Embr: A Creative Framework for Hand Embroidered Liquid Crystal Textile Displays

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Figure 1: A hand-embroidered Liquid Crystal Textile Display (LCTD) is created by interlacing a conductive thread along the back of a satin stitch. When powered, the thread acts as a resistive heater causing painted liquid crystal to change colors.

ABSTRACT

Conductive thread is a common material in e-textile toolkits that allows practitioners to create connections between electronic components sewn on fabric. When powered, conductive threads are used as resistive heaters to activate thermochromic dyes or pigments on textiles to create interactive, aesthetic, and ambient textile displays. In this work, we introduce Embr, a creative framework for supporting hand-embroidered liquid crystal textile displays (LCTDs). This framework includes a characterization of conductive embroidery stitches, an expanded repertoire of thermal formgiving techniques, and a thread modeling tool used to simulate mechanical, thermal, and electrical behaviors of LCTDs. Through exemplar artifacts, we annotate a morphological design space of LCTDs and discuss the tensions and opportunities of satisfying the wider range of electrical, craft, cultural, aesthetic, and functional concerns inherent to e-textile practices.

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CCS CONCEPTS

• **Human-centered computing** **HCI design and evaluation methods**; • **Applied computing** *Fine arts*; • **Hardware** *Wire routing*.

KEYWORDS

craft, e-textiles, making

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1 INTRODUCTION

Within electronic textile, or *e-textile*, practices, conductive thread is a common material used to create fabric-friendly electrical connections, sensors[1, 20], and actuators[36, 45]. When powered, these threads have been used to create resistive heaters that activate thermochromic dyes or pigments on yarn or fabric to create interactive, aesthetic, and ambient textile displays. While techniques for creating textile displays have been realized in woven and crocheted textile techniques [5, 9, 56], there is an opportunity to extend these methods to hand-embroidered practices that allow more fine-grained control of resistive heater designs, afford hand construction and experiential knowledge creation, access a wider breadth of cultural traditions, and further develop the range of design possibilities from an elementary material like conductive thread.

Integrating, or hybridizing, embroidery and electronics requires careful negotiation of material and tool interactions. Sennett [49] provides a lens for understanding the different types of negotiations that take place, differentiating elements that a material presents which are exploited to a practitioner's favor, or *paths of least resistance* (LRs), and elements that stand against the will of a practitioner, or *paths of most resistance* (MRs). In this work, we leverage Sennett's lens to capture and define our design process for developing Embr, a creative framework for designing and fabricating liquid crystal textile displays (LCTDs). First introduced by Wakita et al. [56], an LCTD leverages a highly reactive thermochromic material known as liquid crystal to create dramatic color-changing effects on textiles. Our framework specifically contributes:

- A creative framework design approach for negotiating hybrid material practices.
- An LCTD computer-aided design (CAD) tool that supports users in encoding Scalable Vector Graphic (SVG) designs with embroidery stitches, visualizes liquid crystal effects, and generates dynamic fabrication instructions.
- A computational model used to simulate mechanical, thermal, and electrical behaviors of LCTDs. The model is used to generate an *e-stitchbook* that formally characterizes a set of 12 conductive embroidery stitches and their corresponding liquid crystal expressions.
- A portfolio of exemplar artifacts used to annotate a morphological design space of LCTDs.

In this paper, we first review prior textile display design techniques and describe the design frictions inherent to LCTDs. We then describe the design and implementation of an LCTD model and demonstrate its use within the Embr tool. An e-stitchbook is then presented alongside exemplars to better operationalize how HCI designers can utilize the framework in practice. Finally, these exemplar artifacts are used to discuss the creative pathways enabled by our framework and the remaining negotiations of the broader range of electrical, craft, cultural, aesthetic, and functional concerns inherent to e-textile practices.

2 RELATED WORK

We review relevant work in creative frameworks, thermochromic textile displays, electronic embroidery applications, and tools for supporting design and fabrication of electronic embroidery. Our focus is to formally develop electronic hand embroidery and access the manual dexterity in a hybrid practice with embroidered heaters and smart heat-activated materials.

2.1 Creative Frameworks

Creative frameworks within HCI research aim to provide foundational materials and building blocks while providing open-endedness. In the *A kit of no parts*, Perner-Wilson demonstrated how a toolkit of techniques presented as recipes could be used to support creative inquiry when users are presented with different sets of materials and tools [41]. Meissner's concept of a *schnittmuster* [33], or pattern, provided an open-ended space of methods for combining materials in a creative framework. The KnitGIST framework lay the groundwork for design tool fabrication that produces a wide range of knit textures through pluggable user interfaces [17]. Murer et al. [35] focused creative sensemaking on the action of taking things apart through an *uncrafting* framework. In Embr, we use Sennett's lens of pathways of resistances to acknowledge unresolved, unsuccessful, as well as promising trajectories that extend past the original intentions of LCTD displays. The pathways identified provide a framework for other researchers to propose alternative configurations that support more plural design trajectories in e-textiles.

2.2 Thermochromic Textile Displays

Thermochromic materials such as liquid crystal are easy to use, capable of producing subtle shifts in color, and offer non-emissive visual cues valuable to wearable and textile display design [9]. Researchers have exercised different techniques to activate thermochromic material in textile displays. Passive techniques leverage natural thermal changes in the environment, body, or from physical contact [7, 19]. Other displays are powered with peltier semi-conductor elements [6, 39, 40], or conductive yarn [4, 50, 52]. Initially introduced by Wakita et al. [56], Fabcell demonstrated how displays could be decomposed into fabric modules composed of conductive yarns and liquid crystal ink. Conductive yarn had also been coated with thermochromic inks and pigments which are then sewn or woven into fabric to create dynamic displays [9, 37]. While the effects of passive activation such as body temperature yield more organic effects, activation using active elements provide greater control of the thermochromic material's behavior and potential interactions. In this work, we use embroidered conductive yarn to activate thermochromic liquid crystal that has been hand-painted or screenprinted onto fabric.

Thermochromic textile displays have been used in a wide range of interactions and applications in HCI. Many works focus on displaying physiological factors such as heart rate and emotional responses through wearable thermochromic displays [18, 53–55]. Others are geared towards expanding textile expression in garments and facilitating social interactions through clothing artifacts [7, 48]. Our work aims to increase the expressiveness of thermochromic textile displays by providing novel heat-formgiving techniques for hand-embroidered LCTDs. We also expand the design potential of thermochromic textile displays through a lumped-element model that is used to simulate different LCTD behaviors.

2.3 Electronic Embroidery Applications

Post et al. [44] introduced the concept and process of electronic embroidery, or e-broidery, as a means of creating flexible multi-layer circuits on fabric substrates in the early 2000s. Since then, HCI has seen significant progress in incorporating embroidery with electronic circuitry to give rise to a wide range of applications. Mecnika et al. provides an overview of embroidered smart textile applications, including embroidered circuits, electroconductive interconnections, antennas, heating, and keypads [32]. Machine embroidery techniques have been used to protect the integrity of e-textiles [12], bind with a wider range of materials (3D-printed mechanical springs [11]), create e-textile components including

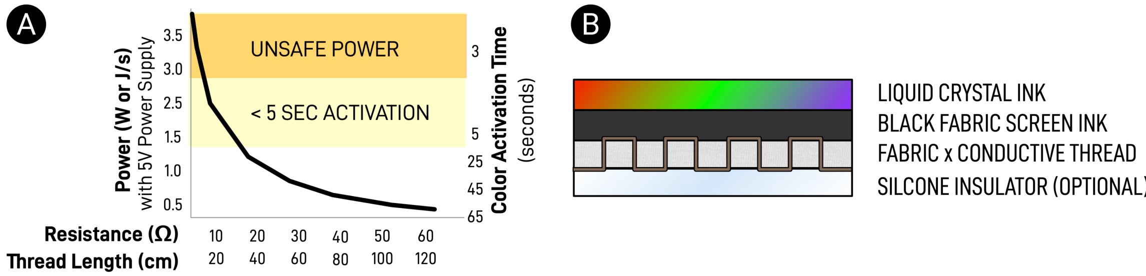

Figure 2: LCTD Parameters. (A) Embroidered resistive heaters match well with the power and heat requirements needed to activate liquid crystal; (B) liquid crystal requires a black substrate to maximize the visual effect.

sensors (resistive pressure [2], pressure [57], resistors [13], displacement [29], capacitive [1]) and actuators (speakers [36, 45]) and support aesthetics in dynamic fabrics [25]. Embroidered elements have also been used to create tactile contrast in embroidered UI elements [34], fabricate on-skin interfaces [20], or create a hand embroidered 8-bit programmable computer using magnets, metal thread, and glass [43]. Despite the significant progress that has been made in applications of electronic embroidery, few works focus on applications of hand embroidery, especially in textile displays. Our framework motivates the use of hand embroidery as a means to access a wide range of cultural traditions for more personalized and meaningful textile displays and foreground experiential learning opportunities inherent in craft practices [38].

2.4 Computer-Aided Design and Fabrication

Computer-aided design tools for electronic embroidery draw from established HCI paradigms including direct manipulation through sketchable interfaces [14] and visual-programming languages [58]. Some works focus on simulating embroidery techniques using image rendering to capture the texture of embroidered artifacts [59, 60]. L-systems, commonly used in generative art, have also been used to capture embroidery patterns within Bulgarian folklore [3]. Our framework provides a computer-aided modeling tool that simulates mechanical, thermal and electrical behaviors through imperative, declarative and direct manipulation.

Computational methods have also been used to assist with embroidery actions. Takahashi et al. [51] proposed using removable computationally generated paper templates to assist with stitch execution, emulating chemical embroidery methods to produce textile substrates. Alternatively, CNC techniques have been used to carry out punch needle embroidery using repurposed plotters [15]. Closely related to our work is Hybrid Embroidery, an interactive fabrication framework that uses computational methods to combine electronic embroidery techniques, computer vision, generative design methods, and an embroidery machine to facilitate open-ended exploration and improvisation of the craft [26]. In contrast, our framework aims to support hand-embroidery practices using a lumped modeling tool that simulates electrical and thermal behaviors of LCTDs. Our thread model assists with performing embroidery stitches by hand by generating instructions for stitch executions. It is unique in its ability to model pulling interactions which is useful for complex stitchwork.

3 LIQUID CRYSTAL TEXTILE DISPLAYS

3.1 Anatomy of an LCTD

LCTDs are composed of a resistive heater set alongside thermochromic liquid crystal (TLC), a substance whose crystalline structure changes at different temperatures. These structures absorb light differently, resulting in color changes. We are using conductive thread (0.5 Ω/cm, JAMECO92) as a resistive heater and screenprintable SFXC TLC [1] which transitions through red, green, and blue when 9-12 joules of energy are transferred (at room temperature) and readily activates from body heat. By embroidering the resistive heater in different patterns, it is possible to create unique thermal images.

3.2 LCTD Design and Fabrication

To maximize the visual thermochromic effect, liquid crystal ink should be placed on a black fabric or substrate. The low activation energy of liquid crystal translates to very light heater requirements as depicted in Figure 2. Given a battery power supply running at a nominal 5 volts, the heaters need to produce at most 1.3 watts to achieve reactive speeds (5-10 second activation). As a point of reference, the human body produces about 100W (or joules/second) of power [28]. To fabricate such heaters, a conductive thread between 14 cm - 60 cm long achieves resistance values of 7-30 Ω and power ranges of 0.36-1.6 watts. Note that the longer the thread, the less power it will produce. This particular coupling allows a wider range of successful designs, efficient heaters (thread is closely bound to the thermoreactive material, constraining heat transfer to chiefly diffusion), and safer and longer-lasting wearable interactions (lower power requirements). Larger heaters (>60 cm; 30 Ω) can be achieved by connecting multiple heaters in parallel to efficiently distribute current across heater branches [52].

3.3 LCTD Pathways

The practice of embroidering resistive heaters with conductive thread is a craft requiring the careful negotiation of different material properties and behaviors, especially those resulting from interfacing between soft and hard materials. Following Sennet's lens of paths of most resistance (MRs) and paths of least resistance (LRs) [49], we describe the material and tool relations present in the design and fabrication of LCTDs. These pathways are useful in allowing us to position this design problem as a negotiation of

[1] https://www.sfxc.co.uk/products/sprayable-liquid-crystal-inks

different tools and materials and provide other e-textile researchers documentation of our design process and design space. The LCTDs developed through this work are used to operationalize one negotiation but can be leveraged to motivate research directions towards plural e-textile practices.

3.4 Paths of Least Resistance

LR1 **Foundational Development** Conductive thread is a foundational material in e-textile toolkits with a variety of uses including interconnections, as electrodes in capacitive touch circuits, or to form resistive heaters. Expanding the expressivity of such a material can have implications in expanding the "walls" of a practice [46], giving e-textile practitioners a wider range of design possibilities from primitive elements.

LR2 **Handedness and availability of materials** The tools and materials for fabricating LCTDs are becoming readily accessible. Techniques for creating LCTDs require as little as a needle, thread, paintbrush, and liquid crystal ink. Other techniques can be used to extend the capabilities of this practice through screenprinting and airbrushing methods. The scale of e-textile circuits supports hands-on exploration and engagement and allow craft skill to emerge and develop without specialized equipment.

LR3 **Defamiliarizing Electronics** E-textiles have demonstrated great promise in broadening participation in computing, especially in "building a new clubhouse" [8] that has a different user demographic and its own set of values[2]. The appeal and access of everyday materials contextualized with electronic practices have been shown to shift perceptions of the intimidation of electronics [30]. Thermochromic elements have also been used to externalize abstract and invisible immaterials like electricity, allowing practitioners to see and physically experience electricity as a material [52]. Liquid crystal, as a more dynamic material than single-phase thermochromic inks, provides a more engaging expression.

LR4 **Culturally Diverse** Embroidery is part of several different cultural practices around the world with established histories, design motifs, and communities of practice. Engaging with these practices can support creating personally meaningful experiences, especially with respect to little-C creative development [22]. This quality has been leveraged especially in the development of STEAM toolkits in K-12 education, however, the practical challenges of working with e-textiles remain a barrier to their adoption as a cultural practice [21].

LR5 **Structural Integration** The act of establishing electrical connections through multiple planes, or *vias*, is important for the integration of circuits onto structural surfaces. Existing circuit building techniques are limited in their ability to support connections between two planes (e.g., front and back of a PCB board) and are much more restricted across multiple surfaces. Thread offers the unique advantage of being able to establish electrical vias across multiple substrates with little effort, supporting complex circuit designs. The ease of moving through multiple substrates can be especially beneficial in developing multi-layered and structural electronics.

[2]In 2010, Buechley et al. reported Lilypad projects created by 65% women to 25% male versus Arduino projects created by 86% male makers [8].

3.5 Paths of Most Resistance

MR1 **Thread-Thread Interconnects** To establish electrical continuity with conductive thread, the most common method is to sew or knot two threads together – this results in a tension-based connection that has a proclivity to detach. While some e-textile practitioners use nail polish acrylic to secure these connections, it presents challenges for editing or debugging e-textile circuits. In order to be thermally efficient, LCTDs need to be connected in parallel, which for an incremental development approach requires long tails to test and later interconnect. These long tails were prone to entangling and causing electrical shorts; while insulated thread can correct the issue of unintentional shorts, it also restricts the ability to interconnect with other threads.

MR2 **Thread-Component Connections** Many solutions for interfacing with conductive thread resulted in connectivity or damage issues. Tools, such as pin-based connectors proposed by Posch et al. [42], were less useful on thin fabrics that do not provide enough tension to hold a reliable electrical connection with pinned thread. Tethering thread to electronics can also introduce tension from the weight of connected components which can negatively affect the stitchwork.

MR3 **Tension-based Resistivity** Certain conductive threads exhibit variable resistance depending on a thread's tension. Creating precise resistive heaters requires tuning the final LCTD circuit with appropriate tension.

MR4 **Aesthetics and Mechanical Limitations** Conductive thread innovations are readily improving the resistivity and solderability of e-textile circuits, however, these threads still have several practical mismatches with embroidery floss. While conductive thread's limited color range may be the most salient, its smoother surface properties present practical limitations in holding the same tension in stitchwork; embellishers navigate this friction in embroidery floss by using fewer strands, yet separating conductive thread would diminish the electrical conductivity within LCTDs. To obtain the maximum intensity of color change in liquid crystal ink, the LCTDs require a black substrate which limits the range of visual forms.

MR5 **Power Consumption** LCTDs need to draw between 150-300 mA of current to activate liquid crystal. The high power consumption often limits the power source to benchtop power supplies which makes integration to standalone wearable artifacts challenging. Like other resistive heating applications, LCTDs are not bistable, requiring an active power source to maintain the liquid crystal activated.

MR6 **Parasitic Heat** Environmental and body heat can play a significant role in unintentionally activating worn LCTDs. Closed-loop control using thermistors are often limited in spatial resolution.

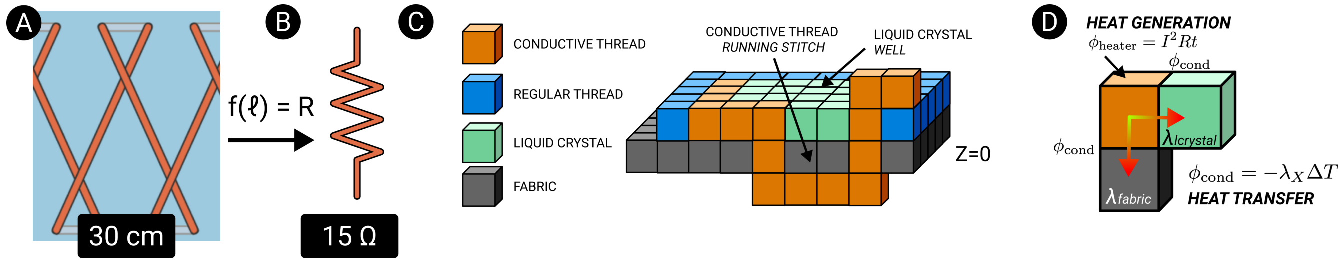

Figure 3: LCTD Model. A lumped model is constructed by (A) creating a physical model of stitches; (B) stitch length is converted to electrical resistance using a linear model; (C) a voxel grid is constructed from the physical model and used to (D) simulate heat transfer; conductive thread voxels generate heat according to Ohms' Law.

4 MODELING LCTDS

Representing an LCTD computationally is complicated by the many ways embroidery and circuit designs are represented. In traditional textiles, symbols are used to indicate the color of the embroidery floss, the number of strands, and the type of embroidery stitch to carry out over a specific region. In electronic embroidery design tools, a raster or vector image is translated into single-layer machine stitches. In EDA tools, circuit designs are presented as stacked layer models that separate geometries for holes, traces, solder masks, and text silkscreens. While useful to their respective communities, these representations are limited in their ability to support LCTDs. We introduce a computational model to unify these representations to better encode electronic embroidery geometries.

4.1 The Lumped LCTD Model

The Embr model is a lumped-element model that combines physical, thermal, and electrical simulations to identify the properties and behaviors of different LCTD designs. This model was created in coffeescript and rendered using the Scalable Vector Graphic (SVG) manipulation library `paper.js` [27] on an HTML5 Canvas.

Stitch Model. A stitch corresponds to a movement of thread in-and-out of a fabric. Many existing thread models offer the ability to simulate environmental physics (e.g., gravity and inertia influencing thread movement) [23], however, the physics relevant to executing embroidery stitches are focused on the forces from pulling a stitch taut, constrained by the previous geometries that the pulled stitch interacts with. Stitches can be as simple as the in-and-out segment of a cross-stitch, as complex as the needle-wrapping geometries of a french knot, and as intricate as a self-constrained feather stitch.

- **Encoding.** To simulate stitching behaviors, we first encode a stitch as a set of stacked paths using the Scalable Vector Graphics (SVG) format. Each stitch path has a z-index that designates whether the path is in front (z>0) or back (z<0) of the canvas (z=0). The z-index is also used to encode the relationship of one path to another (Figure 4A).
- **Scene Setup.** Each stitch path is then resolved into a linked-particle system. Particles are evenly distributed along the length of the path. Links between the particles are rigid and extendable, allowing the distance between two particles to increase and the overall length of the path to be dynamic. Each particle can be fixed (resisting forces) or free. The particle at the start and end of each path is fixed, representing the fabric constraining a stitch at its ingress and egress. Special *obstacle particles* are added into the scene representing geometries that a stitch path is constrained by and are computed by gathering all constraining stitch paths (paths above the target path) and placing an obstacle particle at the ingress and egress of each constraining path (Figure 4B).
- **Simulation Step.** The overall aim of the simulation is to minimize the length of a stitch path while satisfying physical constraints with other stitch paths, i.e., pulling a stitch taut. For each simulation step, (1) we walk each path in the stitch and construct a simulation scene as detailed above; (2) for each particle, a force proportional to the length of each of its links is applied; the summative force is used to displace the particle; (3) when the length of a link between two particles is above a parameter value, i.e., overstretched, the stitch path is uniformly re-sampled to have a uniform distribution of particles. If a particle collides with an obstacle, the particle becomes fixed (Figure 4C). The simulation step is repeated until the stitch path has reached a stable length.

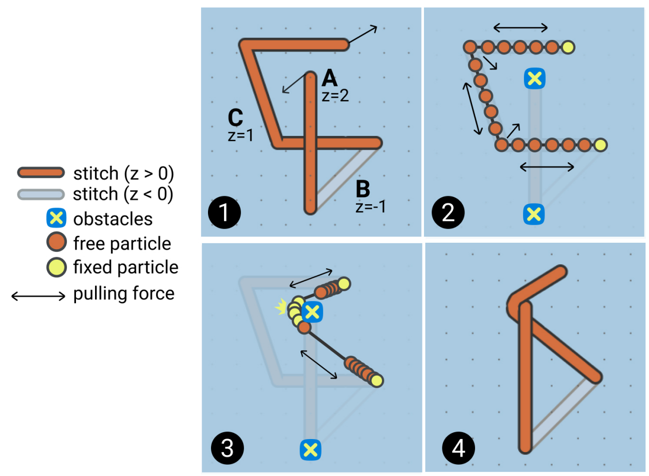

Figure 4: Pulling a thread. (1) Embroidery geometries are encoded as a set of stacked stitches; (2) stitch C is simulated as a linked particle system; the ingress and egress of stitches above C are set as obstacles – a pulling force is applied on the particles; (3) as particles collide with obstacles, they become fixed; the simulation runs until the change in stitch length is negligible; (4) stitch C is constrained by stitch A.

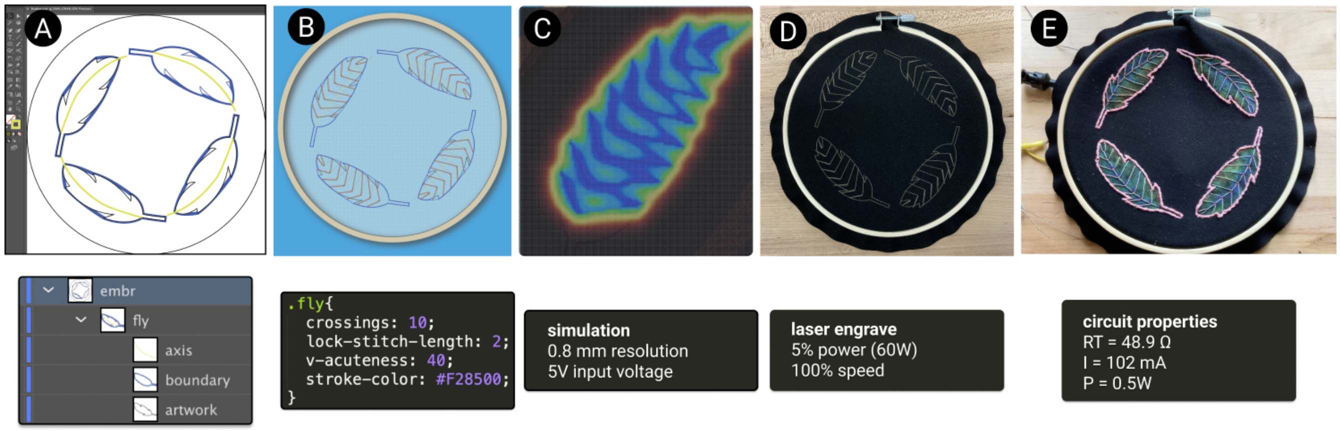

Figure 5: LCTD Design and Fabrication Workflow. (A) In an SVG editor, stitch regions are assembled from paths into named groups; (B) a declarative interface allows a user to assign stitch parameters to each region; the stitch is computationally generated on a digital canvas; (C) heat simulation is run on the modeled stitches allowing for fine-tuning of stitch parameters; (D) the tool outputs an SVG file that is used to create laser-etched guides; (E) liquid crystal is brushed on and conductive thread is hand embroidered; the fabricated LCTD is then powered from a benchtop power supply.

Circuit Model. Since the conductive thread is being used primarily as a resistive heater, we have formulated a circuit model that simply computes the resistance of a stitch as a function of its length. For simplicity, the model assumes that conductive thread has uniform resistivity and is pulled taut, that each region of a LCTD is being stitched with a single thread, and regions (when grouped) are connecting corresponding threads in parallel i.e., in a current divider configuration. In earlier iterations, we represented the stitchwork as an undirected spatial graph and computed self-intersections to identify electrical shorts; however, when compared to real-world embroidered circuits, electrical shorts from overlapping conductive thread were heavily probabilistic due to difference in tension and contact between traces [MR3]. For this reason, we instead report the resistance of thread as a function of thread length (Figure 3A). Within the design tool, our short-detection approach is used to mark the circuit diagram with potential shorting connections.

Liquid Crystal Model. Liquid crystal produces different color expressions depending on its crystalline structure that changes as a function of temperature. To model color as a function of temperature, we constructed a thermal characterization experiment as follows: a sample of liquid crystal was screenprinted on a cotton fabric with uniform thickness; a resistive heater (P=0.5W) was tightly coupled to the sample and activated from room temperature; an infrared thermometer measured the temperature of the sample every 3 seconds; the overall experiment was videographed. Reviewing the video, the average color of the video pixels corresponding to the liquid crystal was sampled at each temperature measurement. We use linear interpolation to query the model for liquid crystal's color for any temperature within the range of sampled values.

Heat Transfer Model. In order to model the thermal interactions between the resistive heaters, liquid crystal, and other materials (e.g. fabric, embroidery floss, glue), we implemented a voxel-based heat transfer simulation for LCTDs. Leveraging techniques proposed by Maréchal et al. for modeling winter sceneries [31], our implementation converts the stitch model by rasterizing the scene into a coarse voxel-based grid. Each voxel stores information regarding its material composition and the thermal energy after each simulation timestep. Together, this information is used to compute the phase change in the liquid crystal and render a representative color (Figure 3C). The heat transfer simulation assumes that the environment is at room temperature and that materials are tightly coupled such that heat transfer largely occurs from conduction. At each timestep, conductive heat transfer ($\phi_{\text{cond}} = -\lambda_{\text{voxel}}\Delta$) is computed for a given voxel and distributed to all adjoining voxels (that share a face) with respect to a neighbor's *lambda* heat conductivity. A heat generation component is computed from voxels with a resistive heater following Ohm's Law: $\phi_{\text{heater}} = I^2Rt$, where R is the resistance of the thread in a voxel and V is the driving voltage of the heater circuit. Globally, we include heat loss to the environment using Newtonian cooling ($\phi_{\text{cool}} = -h_{\text{air}}A\Delta$)(Figure 3D). At the render phase, we take liquid crystal voxels and query the liquid crystal model with the thermal energy of the voxel to compute the final color of the voxel.

4.2 Tuning the Model

To adjust the free parameters of the model, we constructed embroidered heaters using modified e-star and e-daisy stitches, each across three sizes on a single embroidery hoop over screen printed liquid crystal – these stitches represent both simple and complex geometries. The stitches were constructed by three of the paper's authors. The length and resistance of each stitch was recorded, and each stitch was powered using a 5V input voltage and videographed. For precise measurement, we used minigrabber probes to attach a multimeter and drive current to the stitch geometries, versus applying current to the tail ends of the stitch. A simulated stitch was constructed and compared against its physical counterparts.

We found that length and resistance of the physical versus simulated stitch varied mildly as a function of the overall stitch length,

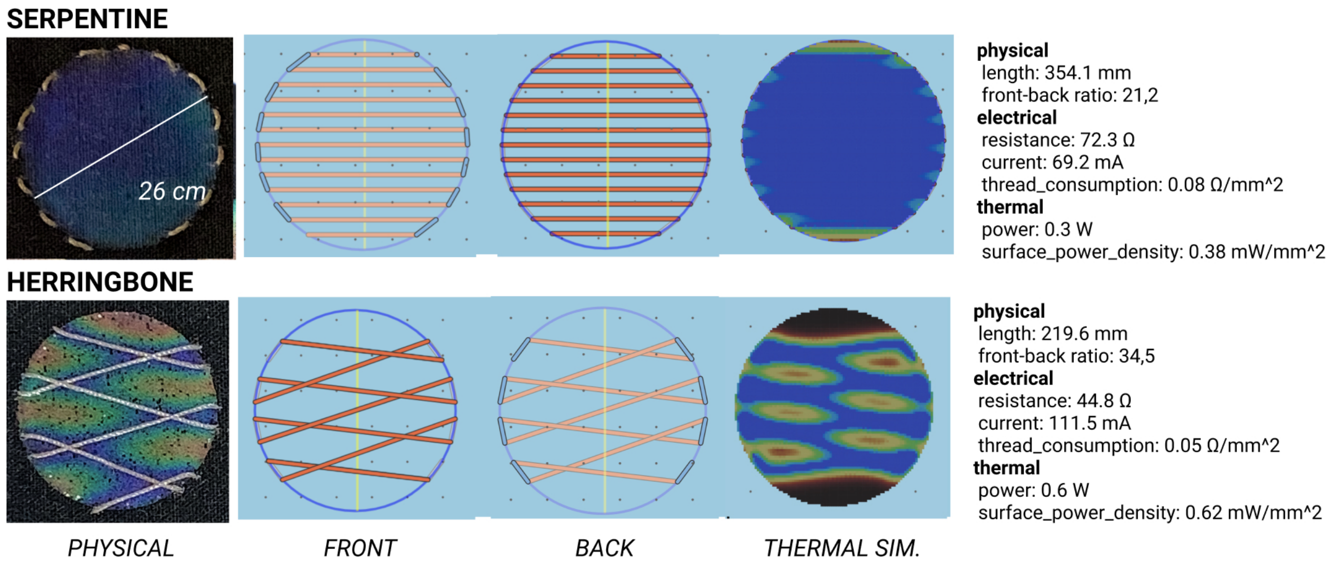

Figure 6: E-Stitchbook. 12 stitches are computationally modeled and characterized according to their physical, electrical, and thermal properties. (left) depicts the hand-embroidered stitch, and (right) the stitch shown from the front and back of the canvas alongside a thermal simulation (10 timesteps, 0.80 mm resolution)

but was not correlated to stitch size. This could be explained by the natural user variation in the tightness of the stitchwork resulting in variable resistance [MR3]. The h_{cool} and h_{cond} coefficients were tuned empirically until they visually matched the thermal webbing of the ground truth video; the results are depicted in the supplemental e-stitchbook (Figure 6).

5 EMBR DESIGN WORKFLOW

The resulting model was used to generate a computer-aided design and fabrication tool. The workflow, depicted in Figure 5, allows a user to specify embroidery designs declaratively. Within an SVG file, a user first labels high level geometries including the boundary and primary axis of the embroidery region. Each region is then named and assigned rules using stitch-specific parameters. The tool then constructs a physical model and allows the user to: 1) scrub through animated stitch construction instructions, 2) query regions for physical, electrical, and thermal properties, and 3) simulate thermal behaviors while refining stitchwork parameters.

When a design is finalized, the tool allows a user to export the design as high-level (e.g., pattern shapes) and low-level (e.g., stitch spacing) construction guides that are laserengraved onto fabric. We use a 60W lasercutter to singe the surface of the fabric at low power (1%, 50 Hz, 30% speed). Liquid crystal is then applied to the regions using a brush and hand embroidered. Each embroidered heater is cross-checked with the design tool to validate that the embroidered trace matches the target resistance. The final design is powered using a benchtop power supply and minigrabber connectors [MR2].

6 E-STITCHBOOK

To investigate the affordances and frictions of hand embroidery, we conducted a set of morphological modeling and experiments of 12 established embroidery stitches. The stitches were sourced from *DMC Embroidery Stitch Guide*, a common visual handbook that showcases 18 foundational border, fill, and edge stitches; due to limitations in the physical model, we omitted edge stitches (e.g., saddlestitch) which are mainly used to finish raw edges of fabric or integrate embroidered work with other textiles. Stitch construction patterns are often conveyed through static visuals in booklets or video tutorials - we emulate this practice by presenting the results as an e-stitchbook (Figure 6) and through interactive construction instructions using the Embr tool. The e-stitchbook serves as a resource to designers to assess different stitches' compatibility with LCTD forms. The e-stitchbook annotates each stitch with a diagram, physical, thermal, and practical results, accompanied by an interactive assembly guide.

Procedure. Each embroidery stitch was executed on a six-inch hoop with cotton fabric that had been previously screen printed with liquid crystal. For each stitch, we filled or bordered a 26 mm diameter circle. All embroidered stitches were executed with a single conductive thread with a 20 cm running head and tail that are used to connect them to the power supply. For complex stitches with overlapping elements, we modified the stitch to maintain electrical validity (i.e., not produce a short). Resistance was measured using a Fluke multimeter and minigrabber probes and measured excluding the head and tail of the heater. During photodocumentation, all heaters were activated from a variable power supply at room temperature; we used a 5V input voltage for all heaters. Each stitch was modeled using the Embr tool on an equivalent 26 mm diameter circle. The following characteristics were computed from the model: stitch length, resistance, current draw, power, front-to-back ratio, thread consumption rate (i.e., thread used per unit area), and power density (power per unit area (fill); power per unit length (border stitches)). Heat simulation images accompany each stitch,

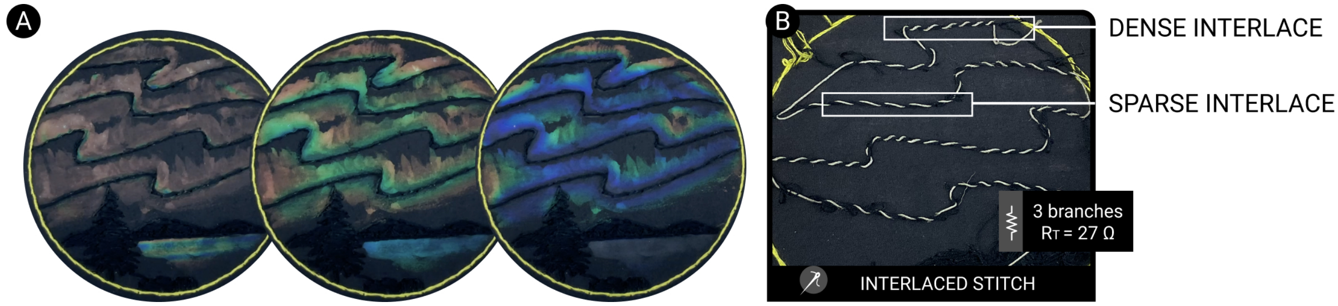

Figure 7: Aurora Borealis. (A) A heat-variant LCTD produces non-uniform regions of heat to activate the larger spectrum of liquid crystal colors over time; (B) a conductive thread is interlaced on the structure of a regular thread backstitch to reduce thread visibility.

ran through ten steps on the front face of the model at 0.80 mm resolution. The resulting e-stitchbook is depicted in Figure 6; the full e-stitchbook has been provided as supplemental material[3] and contains a rank-order of each stitch based on LCTD properties.

7 EXEMPLARS

To operationalize how the LCTD model, e-stitchbook, and tool interactions can be used together to engender novel LCTDs, we describe a set of exemplar artifacts that indicate the extensibility and expressiveness of the Embr framework and annotate the design space of LCTDs. We use the exemplars to facilitate a discussion about how Embr supports or restricts electrical, craft, cultural, aesthetic and functional expectations and concerns that are inherent to the wider range of e-textile practices.

Process. All exemplars were constructed on a 6-inch embroidery hoop on gabardine, cotton or nylon fabric. A tighter woven fabric was chosen to create cleaner stitches whereas a thicker fabric was used to enhance the visibility of engraved guidelines and prevent tears from complex stitchwork. All designs were generated as vector graphics which were then engraved on the fabric using a lasercutter. A mixture of regular embroidery floss and conductive thread was used to create hand-embroidered heaters. A benchtop power supply (30A max) and an off-the-shelf multimeter were used to power and characterize the heaters.

Each exemplar is annotated with the paths of least resistance (LR) and most resistance (MR) identified in Section 3.3 to identify how these obstacles were negotiated. *CT* denotes conductive thread stitchwork and *RT* denotes regular thread stitchwork.

7.1 Heat Density Variant LCTDs

Conductive heaters in LCTDs are typically designed to dissipate heat uniformly, leading to a synchronous color change across all regions of the LCTD. In this exemplar (Figure 7), we demonstrate how conductive heaters can be used to activate liquid crystal non-uniformly using an **interlaced stitch**. The non-uniformity can be used to access more analog expressions of liquid crystal and larger variations in color. In this design, we mirror the shades of blue, green, violet, purple, yellow and red in a figurative design depicting the *aurora borealis*, or the northern lights.

[3]https://github.com/The-Hybrid-Atelier/embr

To create the impression of shadow, the background landscape elements are filled with a black satin stitch (RT) - in this situation, the non-reactive stitchwork acts to create atmospheric depth. The lights are rendered using a whipped backstitch (RT); when seen from underneath, the backstitch provides the structural foundation to run a CT interlaced stitch on the underside of the composition (27 ohms). Due to the limited color range of CT [MR4], we found that the interlacing method allowed us to integrate the gray CT without needing to penetrate the fabric and expose the thread. The interlace stitch is used to vary the density of CT along the backstitch structure; when powered, the higher density regions heat up more quickly, creating an illusion of motion. The handedness of painted liquid crystal [LR2] allows for greater control of the amount of liquid crystal that is laid onto an area. We reflectively incorporated thicker and varied layers of liquid crystal through iteration. This exemplar navigated issues with thread visibility [MR4] by hiding the conductive thread in the back of the display and elevated a simple interlacing technique to create heat density variant LCTDs.

7.2 Thermal Generators and Insulators in LCTDs

Several stitches create concentrated regions of power generation described in the stitchbook as the surface or line power density (power/area). These stitches hold in common a low thread consumption rate – less thread is needed to accomplish the stitch which in turn creates a lower resistance and higher current draw. All border stitches fit the distinction of thermal generators as well as sparse fill stitches such as a lazy daisy (so named for the use of a loop geometry to quickly fill a space), the herringbone stitch, the serpentine stitch, and any of the seed stitch variants. These thermal generators are useful for creating "halo" effects — the high thermal density causes the immediate surrounding areas to activate quickly and travel (disperse heat) farther through the fabric. This concentrated thermal expression is also the only type of stitch that generates a thermal sensation perceivable by human thermoreceptors making it particularly viable for relaying haptic information to users through a tangible user interface.

To explore thermal generators in LCTD, we created a functional textile user interface rendering canonical play and stop buttons (Figure 8). Mirroring the visual cues found in digital buttons, we created a liquid crystal halo around each button using a running

Figure 8: Play/Stop Textile User Interface. A) an LCTD is constructed by gluing two fabric layers, each with a high-power density embroidered heater; the glue and reinforcing satin stitch border are used as thermal barriers to isolate heat to each heater's respective regions. B) A user activates the satin stitch capacitive touch electrode in the center of each button through touch; a halo region around each button indicates available actions whereas the inner button region indicates current state.

stitch (CT) – the stitch with the highest power density. This halo cue was used to communicate to users buttons that were available for input. To designate an active button cue, we added a serpentine pattern (CT) to the region under icons for play and stop. However, alone, these two heaters interacted with each other introducing parasitic heat into each other's regions [MR6]. To navigate this issue, we leveraged the structural affordances of conductive thread [LR5] to create the serpentine heater on a separate piece of fabric. We affixed the separate layer to the main fabric using a thick, tacky glue, reinforced with a satin border stitch (RT). The glue and border stitch acted as a thermal barrier, building a thermal mass that heat from respective heaters must penetrate to interfere with each other. For the capacitive touch electrode, we used the e-stitchbook characterization to elect an ideal electrode – specifically, one that provides sufficient surface area to provide contact with the skin and has a skewed front-to-back ratio so as to bias the conductive mass towards the user-facing side of the textile. In this regard, the satin stitch has the highest thread consumption rate and when modified with a serpentine construction can be largely one-sided.

The final textile UI was composed of four heaters (2 halo running stitches, 2 active serpentine stitches) and 1 capacitive touch electrode; using off the shelf motor drivers and an MPR121 captouch board, we created a dynamic touch interaction; however, challenges remain on navigating the power consumption [MR5] of these tangible interfaces, especially since a constant electric current or closed-loop circuit is needed to maintain these cues active. This exemplar demonstrates how a wider breadth of materials can be integrated into LCTDs to leverage thermal mass and thermal insulation to control thermal expressions.

7.3 Thermal Conductivity as a Sharpening or Blurring Agent

When engaging with the Embr tool's thermal simulation, having control of the conductivity of the fabric allowed us to consider how the fabric may function as a creative actor in LCTDs. As depicted in Figure 9, we found that thermal conductivity or by extension thermal mass (i.e., the thickness of the fabric) had the ability to limit the heat transfer from stitchwork that occurred in the back of the canvas. While rarely a site of creative inquiry in traditional embroidery work, the underside of electronic embroidery pieces must be attended to in order to prevent electric shorts [MR1].

To *recast* this path of most resistance, or reconfigure the problem in favorable terms, we used the e-stitchbook to identify stitches with high front-to-back biases. While more evenly distributed, the seed-stitch simulation shows a contrast in behavior that could work well for showcasing this technique. We synthesized a seed stitch on a constellation map of Orion's Belt and modified major stars in the constellations with a star stitch, allowing us to make a meaningful design variation [LR4]. The design was executed on a thicker fabric (nylon) than the other exemplars which created a similar effect to that modeled by the Embr tool. The resulting heater activated liquid crystal lines that join the stars of the constellation on the back of the fabric and reveal the constellation. The Orion exemplar (Figure 9) tackles a unique electronic embroidery challenge of executing a star stitch without shorting the heater. The modified star stitch ensures that the heater does not pass through a single point, but rather through a circular region (Figure 9B). This exemplar leverages the thermal conductivity of materials to control thermal expression; while a figurative example, this technique could be used to create calligraphic fonts with variable line weights by "heat sinking" the underside of a fabric with thermal conductors or "masking" the regions with thermal insulators [MR4].

7.4 Thermal Textures and Heat Fences

Heat fences have thermal generation properties that create a thermal halo around the thread; unlike halo elements, these heating elements are close together, and "trap" and build up thermal energy, creating interesting visual textures that extend past the halo effects. While a fence includes border stitches that surround regions like circles and rectangles, it can also be seen in spiral configurations. The *cloud-filling* and *herringbone* stitches are particularly unique in their ability to create unique thermo-visual effects more strongly suited for large outward-facing displays or output on wearables. *Heat fence* stitches allow for a one-to-one relation between the embroidered pattern and the visual effect. While these stitches are presented in a grid construction, there is also opportunity here to

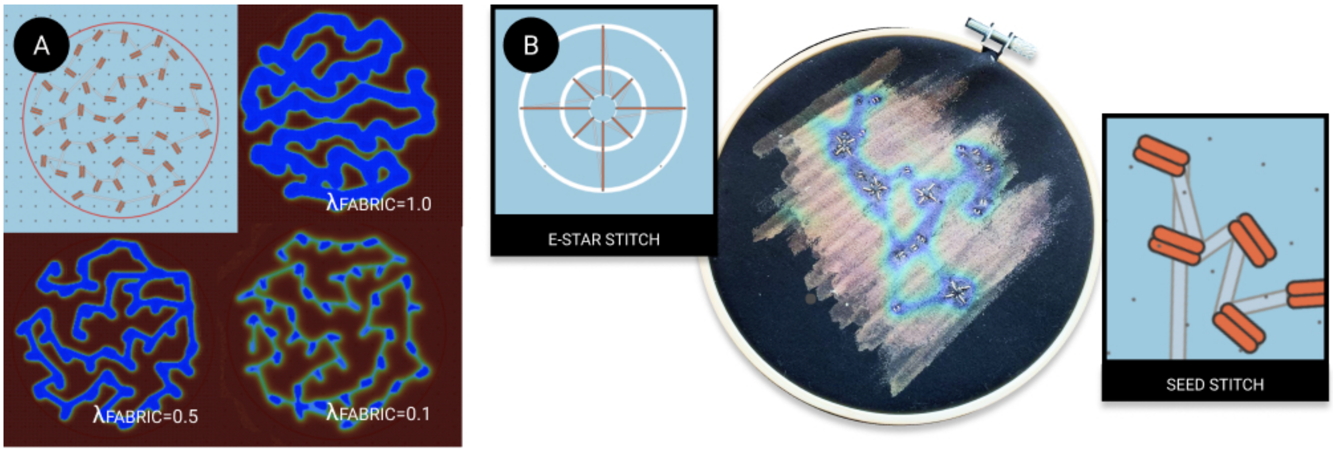

Figure 9: Orion's Belt. A) A seed stitch heat transfer simulation is run with different fabric thermal conductivity values; B) a seed and star stitch is used on a thick fabric along the points of the Orion's Belt constellation — when powered, the connected constellation becomes visible in the liquid crystal display.

explore irregular grids, similar to the expressive variability Efrat et al. [10] found in parametrically modifying smocking patterns.

In Figure 10, we demonstrate how three branches of a feather stitch can be used to trap heat within the body of "rainbow fish". Notably, the three branches do not cover the entire region but act as heat fences that activate the entire liquid crystal region. The feather stitch also mimics the scales of the fish, providing a unified visual and textural representation. The wider space of textural stitches (Figure 10B) can be used to denote other affordances, a herringbone texture may be used to denote caution (from crossing past "red tape") or a frenchknot seed could be used to denote a stopping condition in lateral haptic exploration motions. Consequently, a fly stitch with a strong central axis and directional crossing elements could be used to denote directionality in sliding interactions. The stitches used to create diverse three-dimensional forms have limited support in machine embroidery; handed embroidery expands the repertoire of textural elements in textile interfaces and provides richer haptic feedback [LR2].

7.5 Preventative and Purposeful Electric Shorting

Heat fillers denote stitches that evenly distribute heat typically achieved through space-filling curves like spiral and serpentine patterns. However, such stitches typically traverse larger distances or are close together and have a higher proclivity to create electric shorts. For instance, a *serpentine stitch* follows a common heater construction pattern that maximizes heat output over an area and is equivalent to a modified running stitch. The ingress of running stitch occurs on the frontside and the egress on the underside. This minimizes the presence of the stitch on the user-facing side. This stitch is particularly quick and easy to execute, filling a large area with low complexity stitchwork. One consideration is to maintain a short serpentine traversal, else folding the fabric can lead to electrical shorts. Long serpentine runs, however, can be secured through couching stitches.

In contrast, some heat filling stitches have more structural integrity [LR5] and are self-securing. Usually constructed in a "V" reminiscent of a bird in flight, a *fly stitch* has a symmetric front and underside pattern, but also results in a 2X thread (and resistance) consumption rate; this property can be leveraged for small heater areas to increase heater resistance. An increased heater resistance results in cooldown times being significantly longer than heat up times (measured to peak heat distribution), which may be used to create passive visual displays or notifications. The flying stitch is also well suited for long traversals along the fabric surface since a locking stitch is used to secure the midpoint of the stitch. Despite the negative connotations of shorts in electrical circuit building, purposefully introducing shorts in heater stitches yields expressive results in LCTDs. The rainbow fish exemplar (Figure 10A) benefits from elements of the feather stitch creating small electric shorts in the lock stitch. These qualities are highly dependent on an embellisher's use of tension whose results can be a site for happy accidents.

7.6 Navigating Wearable LCTDs

In order to explore the cultural diversity of embroidery practices [LR4], we created the *embellisher's glove* (Figure: 11) to foreground the hand's role in the act of embroidery [LR2], the hand's connection to ethnic and cultural traditions, and the hand's ability to tell stories through the artifacts it produces, therefore converting the act of embroidery into a performative act. Inspired by crafting gloves, we chose an olive knit solid (73% modal, 17% polyester) fabric that could be sized to compress the hand and prevent repetitive stress injuries. The glove was designed with a covered thumb and index finger to concentrate compression and protection during an embroidery practice. The pads of the fingers were fused with a silicone pad to provide friction and function similar to a thimble.

Despite the appeal of LCTDs on worn artifacts, natural body heat negates using embroidered heaters to activate the thermochromic liquid crystal [MR6]. Incorporating heat sinks or insulators in wearable artifacts can be used to minimize parasitic heat. Heat sinks

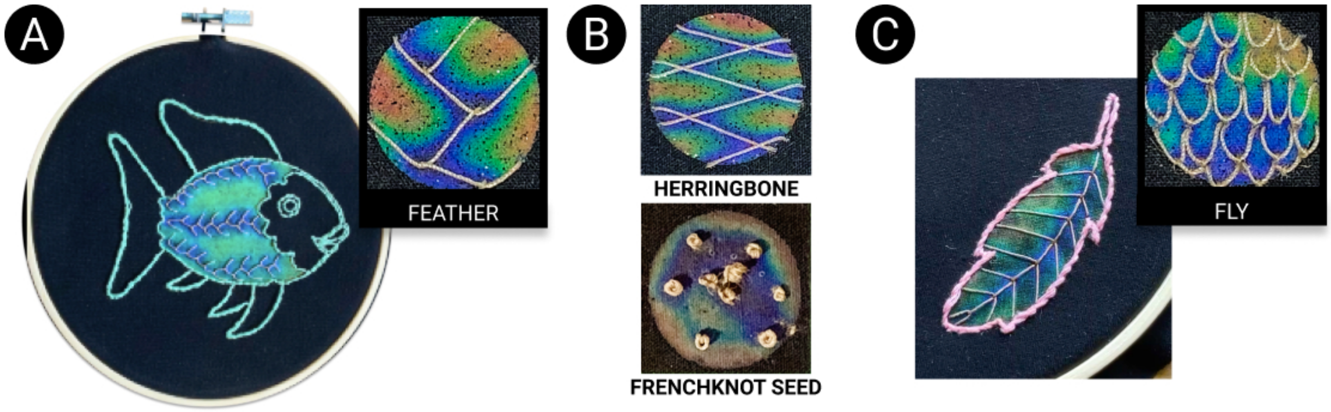

Figure 10: Thermal Textures. A) A rainbow fish design is illuminated with a visual and haptic fish scale texture using a feather stitch; B) the herringbone and frenchknot provide unique heat fence effects and haptic features; C) A feather is embellished with a fly stitch which provides a directional haptic feature useful for denoting sliding touch interactions.

describe a material that has both high conductivity and heat capacity. Acting similar to a capacitor, thermal energy can be transferred and stored in these materials and used to draw away thermal energy. In the embellisher's heated glove exemplar, we overcame body heat activation by incorporating a water-filled silicone balloon as a heat sink (leveraging water's high heat capacity). When fused to the fabric with silicone, this heat sink strategy outperformed introducing air gaps or using thicker fabrics. By incorporating materials with different heat capacities such as water, body and environmental heat can be negated to allow more controlled activation of the liquid crystal in wearable LCTDs.

To avoid limiting LCTDs to black fabric[4], a screenprinting process can be used to selectively lay down areas of black, liquid crystal, and colored regions on tightly woven or knit fabrics, emulating the process of multi-layered printed circuit boards [MR4]. Screenprinting is widely used for laying conductive traces due to its ability to deposit a uniform layer of material in a controlled and reproducible manner [24]. Our embellished glove design showcases Balochi embroidery, an ancient needlecraft practice originating from Southern Iran. For the heater, a serpentine stitch was used to fill the radial chevron motifs, or *zarif-duzi*, around the cross. We designed a standalone, worn power control board strapped to the wrist to power the embroidered heater. The act of making and using the glove made salient the different aesthetics of LCTDs (operating on background and flat surfaces) and embroidered elements (raised, colorful, and textured). While one potential is to incorporate liquid crystal thread or liquid crystal beads, there remains a fundamental disconnect between two- and three-dimensional materials.

8 DISCUSSION

In developing the Embr framework, we leveraged Sennett's pathways to negotiate the different creative trajectories of LCTDs.

[4]Alternatively, the conductive thread could have been doped in black paint and TLC, however we found this hampered the thread's ability to be embroidered in complex stitchwork without degrading from the friction between the fabric and thread

8.1 Navigating Paths of Most Resistance (MR)

In the face of difficult obstacles, Sennett describes strategies to overcome challenges that materials, tools, or situations present: (1) identifying with the most forgiving element, (2) readjusting one's behavior to tolerate unexpected complications, or (3) recasting, or reconfiguring the problem so that the antagonist becomes the protagonist [49].

Navigating electrical shorts. In Embr, the proclivity of threads to short from accidental contact with each other [MR1] limited the potential for reliable heater designs in LCTDs. We *tolerated* this MR by first modifying stitches to remove overlapping regions, using lock stitches to hold long stretches of thread in place or encapsulating a conductive thread in a satin stitch of regular thread. However, some fill stitches could not be modified to remove potential shorts; often, these shorts were probabilistic, dependent on the specific amount of tension in the stitchwork.

As an alternative, we *identified with* the most forgiving element of the conductive thread – the thread can easily be incorporated into existing stitchwork and traverse between the front and back of the textile, lending itself well with couching and interlacing techniques (e.g., *CHI* exemplar). These techniques allowed us to hide the thread in the back of the LCTDs and provided method for us to edit conductive embroidery patterns. In the *Orion's Belt* exemplar, we leveraged the seed stitch's even traversal between the front and back of the fabric to minimize the presence of electric shorts.

Lastly, we leveraged *recasting*, to view shorting as a desired effect. While the design of the *Rainbow Fish exemplar* still protected against catastrophic shorts, the shorts inherent in overlapping elements of fill stitches provided sites for probabilistic shorts. We demonstrated how purposeful shorting could be used to create happy accidents in the thermal expression of scales on a fish figure.

Finding patience in hand construction. In our textile user interface example, we demonstrated how a layered textile circuit construction strategy could be used to create a four-heater design. While the Embr tool was designed for modeling a single textile layer, we

Figure 11: The Embellisher's Glove. A) A simplified glove design is controlled from an external power controller worn on the wrist; a silicone balloon with water forms a barrier between the user's hand and the glove, preventing body heat from activating the LCTD; B) the LCTD activated using a serpentine stitch; C) the glove cycles through its thermal expression as the embellisher works on an embroidery design, serving as a calming ambient display.

see opportunities to expand these capabilities to address 3D circuit constructions. One critical challenge was the need to engage in "thread management", already encountered in traditional electronics but made more devious by a thread's tendency to entangle and knot. While using a running stitch is the most common approach, we found that this approach makes it especially difficult to edit sewn circuits. We altered our approach to readjust for the obstacles faced from thread management. Instead, we use a non-conductive thread to create "couching" points; a conductive thread is then laced through these couches. There is significantly less complexity in pulling out a laced thread which provides the flexibility needed to reroute circuits during electronic embroidery. An alternative solution could be creating textile "breadboards" with conductive power and ground rails already sewn on a separate fabric panel. Interfacing this breadboard with the embroidery fabric could leverage the structural affordance of thread [LR5] to move easily between multiple layers and minimize errors from loose thread causing shorts [MR1].

8.2 Complicating Paths of Least Resistance (LRs)

As an alternative strategy, Sennett identified that craft can develop from the practitioner purposely adding complexity to the deceptively simple elements of a practice. Adding complexity serves as a technique for inquiry, engaging the practitioner to realize that there is more than meets the eye [49]. In Embr, we leveraged conductive thread's status as a foundational material in e-textile toolkits and its simple use (e.g., largely as a running stitch) as a site for creative inquiry [LR1]. We introduced complexity by exploring how conductive thread could operate in more ornamental stitchwork constrained by the electrical properties of conductive thread and the thermal needs of liquid crystal. Our exploration revealed a range of thermal expressions and material configurations to extend LCTDs as an e-textile practice.

LCTD as a Hello World? We demonstrated how a unified model for LCTDs could be used to characterize the physical, thermal, and electrical properties of different stitches in an e-stitchbook and operationalized how the stitchbook could be leveraged to provide control over thermal expressions. When compared to the traditional Hello World circuit in entry e-textile workshops (i.e., a LED connected with a running stitch to a sewn battery), LCTDs present a unique opportunity to provide users with a wider range of expressions and reinforce their understanding of electricity and thermodynamics [LR1]. LCTDs still have the same operational components as a Hello World circuit (a resistor and visual output), but with more open-ended and directly manipulable materials - both the visual output and resistive element are controlled through handed interactions with ink and thread [LR2]. This carries additional implications for defamiliarizing electronics, especially by causing users to reexamine blackboxed components like resistors as an interplay of conductive and thermal materials. However, design and construction errors in the conductive thread circuit, such as causing a short by threads overlapping each other or exceeding the power tolerance by providing too high a current, can lead to burn risks as the conductive thread overheats. While the consequences of such errors are potentially more severe than that of a wrongly constructed LED circuit where the LED simply acts as a fuse, we mitigated these risks using our CAD tool by identifying potential shorts and power hazards in the users' designs prior to implementation. One strategy for improving safety includes adding thread interconnects on the embroidery hoop itself that interface with a power supply – when coupled with safety fuses, these interconnects can prevent excessive current to the electronic stitchwork. While LCTDs access electrical and physical qualities, LCTDs as a Hello World project could be further coupled with work on e-textile sensors and electromagnetic behaviors (e.g., within textile speakers).

Revisiting Machine Embroidery. Machine embroidery has been extensively incorporated with electronics circuitry in a wide range of e-textile applications [1, 2, 11–13, 25, 29, 36, 45, 57]. In this work, we stepped away from machine embroidery to explore and address the challenges of hand-embroidery to allow access to larger cultural influences in creating meaningful textile displays [LR5]. However, machine embroidery is often preferred to hand-embroidery owing to its speed, efficiency, precision of stitches and scalability. Our focus on hand embroidery is aimed at creating a more experiential e-textile experience, but opportunities exist to extend designs created using Embr into machine embroidered production. Stitches with a large front-to-back ratio (i.e., side bias) can be visually reproduced using machine embroidery since a machine stitch biases thread to be either on the top or bottom of the fabric. As a middle ground, machine embroidery can be used to add structural stitches to a textile where conductive thread can then be hand-embroidered using couching, interlacing, or weaving techniques.

8.3 Limitations

We scoped this work to liquid crystal displays on embroidery hoops, however, several other frictions exist in integrating embroidered pieces onto other textile interfaces. The embellisher's glove was used to communicate some of the unresolved challenges with integrating textile interfaces onto worn artifacts. Amongst the unresolved elements is the high power consumption of LCTDs [MR5] which limits the range of applications that can support these types of displays. Alternatively, bi-stable thermochromic ink could be used which does not require a continuous power supply [47]. We also used one type of conductive thread, although a variety of formulations exist - specifically, shape memory alloys could further enhance the capabilities of LCTD with shape-changing qualities, although new frictions are introduced from the tight bends of wire needed in embroidery work. The LCTDs fabricated in this paper used an off-the-shelf power supply and mini-grabbers used in digital logic circuits to interface between soft and hard electronics [MR2] - it remains an open question how to mitigate these thread-to-component connections; we see potential in using magnetic interconnections [16] between electrical components and conductive thread to allow e-textiles to more readily interface with existing electronics infrastructure.

9 CONCLUSION

This work presented a negotiation of frictions and opportunities in integrating hand-embroidery and electronics practices in the design and fabrication of liquid crystal textile displays. Using a lumped model to represent the physical, electrical, and thermal properties and behaviors of LCTDs, we created an e-stitchbook characterizing 12 common embroidery stitches. The model was also used to drive a computational design and fabrication tool that allows for interactive assembly and declarative construction of stitches onto embroidery regions. Through a set of exemplar artifacts, we operationalized how the e-stitchbook could be used to control thermal formgiving by leveraging thermal mass, thermal conductivity, and thermal insulation in hand-embroidered compositions. We discussed the potential for LCTDs in augmenting the Hello World e-textile workshop, especially as a means to aid in foundational development of material literacy, in allowing for experiential encounters with materials, and in further defamiliarizing electronics to spur creative inquiry and curiosity.

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