEDs, the user

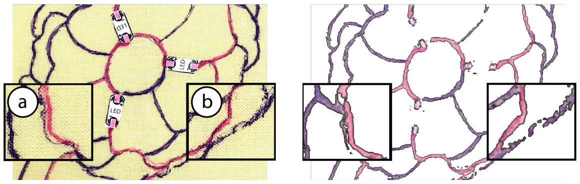


Figure 8. Sketch digitization pitfalls: a. Merged lines. b. Segmented lines. These are caused by, e.g., variable pen pressure and color noise.

may cut openings into the top fabric. Another option is attach these parts on the top fabric and use thread-based attachment to connect them to their contact surface on the bottom layer. This technique can also be used to create multi-layer textile circuits [13, 42], with the addition of an insulator, like non-conductive fabric, between any two conductive layers.

Debugging

Users can debug their designs at three stages in the workflow. The system provides users with feedback to detect pitfalls, such as indistinguishable colors, segmented lines, and merged lines, from sketch digitization (see Fig. 8). After assigning the color palette, our S&S PC app displays the detected colors on the PC screen. Based on this early feedback, the user decides to redo color assignment using, e.g., different pen colors, or to start sketching. Similarly, after each capture of the sketch, the app displays the digitized design on the PC screen. A mismatch between the design (input) and the preview (output) could be caused by poor lighting, shadows, indistinct strokes, color variability, or other artifacts commonly present in photographed images. Indistinct strokes and color variability occur due to pen jitters over textured fabrics and variable pressures applied while drawing a single stroke, causing the stroke color to vary between darker and lighter shades. Consequently, a trace may appear segmented during color detection, resulting in an open circuit in the final product. To handle these issues, the S&S PC app offers an optional slider-based interface for manually tuning color detection. Otherwise, the user should perform the proper adjustments directly on the fabric, e.g., remove sources of shadow, or emphasize the strokes, and recapture her design.

Once the sketch in converted to stitches, the user sees what the end result will look like via the embroidery machine's touch display (WYSIWYG editor). The display offers tools to zoom in, duplicate, mirror, translate, etc. the design as a whole, but it does not allow the user to change the design on the stitch level. Using this preview, the user can detect the issue of merged traces, which occurs when the spacing between two independent lines is less than 0.2 mm (see Technical Stitching). The user fixes this by erasing the problematic traces on fabric and re-sketching them further apart. Finally, the *incremental design* feature allows her to test the physical design, artwork and circuit, by selectively sketching and stitching parts of it. She may also use another piece of fabric to stitch the first iteration before committing on the final fabric.

WALKTHROUGH: INTERACTIVE FLOWER

We illustrate S&S's basic workflow using the example of an interactive flower that emits light patterns when the user touches one of its leaves (Fig. 9).

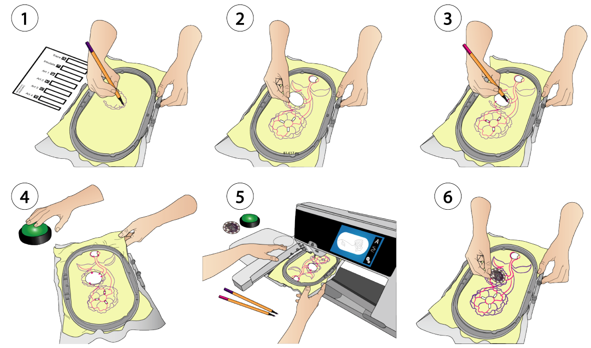


Figure 9. Basic workflow: 1. Sketch a design on fabric, 2. adhere Circuitry Stickers, 3. draw the circuit and electrical connections, 4. capture a picture of the sketch, 5. insert the fabric into the embroidery machine for stitching, and 6. replace the stickers with hardware components.

Sketching and Placing Circuitry Stickers. To start, the user places the color template on her fabric and draws two strokes in the violet and pink pens in the trace and art slits, respectively. She captures a picture of the template, and confirms color detection on the PC screen. She hoops her fabric and starts drawing the outline of a flower using an *art color* pen. She adheres a Component Sticker for a Lilypad controller on the fabric. She draws a trace from a pin on the sticker to the leaf of the flower using the *trace color* pen, creating a capacitive pushbutton. She continues sketching and adding stickers.

Capturing and Stitching Design. The user captures a picture of her sketch, and verifies the digitized design on the PC screen. With no Embroidery Stickers to remove in her design, she secures the hoop in the embroidery machine and uses the embedded display to view the embroidery patterns of her design. She sees objects in *trace color* sequenced to be stitched first. She threads the embroidery needle with conductive thread and starts stitching. Each time the machine finishes stitching one pattern, it pauses and prompts her to change threads.

Attaching Electronics. After embroidery is complete, she removes the hoop from the machine, and trims jump stitches using scissors. She cuts off pieces of Z-tape and sticks them onto the back of her hardware components. Guided by the Component Stickers, she determines the location and orientation of each component. She replaces the stickers with the hardware. Finally, she uses the Arduino IDE to program the LilyPad. More beginner-friendly tools exist, e.g. Scratch [44].

TECHNICAL STITCHING

We used the Bernina 880B embroidery machine and its software, DesignerPlus v.8, with Shieldex 117/17 dtex 2-ply silver sewing thread (linear resistance < 30 Ω/cm) as a top thread. Embroidery is one of the most stressful textile processes for conductive thread [42]. This leads to thread breaks and segmented circuit traces. A stitching speed of 700 stitch/min reduces the heat and friction associated with high speeds.

Table 1 summarizes the stitches that S&S uses to embroider users' designs. The Satin stitch is used to stitch the artwork. The length of a stitch determines the margin of error in the length of sketched and insulated traces when stitched. The width of a sketched line increases by 0–0.2 mm when stitched

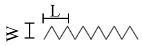
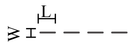
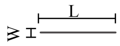
Stitch	Trace	Insulation	Grid	Bridge
Type	Satin	Satin	Triple	Triple
Length	0.8 mm	0.3 mm	1.0-2.5 mm	9.0 mm
Width	1.0+ mm	1.8 mm	1.0 mm	1.0 mm
Purpose	Sketched traces	Insulation	Insulated traces Sensor traces	Shield bridges
Shape				

Table 1. Technical stitches for embroidering fabric traces and sensors.

due to the smoothing algorithm that the embroidery software uses before transforming a digital sketch to embroidery patterns. Thus, gaps that are 0.2 mm wide between adjacent stokes may be closed with stitches. We describe three tests for determining the system's stitches. We compared variants of the basic stitch types, Satin, and Triple and Single Running. We excluded special purpose and decorative stitches. The tests were conducted on cotton and linen fabrics. Measurements were taken directly after embroidery, and after one and two weeks of frequent fabric handling. We report the average measurements.

Resisitivity Test

Fabric circuits with long electrical connections drop significantly more voltage, consuming power and limiting the amount of current that can be delivered to components. To determine the *trace stitch* for hand-sketched traces, we measured the resistance of 30 conductive traces: TRACE LENGTH (5 cm and 10 cm) × STITCH TYPE (Satin, Triple, Single) × STITCH LENGTH (0.4, 0.6, 0.8, 1.0, 2.0 mm), all with minimum width. Table 2 shows sample traces and their average measured resistance. Overall, the resistance of Satin traces was lower than Running traces, independent of STITCH LENGTH. Satin traces of shorter STITCH LENGTHS measured marginally lower resistances. But as the stitch length became shorter, traces became denser. This affects the flexibility of the base fabric, especially if several traces are concentrated in a small area. Longer stitches result in spars traces. Consequently, we chose the Satin stitch of 0.8 mm length as the *trace stitch*. The *grid stitch* is used for stitching insulated traces and sticker sensor traces. As these traces will be covered with an *insulation stitch*, and are often concentrated in a small area, it is essential for them to be flexible. We chose the Triple stitch with an adaptable length of 1–2.5 mm as the *grid stitch*.

Stitch Type	Stitch Length	Resistance	Sample
Satin	0.4 mm	5–12Ω	
Satin	0.6 mm	12–15 Ω	
Satin	2.0 mm	14–20 Ω	
Triple	2.0 mm	27–53 Ω	
Single	2.0 mm	31–80 Ω	

Table 2. A sample of conductive traces stitched with Satin and Running stitches, and their measured resistance for 5 and 10 cm long segments.

Spacing Test

To evaluate the smallest pitch achievable in our touchpad sensor, we tested the minimum allowed spacing between parallel exposed traces to avoid undesired connections. We measured for continuity between 6 conductive traces, stitched with the *grid stitch*, and separated by different SPACINGS (1.0, 1.5, 2.0, 2.5, 3.0, 3.5 mm). Fraying fibers connected traces at 1.0 and 1.5 mm distances. At 2 mm distance, tie-in and tie-off knots, which are often wider than the trace itself, created undesired contacts on the back of fabric. We conclude that a 2.5 mm is the safe minimum distance between exposed traces. These results are independent of the type, length, and width of a stitch, but may differ for other types of conductive thread.

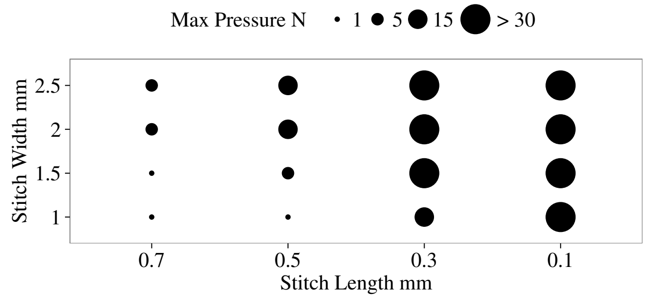


Figure 10. A plot of the relation between the width and length of Satin stitches and the max pressure under which they can insulate a trace.

Insulation Test

Our goal was to find an *insulation stitch* that prevents undesired connections to occur between insulated and exposed traces even if they come in direct contact with each other, such as in shields and sensors. The most common couch stitch is the Satin (Zigzag) stitch. We tested 16 conductive traces, 10 cm long, stitched with the *grid stitch* and couched with a Satin stitch: STITCH WIDTH (1.0, 1.5, 2.0, 2.5 mm) × STITCH LENGTH (0.7, 0.5, 0.3, 0.1 mm). Each insulated trace was pressed against an exposed conductive trace with four amounts of PRESSURE (1, 5, 15, 30 N) at 5 equidistant points along the trace. We measured for continuity. Fig. 10 summarizes the results. We found that the Satin stitch of 1.5 mm width and 0.3 mm length insulates a conductive trace on both sides of the fabric while having the least effect on base fabric flexibility. Thus, two insulated traces can be spaced as close as 2 mm—closer than exposed ones.

IMPLEMENTATION

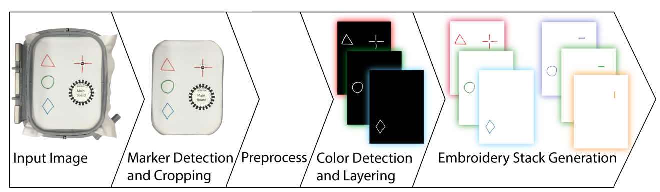


Figure 11. Sketch digitization pipeline. Input design image with color palette: red trace, green insulation, blue art, and a Shield and Component Stickers. Output embroidery stack excludes stickers, separates shapes in single-colored layers, and generates two system layers: grid and bridge. Stack is sent to embroidery software for stitch conversion.

We developed an algorithm for digitizing users design on fabric. It uses computer vision libraries in OpenCV for detecting shapes and colors, and the AR Marker library[2] to generate and detect markers on the color template, hoop, and sensor stickers. Based on the markers in the input image, our algorithm distinguishes between a *color assignment image*, which contains the color template markers, and a *design image*, which contains the hoop markers and, optionally, sensor markers. Figure 11 describes our sketch digitization pipeline, part of S&S PC app.

[2]https://pypi.python.org/pypi/ar-markers/0.4.1

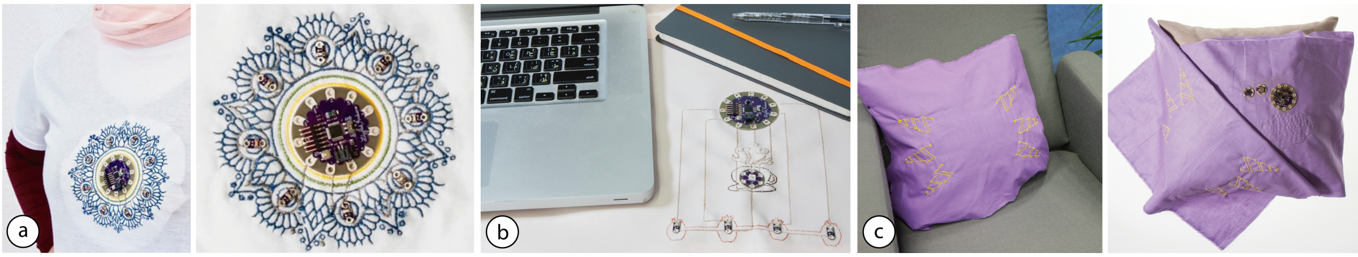


Figure 12. Example applications: a. Wearable Mandala, b. Interactive Desk Mat, c. One-Hour Nap Pillow.

Our app send the output of the pipeline, the *embroidery stack*, to the embroidery software to be converted to patterns, and then to the embroidery machine for stitching.

Marker Detection and Cropping

The algorithm imports the input image from a cloud storage and converts it from the RGB- to the HSV-colorspace. The HSV space allows defining color ranges, making it more suitable for processing images where color variability is expected. Next, it detects the markers in the image. In total, it distinguishes 12 markers: 6 on the color template, 2 on the fabric hoop, 3 on Shield Stickers, and 1 on the Sensor Sticker. In the *design image*, the algorithm uses the hoop markers to 1. create a rotation matrix to rotate the sketch, and 2. create a cropping mask to crop the sketch from the image.

Reprocessing

Our algorithm adjusts the gamma, and increases the sharpness, contrast, and exposure of the input image. These operations were selected carefully to enhance color contrast, remove noise and artefacts, and improve the edges of the sketched shapes.

Color Detection and Layering

Color assignment image. The algorithm scans the lines next to each color marker, reading the Hue, Saturation, and Value of each pixel. Spikes in the Hue channel indicate color change. It calculate the mean HSV values around each spike. Using these values we define color ranges and associate them with the nearest color marker. The color ranges determine the color palette, which is used in *design images*.

Design image. The algorithm thresholds the image using the user's color palette, removes Component Stickers by filtering for *sticker colors*, and creates the following single-colored layers:

1. Trace layer — *trace color* mask: hand-sketched traces and sensors, including traces that extend from stickers.
2. Insulation layer — *insulation color* mask: insulated traces.
3. Art layers — *art colors* masks: artwork lines and shapes.

After color detection is complete, S&S PC app displays the digitized input image—*color assignment image* or *design image*—on the PC screen and provides the user with sliders to optionally tune the upper and lower bounds of the HSV channels. The user sees the results of adjusting the sliders on the screen in real-time. To enable incremental design, the algorithm subtracts the input *design image* from the last user-confirmed image before performing color detection.

Embroidery Stack Generation and Stitch Mapping

In the *design image,*, the algorithm creates the necessary stacks for insulated objects and Embroidery Stickers, as previously described. The combination of layers from the selection masks and the stacks is called the *embroidery stack* (see the last step in Fig. 11). S&S PC app sequences the layers and sends them to the embroidery software in the following order: trace (red), grid (purple), insulation (green), bridge (orange), then art layers (blue), together with the color–to–stitch mapping in Table 1. The embroidery machine stitches the layers in sequence. The user uses the color of each layer, which appear on the machine's display, to resolve the type of thread required.

EXAMPLE APPLICATIONS CREATED BY AN ARTIST

To reveal early opportunities and challenges in S&S workflow, we invited an artist with a technical background (female, 24 years old) to create e-textiles using our system over the course of three days. On the first day, the artist received a twenty-minute introduction of the system. For the next four hours, she practiced sketching and stitching simple shapes and basic circuits. In the following two days, she spent a total of 10 hours of unrestricted creative work. We observed and documented her process and artifacts, conducted 2 unstructured interviews (day 1 and 2) and a retrospective study with her and a researcher reviewing photos of her progress (day 3).

Below, we describe three unique e-textiles that were developed by the artist. She used the LilyPad hardware kit, which she programmed with the Arduino IDE. We follow this with a brief summary of her feedback and emerging processes.

Wearable Mandala

The artist sketched a mandala (150×150 mm) on a white cotton t-shirt. Her circuit consisted of 8 LEDs, a controller, and a battery holder. She used the outlines of the mandala to conceal the circuit traces (2nd integration strategy). She sketched frames to house the LEDs and controller. The battery holder was attached to its contact surface from the back side of the fabric (4th integration strategy). The mandala lit up in different patterns based on a timer.

Interactive Desk Mat

On leather fabric, the artist sketched an interface for the "Pomodoro" time management technique. She used a ruler for sketching, and 4 LEDs, a pixel board, and a controller. She powered the controller from her computer. She programmed a timer to light up an LED every 25 mins to indicate the start of a work interval. Between work intervals, the pixel board blinked to announce a 5 min break. Once all 4 LEDs were lit, the pixel board blinked to announce a longer break. She drew traces between the pixel board and controller in the form of steam coming out of the cup (1st integration strategy).

One-Hour Nap Pillow

The pillow was stitched using our 5th integration strategy—the artwork and circuit were sketched and stitched on separate pieces of fabric and layered afterwards. It contains a touch sensor that detects when a person first puts his head on the pillow, and awakens him using vibration patterns after one hour of continuous contact. The user shakes the pillow to snooze it. An accelerometer signals a 5- or 10-minute snooze based on shaking intensity. On the top fabric, the artist sketched the artwork on one side and used the embroidery machine's touch display to duplicate, mirror, and translate it to the other side.

User Feedback

The artist was very positive about her experience with our system. She was particularly inspired by the range of circuit integration strategies. We summarize her feedback on the design workflow, sketching on fabric, and design processes.

Design workflow. The artist found the workflow particularly efficient for creating e-textiles of substantial artwork and simple circuits. She noted that hand-sketching complex circuits can be challenging and error-prone. For example, drawing and correcting the traces in the Wearable Mandala consumed 40% of the project time. For an 8×8 touchpad sensor, she employed our 5th integration strategy to gain more space to route the sensor traces to a Component Sticker, without affecting her design. She found that using colored pens and stickers for art and circuitry communicate a lower entry threshold. After a few trials, she learned how to use the system's feedback to detect and fix digitization pitfalls. Afterwords, she reported that the outcomes of the system better matched her expectations.

Sketching on fabric. She reported that a main benefit of sketching on fabric is evaluating designs quickly and in context. While sketching the Wearable Mandala, she wore the t-shirt several times to assess how the design looked, or if it constrained her when moving. Sometimes she made changes to her original layout, e.g., strategically repositioning Component Stickers to convey an idea. Another benefit was understanding the material, e.g., leather inspired straight lines and right angles, while cotton afforded curved and flowing lines. She also noted that textured fabrics, such as denim, caused drawing irregularities, while towel fabric and fur did not afford sketching on them.

Emerging Design Processes

Scribble on paper, commit on fabric. The artist always doodled her initial art and circuit on paper. Fabric was not perceived as a medium for scribbling. Even with undo capabilities, she was hesitant to "waste a good piece of fabric". Once her sketch was developed, she transferred it to fabric with adaptations.

Sketch to fit a circuit: She sketched the artwork and circuit separately. She then selected an integration strategy based on the complexity of the circuit and the part of the design she wanted to showcase. Next, she gradually transferred the Circuitry Stickers from the circuit to the artwork, drawing the necessary connections and adapting her art, sometimes erasing art lines and replacing them with traces (1st strategy) or routing traces close to art outlines (2nd strategy).

Use stickers to frame the design: She transferred her sketches from paper to fabric starting with the Circuitry Stickers. This helped her determine the location and scale of the design and evaluate its layout in context before sketching on fabric.

LIMITATIONS AND FUTURE WORK

Our current digitization algorithm expects pen colors to be distinguishable on the base fabric, and fabrics to have uniform colors and smooth textures. Pens that can release uniform color independent of the applied pressure and fabric background, such as gel-based pens and puffy fabric paint, can neutralize most of the algorithm's pitfalls. But they are harder to undo and their texture may impede stitching over them. Alternatively, augmenting fabric pens to behave like digital pens would allow us to create parallel digital sketches without the previous constraints.

Automatic conversion of sketches of many objects often leads to complex tool paths and jump stitches. Trimming jump stitches can be time consuming, and in the case of traces, lead to thread fraying and accidental connections. We suggest to enable our digitization pipeline to algorithmically reorder individual objects in the embroidery stack to influence the tool path and reduce jumps in the embroidery software.

Our system does not offer autorouting and rule checks (ERC/DRC) for fabric circuits. It expects users to have a basic understanding of electronics. In future work, we'd like to examine (a) how to autoroute circuit traces based on the outlines of the artwork, inspired by [47], and (b) alternative media, such as augmented reality displays, for real-time feedback.

Finally, we want to perform studies to inspect user requirements and extend our workflow with advanced features, such as stitch selection and manipulation. We aim to conduct a systematic evaluation of our touchpad sensor, and investigate how to stitch a Faraday cage to improve its accuracy.

CONCLUSION

This paper introduced Sketch&Stitch, an interactive system for creating e-textiles quickly and iteratively. It enables a new design workflow that combines physical sketching with an embroidery machine, offering users the benefits of direct making and the power of digital tools. It implements a digitization algorithm for converting a sketch to an embroidery. We described novel stitch patterns for attaching electronics, shielding wire crossings, and integrating sensors (pushbuttons, sliders, touchpads) directly on fabric. An empirical evaluation of the technical stitches was presented. Finally, we demonstrated the potential and advantages of our workflow.

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