AdaCAD: Crafting Software for Smart Textiles Design

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ABSTRACT

Woven smart textiles are useful in creating flexible electronics because they integrate circuitry into the structure of the fabric itself. However, there do not yet exist tools that support the specific needs of smart textiles weavers. This paper describes the process and development of AdaCAD, an application for composing smart textile weave drafts. By augmenting traditional weaving drafts, AdaCAD allows weavers to design woven structures and circuitry in tandem and offers specific support for common smart textiles techniques. We describe these techniques, how our tool supports them alongside feedback from smart textiles weavers. We conclude with a reflection on smart textiles practice more broadly and suggest that the metaphor of coproduction can be fruitful in creating effective tools and envisioning future applications in this space.

CCS CONCEPTS

• **Human-centered computing** → *User interface programming*.

KEYWORDS

Smart textiles; computer-aided design; weaving;

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1 INTRODUCTION

By seamlessly integrating sensing and actuating capabilities into a textile at the yarn-level, smart textiles allow flexible electronics to look and feel like traditional textiles. Thus, when designing smart textiles, one has to consider the appearance and function of the fabric and electronic components in tandem. As such, a smart textiles weaver is presented with new design considerations and challenges, such as the need to understand the connectivity of the circuit components in addition to the fabric structure and pattern. Some smart textiles developers address these challenges by collaborating with textile craftspeople and/or learning to translate their designs into software that lacks fundamental support for the design decisions they must make. Additionally, it can be hard to access advanced textile design tools outside of professional textile production contexts or institutions.

As this domain grows, there is a need for new tools that foster community between multiple fields of expertise and are accessible to a range of skill levels (for circuit designers and/or weavers). As Posch and Fitzpatrick argue, "Using

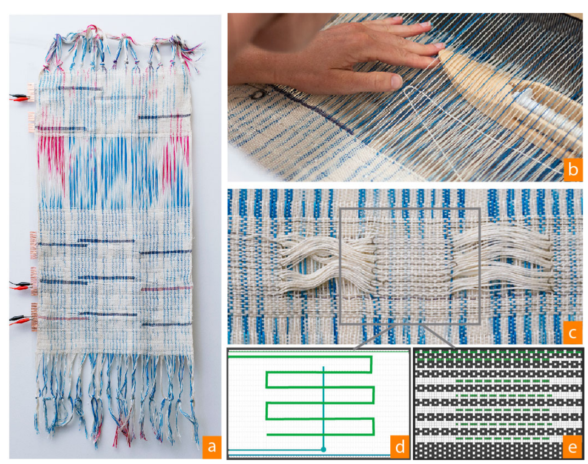

Figure 1: AdaCAD supports the design of woven smart textiles by augmenting traditional weaving drafts with smart textiles specific operations and views. We used the tool to create a prototype we developed with multiple regions of touch sensing and color change (a, b, c). AdaCAD allowed us to view the design as yarn paths (d) or traditional weaving drafts (e).

existing tools from either domain [textiles or electronics] thus inherently ignores essential aspects of electronic textile making processes" [44].

This paper presents AdaCAD, a web-application we developed to support designing woven structures and circuits in tandem. In departure from existing weaving tools, AdaCAD offers specific features to help overcome the unique challenges that come with designing woven circuitry, such as understanding yarn connectivity and built-in support for common smart textiles techniques. We describe our software and its novel features, present examples of smart textiles that can be created using these weaving techniques and practices, and reflect upon feedback from interviews with five practitioners in the smart textiles field.

Our design process combined our first-hand experiences learning to weave smart textiles with the development of a design tool for smart textiles. Through these concurrent processes emerged an interesting conversation between the code, yarns, loom, and weavers past and present. We describe this process as a craft coproduction [15] to acknowledge and discuss the different human and nonhuman/material agencies involved in smart textiles weaving. We discovered through our interviews that our beginner practices were not entirely different from those more experienced with smart textile weaving–both being highly playful and improvisational. This beginner's perspective allowed us to become attuned to these agencies involved in both design and fabrication and we suggest that designing for beginner practices (rather than focusing on experts as the gold-standard) may be particularly useful in textile design contexts. Lastly, coproduction puts our work in conversation with rich histories of technical weaving; inspiring us to consider how these histories, the present community, and a CAD tool could support one another.

2 RELATED WORK

Histories and Applications of Woven Smart Textiles

Within HCI there has been growing interest in leveraging fabric-based forms of sensing and actuation for on-body interactions (e.g. [26, 27, 38, 51, 52, 54]) or interactions with objects that are typically formed from textiles [9, 53]. The integrated nature of smart textiles offers designers a wide range of aesthetic and functional properties in these domains. While techniques for smart textiles production often utilize weaving [10–12, 14, 18, 33, 45, 56], knitting [31] and embroidery [45, 46], our project focuses specifically on weaving smart textiles. The structure and fabrication processes of weaving offer weavers control over the tension of "smart" components, which tend to be brittle and break under higher tensions in knitting and embroidery. Furthermore, woven fabrics tend not to stretch, allowing for more constructed and stable designs suited for tailored clothing, upholstery, or housewares. Researchers in a range of fields have already leveraged weaving to create textiles that sense temperature and touch [38, 47, 52, 56], change color or shape [48], harvest energy [30], and even reimagine logic gates [45]. These projects involve integrating "smart" threads such as conductive (e.g. [56]), shape-changing (e.g. [52]), or color-changing yarns (e.g. [11]) into the structures of fabrics.

While woven smart textiles applications like Project Jacquard [47] have received popular attention within HCI, there has been significant amounts of exploration conducted by artists, craftspeople, and designers beginning as early as 1998 [37, 46]. Yet, one can look even further in history to align smart textiles with historical practices of weaving with metallic fibers, as demonstrated by Daniela Rosner's retelling of the production of woven core memory [49]. This lineage helps us understand smart textiles as less of a new or "disruptive" form of technology, but as a next step along an already rich history of textiles informing both the structure [17] and metaphors that define modern computing [34]. The name of our software, AdaCAD, honors this lineage by taking its name from Ada Lovelace. Lovelace worked with Charles Babbage on the production and use of the Analytical Engine which, as she described in 1843, "weaves algebraic patterns just as the Jacquard loom weaves flowers and leaves" [5]. Acknowledging these histories allows weavers of smart textiles to create innovative designs while also attending to the complex and interwoven lineages of textile manufacturing and technological innovation [17].

Fabricating Smart Textiles

Producing smart textiles requires forms of design and fabrication that accommodate the unique properties of fibers and yarns. For instance, Hudson reimagines 3D printing in fibers by creating a 3D printer that felts fibers [20] and Peng et al. explore fabric constructions that layer flexible fabrics with circuitry components [39]. Other examples of fiber/yarn-based CAD and fabrication tools include innovations in knitting 3D forms, by hand [21, 35] or machine [32], as well as novel platforms for generatively designing of silkscreen patterns [24] or gathering fabrics [16]. Yet, within this emerging field of "hybrid" craft (e.g. [21, 36]), there do not yet exist CAD tools that support users in weaving circuitry into their fabrics. As such, smart textiles development often requires collaboration between textile craftspeople and technologists (as in [55]) or dual skillsets in both fields (as seen in practitioners such as Irene Posch, Mika Satomi, or Hannah Perner-Wilson). They also require the designers to work across platforms for weaving design (using software like WeavePoint, ArahWeave, PointCarré, JaqCAD, etc) and circuit design (e.g. Fritzing, Eagle). The lack of unifying software that supports both woven design and circuitry can

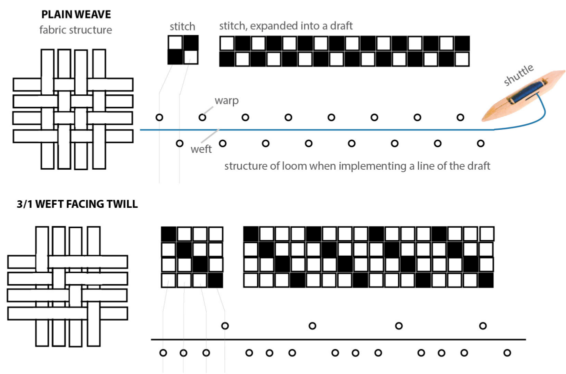

Figure 2: Descriptions of how a weave draft represents a woven structures and how a loom implements those drafts to create those structures

hinder not only how one plans and executes their designs, but also how they document and share their designs with a broader community, which some have argued is a core value shared by smart textiles researchers [19, 40]. AdaCAD attempts to address this by adding circuitry specific annotations and views to traditional weaving patterns or "drafts." Our software is designed to communicate with a TC2 Digital Jacquard loom [36] but the designs could also be realized by handweaving. In the words of Bauhaus weaver Anni Albers, "Any weaving, even the most elaborate, can be done, given time, with a minimum of equipment" [8]. Digital Jacquard looms are becoming increasingly accessible, as a TC2 costs roughly the same as a high-end 3D printer. Services like WOVNS [2] use Jacquard looms to aid the production of woven prototypes, modeling send-out services like Shapeways [6] or Ponoko [3]. Projects like Pamela Liou's *Doti* [29] work towards open-source kits for DIY Jacquard looms. Furthermore, textiles specific maker spaces and programs such as the "textile academy" [4] take up fablab logic to make textiles fabrication more accessible. We see the emergence of new weaving technologies and spaces as a long-overdue contribution to the "maker movement," bringing advanced textile production alongside innovations in solid modeling and end-user electronics.

Weaving Process and Key Terminology

A woven fabric is created by interlacing yarns in perpendicular directions (Fig. 2). Yarns that run the length of the fabric are referred to as the warp (up and down), and yarns that span the width of the fabric are called the weft (left and right). Before any weaving takes place, the weaver must "warp" the loom (i.e. set up the warp yarns so that they are parallel and under even tension). Then during weaving, the weaver and/or loom select certain warp yarns to raise, creating a space between the yarns called the shed. Weft yarns are inserted through the shed, usually aided by a shuttle carrying the weft yarn (Fig. 2). The sequence in which the shuttle travels over and under the warp determines the visual and textural pattern of the fabric. This pattern is represented as a draft, a two-dimensional representation of fabric structure with solid/black cells representing a raised warp (i.e. weft travels under warp) and white cells representing a warp that is not raised (i.e. weft travels over warp).

3 THE PROCESS OF DESIGNING ADACAD

Friske built AdaCAD with the goal of using it to interface with a TC2 Digital Jacquard loom, which can read drafts as bitmap files, interpreting each pixel in the image as a command to raise and lower warp threads in specific combinations. While the loom controls the warp, the TC2 still requires the weaver to throw the shuttle through the warps to interlace the weft. As such, the weaver is still physically involved in the production of the textile. In parallel to developing the software, Friske used her own experience learning to weave and implementing patterns to inform the kinds of operations the software should support. Because we built the bulk of the software prior to receiving our TC2 loom, we tested our software and drafts by interpreting them by hand on other kinds of looms, manually "performing" as though we were Jacquard looms. Friske continually tested drafts by hand-weaving them on a rigid heddle loom. Wu attended a weeklong Jacquard weaving workshop where they learned to design weave drafts in Photoshop and produce those drafts on a TC2 loom. They later tested the software by using it to design and implement several smart textiles prototypes. Devendorf contributed by iteratively designing drafts and weaving prototypes on an 8-shaft loom. Our collective experiences helped us understand, from a conceptual and embodied perspective, where design tools could be most effective in supporting smart textiles development. Through these process, four key principles emerged:

Prioritize Drafts over Simulation

The draft (Fig 2) can be understood as describing the state of the loom during weaving rather than a blue-print for the look and feel of the resulting fabric. By analogy to other forms of additive manufacturing, drafts may be thought of as G-Code, a programming language used often by 3D printers, rather than a 3D model. The draft will specify a fabric's structure, but the aesthetic, texture, and "hand" is emergent from the interplay of yarns with various colors, textures, and material properties. Because of the complexity of fibers, the results of weaving often differ from the weaver's intent. As such, the process of following a draft involves a conversation between the weaver, material, and loom. This conversation is a friendly exchange with the weaver as a participant—managing yarn-tensions and making choices about the emergent form of the textile. Early iterations of AdaCAD focused on trying to simulate the look of the final design. However, we found that this made limiting assumptions about how the user would be weaving since its accuracy still relied on the user's ability to understand how the fabric would behave structurally. We learned that the visual appearance is both an intuition to be developed and an experience in the discovery of what happens at weaving time.

Support Smart Textiles Techniques

Through our practice and surveys of related work we discovered that smart textiles weavers tend to utilize a common set of techniques such as double weaving (e.g. [1, 33]) and supplemental warps and wefts [41]. Some of these techniques are easy to represent in existing pattern drafts. Others can be understood as "hacks" that are not represented on present forms of drafts. Thus, our software is made to more robustly accommodate these practices.

Visualize Yarn Paths

Drafts function as a set of instructions or for creating a weave. They do not show the paths of the individual yarns within the weave. When integrating circuitry, these paths are especially important to view in order for the designer to analyze connectivity of "smart" yarns. We felt that the user should be able to augment the draft view to visualize and plan the paths of "smart" materials (i.e. thermochromic yarn, conductive material) in relation to standard yarns (i.e. cotton or wool).

Adapt from Weaving Software

We felt there to be a benefit in adapting conventions in current weaving software to include circuit design instead of adapting circuit design tools to include weaving design. Current weaving design tools are based on designing drafts, which are an established and entrenched way of communicating information between weavers or a weaver and a computational loom. By supporting drafts, AdaCAD is better able to integrate into these flows.

4 DESIGNING SMART WOVEN TEXTILES WITH ADACAD

AdaCAD is a web-based tool that allows users to design weave drafts for smart textiles. Our application is an Angular project. We chose Angular, a JavaScript framework written in Typescript, because of its data-binding capabilities and the ease of integration with libraries from Node Package Manager (NPM). We chose to distribute the application on the web to make it accessible to a wider majority of people. We plan to make the code available for free on a platform such as GitHub under a GNU General Public License (GPL), inviting a growing community to enhance the features of AdaCAD[1]. Upon launching AdaCAD, a user is prompted to select the number of warps and ends per inch (EPI) for their weave, two numbers that are preset on the loom by the weaver before weaving. Next, they see a two-dimensional grid of cells (an empty draft) and a set of operations for: drawing on this draft; importing images to the draft; and downloading their pattern in human and machine-readable formats (Fig. 4). We offer more detailed descriptions of the design operations, views, and features below.

Support for Standard Weave Design Operations

We designed several operations which are common to our software as well as existing weaving design tools. Some operations work on a single grid square. For instance, a user has options to fill, erase, or invert a single grid-square using the point, erase and invert brushes respectively. Other operations work on a larger selected area. These operations begin with selection, where a user clicks and drags to select a region of the weave draft. While dragging the selection, the user is informed of the total number or wefts and warps in their selection (Fig. 5a), which is helpful when working with patterns that repeat in specific intervals. Once a region is selected, they can copy it into a temporary stitch. This temporary stitch can be pasted into a new or the same selection. Users can also paste inverted or flipped versions of their stitch (Fig. 4). Within a selected region, the user may insert a stitch using the fill and mask operations. A fill inserts the stitch into the selected region, repeating that stitch as necessary. Mask applies the stitch only to cells that were filled in the original selection. This operation supports users in defining patterned regions to fill with a common stitch. We also offer users several "row" or weft-based operations. Using buttons that dynamically appear next to a row over which the user is hovering, the user can easily insert a row, clone a row, or delete a row (Fig. 5).

Lastly, weavers often utilize and repeat predefined stitches (e.g. twill, double weave, sateen, etc.) to create drafts. Arahweave allows users to correlate a stitch with a specific color of an imported image. Some Jacquard weavers use Photoshop to do this by importing pattern brushes, making selections and then filling that region with the pattern [50]. To support this common practice, we included a stitch library in our software, which contains stitches that can be used by the fill and mask operations.

Novel Operations for Smart Textiles Design

In addition to supporting many common features of weaving design software, the following operations offer specific

[1] https://github.com/UnstableDesign/AdaCAD-weaver

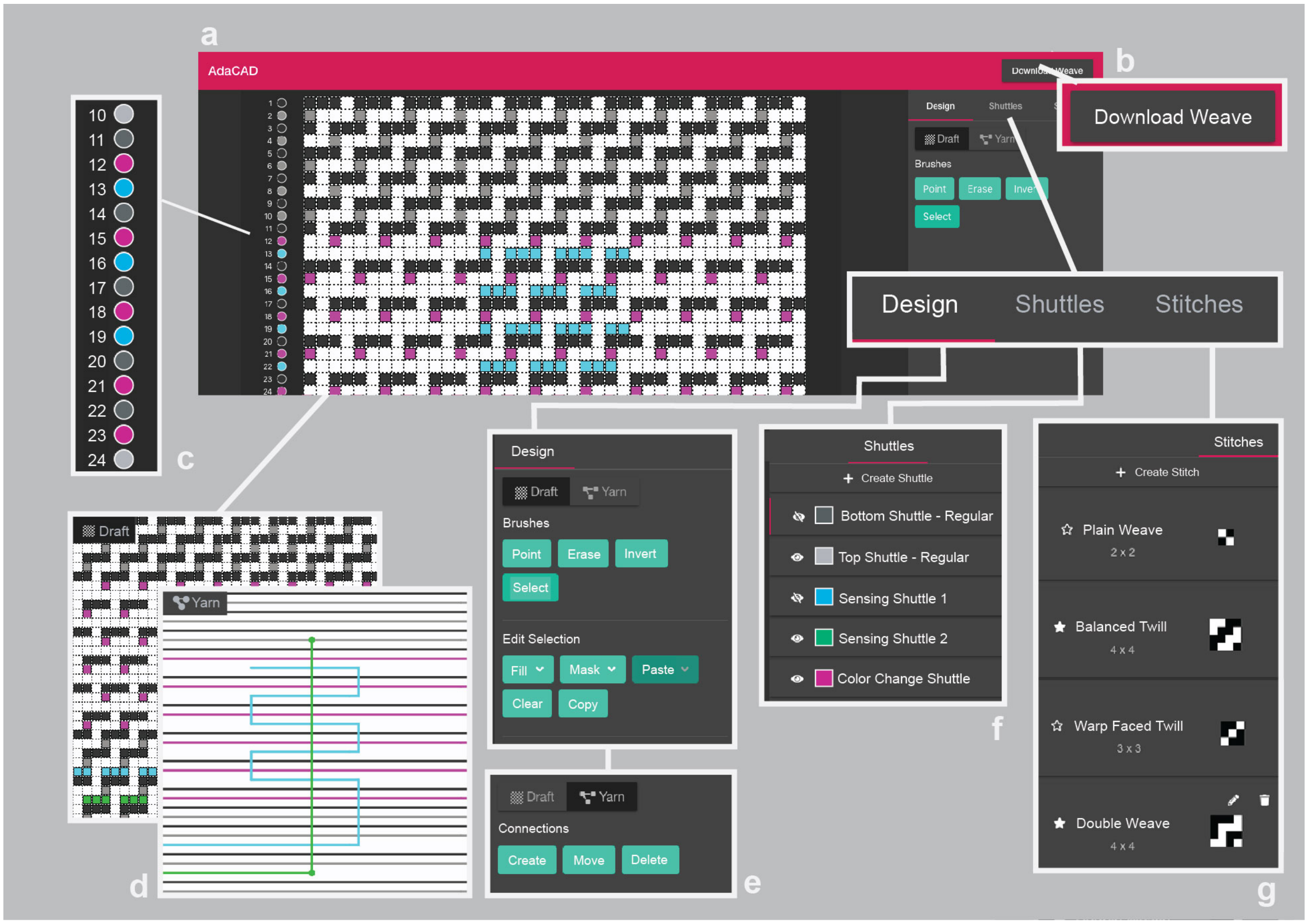

Figure 3: An overview of AdaCAD. (a) the main view panel. (b) a download button allows users to export the draft. (c) row numbers and indications of the shuttle to be thrown at that row. (d) users can visualize their design as a draft or as yarn paths (e) design operations (e.g. fill, mask, copy, paste) associated with the draft and yarn views. (f) a list of user defined shuttles, with options to show or hide. (g) a stitch library allows users to create, edit, delete and "favorite" stitches.

support for the needs of smart textiles weavers. We begin by describing each feature in general and will illustrate how we employed them in the "Workflows and Examples" section:

Designing using Shuttles. Many weavers, in both industrial and handcraft settings, use one or two types of yarn throughout a design. Smart textile weavers often design with a mix of conductive and non-conductive yarns to achieve the desired functionality and structures for their pieces. While options for conductive yarns continue to improve, it is still impractical to weave solely with conductive yarns as they have yet to match traditional yarns in elasticity, cost, tensile stretch, texture, and other properties. To better accommodate designs using multiple yarns, we designed AdaCAD to distinguish between different "shuttles" of yarn.

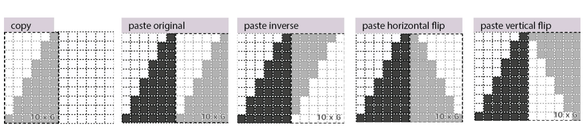

Figure 4: a user can copy a section of their weave and paste it as a copy, inversion, or horizontal and vertical flip

Shuttles within AdaCAD represent one continuous piece of yarn and correspond to the physical shuttles used in weaving to pass the yarn through the shed (Fig. 3). For instance, a user can define one section of their weave to be created using a shuttle of white cotton yarn, and other sections with a different shuttle of conductive yarn. When adding a shuttle to one's weave, the user has the ability to define properties, such as: yarn type to denote different "smart" and regular materials; labels to denote where the ends of the shuttle would be routed on a circuit (ground, A0); and the direction from which the shuttle first enters the weaving (e.g. from the left or right side of the fabric).

A user can assign sections or rows of their draft to shuttles by clicking the colored circle icon to the left of each row (Fig 3c). Once draft rows are assigned to a shuttle, we allow the user to show or hide multiple shuttles from the view of the weave (similar to how Photoshop allows one to hide layers). Hiding and revealing shuttles makes it easy to customize the pattern or path of one yarn, say a conductive yarn, independently from the other yarns in the weave. It also allows the user to focus more on individual sections or related components within their weaves, rather than having to work exclusively on the global pattern.

Describing Yarn Paths. AdaCAD offers two view options for the user while creating the weave draft: yarn view and pattern view. The pattern view is used to design the draft itself, while the yarn view shows the path of each continuous piece of yarn. Thus, the pattern view shows the traditional weave information while the yarn view shows a schematic view like one might see in Eagle or Fritzing. Jacobs suggests that linked views in CAD tools support viewing the design through multiple lenses [23]. In our case, these lenses are those of a weaver and a circuit designer.

The primary purpose of the yarn view is to aid in visualizing the connectivity of the circuit components: the yarn view helps a smart textiles weaver assess whether or not their yarns are going to cross or short; it offers insight into how the human ought to execute the pattern by showing them, for instance, whether or not they should pass the shuttle into the weave on the left or right side to achieve their desired structure; And lastly, the yarn view includes labels on the ends of the yarn path for planning connections to elements like PCBs and microcontrollers.

Inserting Supplemental Warp Connections. Supplemental warps, one of the more common smart textiles techniques, are warp-oriented yarns that do not run the entire length of the fabric. They are used because conductive or other "smart" threads are hard to integrate into the entire warp, as they tend to break under tension and may produce undesirable effects in the fabric texture. Thus, smart textiles weavers use hand techniques to insert small segments into the warp as they are weaving. To symbolize this procedure within a draft, we utilize the yarn view. When a user is within this view, they can create a vertical "connection" in the warp, define where it lies, and what shuttle it uses. This allows the weaver to encode not only machine specific operations into the draft, as well as hand-modifications to realize certain designs.

Importing Images to Shuttles. AdaCAD supports the ability to import an image when creating a new shuttle, assigning that image to a unique and continuous piece of yarn. When the user imports an image, the software creates a draft based on the image. Specifically, if maps pixels over predefined threshold as an black or raised warp within the corresponding draft cell. It inserts that image on a new shuttle, row by row, in between the existing weft rows. By assigning that image to a shuttle, it associates a design with a particular material. As such, one can upload an image of their conductive paths through a fabric, or an image that will "appear" when a color-changing yarn is given power.

Workflows & Examples

In this section, we present prototypes of smart textiles, which we realized by creating and documenting drafts using AdaCAD. To demonstrate how these features are integral to the smart textiles design process, we will describe a few of our workflows and examples in order of complexity:

Woven Press Button. This first example demonstrates a common technique in smart textiles: creating press buttons by leveraging the 2-layer structure of double weaving [1, 11]. Double weaving allows for the integration of 2-layered pockets or tunnels within the structure of a weave. By adding conductive materials to these pockets one can create press buttons. Furthermore, one can insert a piece of piezoresistive fabric between the layers to create force-sensitive resistors [1].

We invite readers to carefully review Figure 5 and its caption in order to learn more about how we designed this structure using AdaCAD. To fabricate this draft, we could interpret each row by hand or export the design to our computerized loom. In both cases, we would follow the "picking" order on the left side of the draft to understand which shuttles we should throw through the shed when we reach each row. As we demonstrate in the next example, a double woven press button may be used to signal change of state in the smart textiles, allowing for a transformation of appearance.

13-Region Touch Weave. The second design is much like the first, but is more complex in its visual patterning and structure. This weave contains 13 distinct regions that couple a press-sensor (described above) with a region of color-changing thermochromic yarns (Fig. 1). Though this example using rectangular regions, this prototype shows how thermochromic yarns and press-sensors can be coupled to change patterns. We imagine this same coupling could be used to switch between patterns, such as paisley to polka dots.

The entire fabric is double woven, ensuring that the color-changing visual pattern appears on the top/visible surface while the press pads sit on the bottom/hidden surface. Adjusting the visibility of the shuttles was critical in this example, as it allowed us to draft the visual pattern on the surface independently from the press regions on the bottom. The yarn view helped us make sure that our color-changing yarns

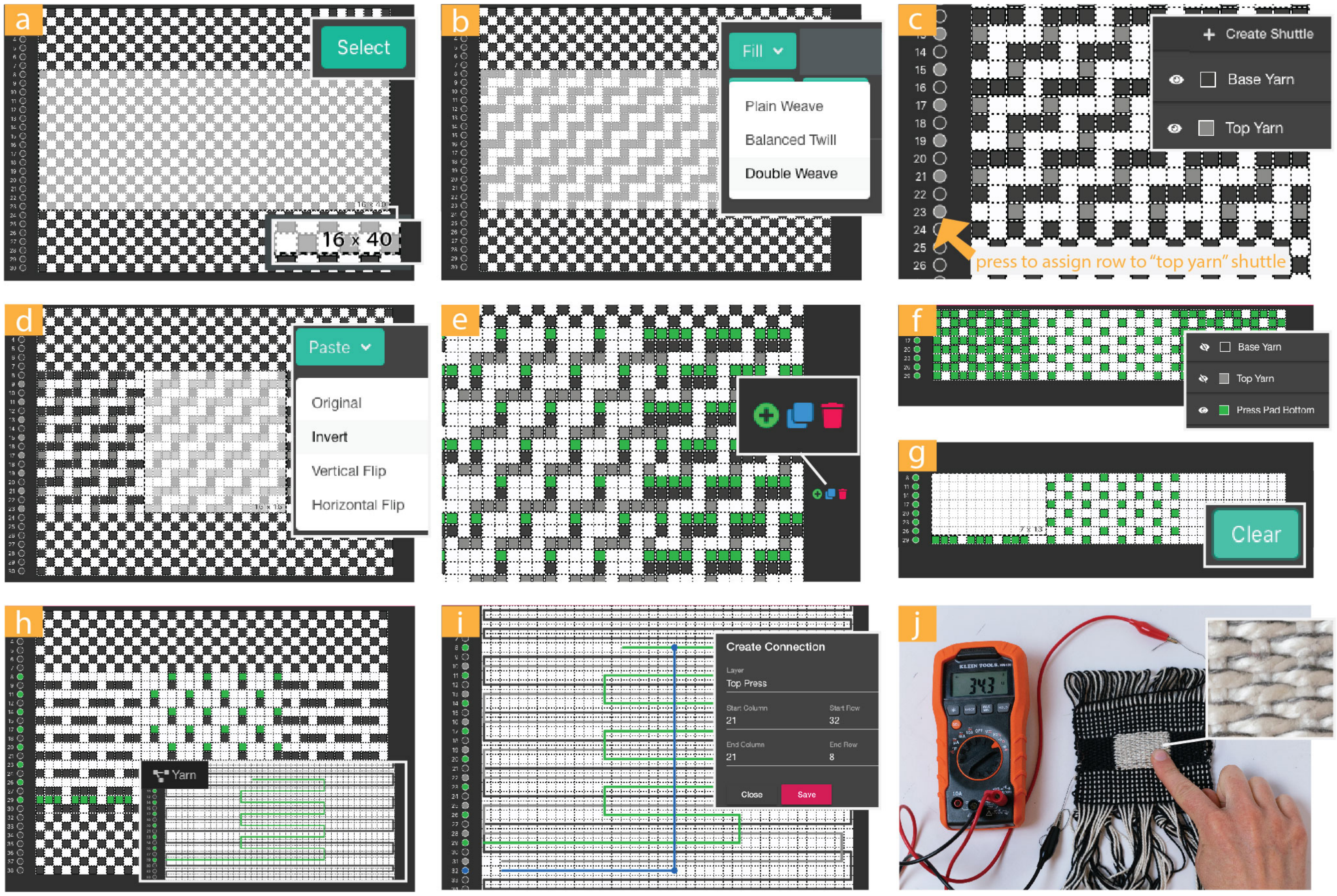

Figure 5: A workflow through AdaCAD to design a smart textile press sensor. (a) The user initializes a weave, selects all cells, and "fills" with a plain weave stitch. (b) Next, they select a region to "fill" with a double weave stitch. (c) They create a new shuttle to signify that the top layer of the double woven pocket will be separate from the bottom. Once they create the shuttle, they assign it to the appropriate draft rows. (d) They select and "invert" a square in the middle of the row to create a more structured pocket. (e) Now they are ready to integrate their conductive yarns. They duplicate the rows corresponding to the bottom layer of the pocket and assign them to a new shuttle of conductive yarn. (f) They hide all shuttles except those corresponding to conductive yarn. (g) Next, they clear the stitch from the right and left regions except for the last row where the yarn "exit" the side of the fabric (h) Then, we analyze this structure by switching to yarn view and seeing that the path of the conductive element in the base layer conforms to our needs. (i) To complete the button, they need to integrate a warp-oriented conductive yarn on the top layer. They create this using the "connection" feature. (j) Final product is woven to create a press button. The detail shows the bottom layer stitch that integrates cotton and conductive yarn.

would properly interlock with our non-color changing yarns to create a seamless look of integration on the surface of the fabric. The yarn view was also instrumental in ensuring that the conductive yarns to sense presses could be routed to the left side of the fabric in a way that ensured that they would not cross. Documenting our pattern in this way allows us to have a more robust representation to share with other designers and researchers [2]. Previous attempts to draft with Illustrator and in Excel were unsuccessful. AdaCAD's shuttles and yarn view were instrumental in capturing the complexity of the pattern and construction (which required up to 12 shuttles to be in use simultaneously).

Multi-Component Weave. The Multi-Component Weave example shows how a woven smart textile can be a complete embedded system, a system that handles real-time inputs and outputs to achieve a specific function. The weaving integrates a sensor input (pressure) and an output (color change) into the fabric structure, while creating a pocket for an external PCB (e.g. an Arduino microprocessor) to integrate processing (Fig. 6). This mixture of techniques and materi-

[2]http://unstable.design/force-fabric/

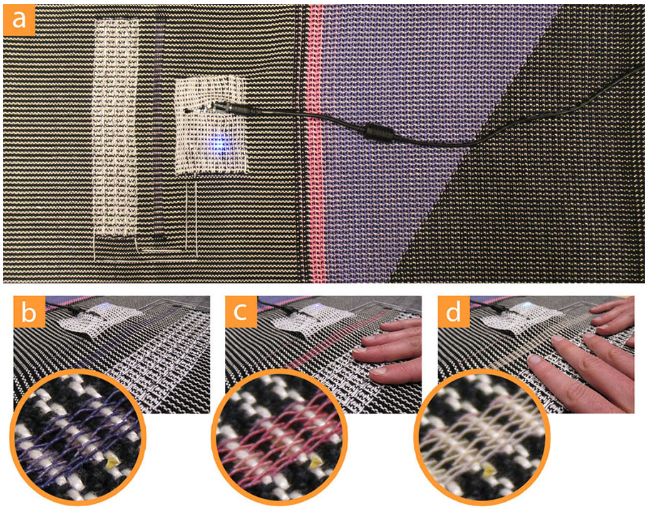

Figure 6: Multi-Component woven smart textile, containing (a, left to right) waffle stitch pressure sensor, color changing strip, and pocket for PCB; (b) initial state before press; (c) pressure sensor state 1, color change to red/pink; (d) pressure sensor state 2, color change to white.

als demonstrates how the weaving process can be used to develop complex, multi-functional smart textiles.

Rather than drafting the entire piece, AdaCAD was first used to draft the repeating units of stitches used in each section. Because Wu wove this example on a frame loom, these drafts of unit blocks were then "tied up" onto the loom, configuring it to carry out the stitches with user input.

To weave the pressure sensor, Wu created a draft of the waffle weave stitch in AdaCAD. Waffle weave is a stitch that creates a thick, compressible fabric. Perner-Wilson describes one can leverage this structure to make a robust pressure sensor using conductive fibers and non-conductive yarns [42]. Specifically, when the two-types are yarns are combined, waffle weave's resistivity significantly changes with vertical compression, making it effective for pressure sensing. The waffle stitch was woven in the center of the piece, surrounded by plain weave. To control the stitches' placements, Wu selected sections of each row to manually pick up or depress segments of warp, mimicking AdaCAD's select and fill operations on the loom itself. To create the thermochromic section, Wu loaded the double weave stitch onto the loom, as though replacing waffle weave in its memory. Lastly, Wu integrated another section of double weave, left open at the sides as a pocket to house a custom PCB. The pocket was divided between two separate shuttles to create a slit for easy access to the power jack on the PCB.

In contrast to the previous examples, this prototype demonstrates how some operations are easier to perform first by hand, especially when considering integrating components like PCBs of particular sizes and shapes. AdaCAD assisted by helping manage the component stitches as opposed to the overall fabric. After weaving this prototype, Wu then created a large draft to represent loom operations, with several annotations to record human operations, to revisit these structures on a TC2. While the software's operations can create drafts of an entire fabric as machine instructions for a Jacquard loom, these tools can also, with some interpretation, be adapted for other loom-weaver partnerships.

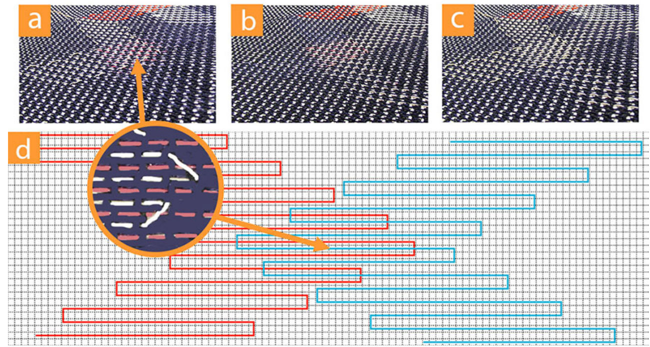

Figure 7: Interwoven Images smart textile, containing two overlapping color-changing chevron regions; (a) left side activated; (b) right side activated; (c) both sides activated; (d) AdaCAD shuttle view of the two thermochromic shuttles used.

Interwoven Images. The Interwoven Images example is a woven fabric of two chevrons created using thermochromic yarn and interlaced on the fabric design (i.e. one continuous thread of thermochromic yarn is used for each chevron). Each chevron can be independently activated, thus allowing the fabric to have four visual states (Fig. 7). We imagine this technique could be used to create displays that signal different interaction states to the user. By interlacing the images, one can reduce the total amount of space required to show this information.

The main technical challenge was sufficiently isolating two different thermochromic yarns so that they did not heat each other up when only one was active. In developing this weave, Wu started in AdaCAD by creating a large canvas and filling it with the desired stitch, representing the background fabric. The thermochromic yarn images were to be woven as supplemental wefts, isolated regions where the pattern of the base weft yarn is duplicated by another yarn, in this case a thermochromic yarn. This supplemental weft could be represented in AdaCAD by cloning particular rows and assigning these cloned rows to two different thermochromic shuttles. This process allowed Wu to determine the sequence of shuttles to be used during weaving. Once this structure was set, Wu was able to isolate each thermochromic shuttle and import the desired image using the image to shuttle feature, defining the specific path of the supplemental weft within the fabric to reveal the image.

In the final design, two rows of cotton separated each row of thermochromic yarn. As with all of the previous examples, the software's yarn view was crucial in choreographing multiple shuttles and their directions of motion.

5 FEEDBACK

We conducted semi-structured interviews with five people related to the smart textiles development community to (1) better understand their design processes and (2) show them the tool we built and ask for feedback and design suggestions. Three interviews were held over Skype and two were in person. We asked participants about their background in textiles and design process when creating textiles. We followed with a demo of AdaCAD, walking through the software and its features. In response, the participants offered insights into the perceived utility of features based on their prior experience and offered suggestions for improvements. By choosing this format of evaluation, we intended to focus on the high-level concepts and workflows, make sure we were addressing the correct issues and challenges, and offer room for the feedback to actively shape future iterations of the tool, which we intend to release as open-source software.

Our participants included: Zoe, a PhD student in aerospace who is building smart textiles and experienced in circuit design but not weaving; Kaylee, an artist, technologist and weaver developing open-source weaving equipment and smart textile prototypes; River, a pioneer in e-textiles with previous experience using industrial jacquard weaving software and hardware; Inara, a specialist in e-textile and technology for its mass-market realization; and Malcolm, a skilled weaver whose work includes personal hobby, instruction, and industrial freelancing with no circuit design experience. The names above are pseudonyms. We organize the responses in terms of "themes" in smart textiles practice and "reactions" to our software.

Themes in Smart Weave Design

The first theme that emerged in our interviews concerned the playful and improvisational nature of weaving. Our participants spoke both practically, as well as poetically, about weaving and circuitry. Inara noted that, "designing a circuit is like patterning electricity." Kaylee related the "form factor" of a loom to a "musical instrument like a glockenspiel or a piano," describing the "musicality" of the weaving process. These quotes represent the playfulness and experimentation involved in weaving. Even when working from a draft, the expert weavers, Kaylee and Malcolm, described approaching the draft as a starting point and making modifications when working the draft on the loom. The loom, while a heavily structured apparatus, was described as a tool for "sketching" and then using what is discovered to iterate on drafts. For some, like Zoe the beginning weaver, that meant following a draft like a "map." The more expert weavers described it as more open ended: Kaylee and Malcolm described "free weaving" as a large part of their design process. Free weaving for Kaylee means "treadling randomly to see what emerges" and finally creating a draft after their experimentation. To this end, the choice to prioritize the draft, rather than simulating, was seen as a wise choice to start (though some still dream of an accurate simulator).

The second theme concerned the many uses of drafts in smart textiles practice. Participants' descriptions of how and why they used drafts displayed many different uses, beyond directing action, in weaving. Kaylee and Malcolm described using drafts as a means of translating their work into larger-scale production. Inara described the draft as a coordinating device between their practice and that of their collaborators in manufacturing, exchanging revisions as a means of understanding possibilities and requirements. These responses describe drafts as an organizing, documenting and, coordinating device. They echo Janis Jefferies', a researcher of textile culture, statement that: "Pattern as device encourages us to think in terms of multiple perspectives and mobile subjectivities, of forging collaborations and alliances and juxtaposing different viewpoints" [25]. Whether it is an entity fixed in time or one that evolves with a project, we saw that a draft can be a road-map, a suggestion, or a memory.

Reactions

Participants responded positively to our design, and some, like Kaylee, even wanted to incorporate it immediately into their weaving practices. In relation to our software features, the ability to show and hide shuttles was seen as exciting, even inspiring a gasp of excitement from Kaylee who elaborated by saying it felt more "approachable" than other weaving software for the specific challenges she faced in smart weaving. The shuttles, combined with the image import feature, inspired some to imagine ways to create pockets and tunnels through a fabric along arbitrary paths. Zoe imagined custom fit garments with integrated sensing. Yet, the image import feature, while seen to be useful, was a feature many had been able to accomplish in other tools. The ability to assign the image to a shuttle and hide and view that image independently of the overall design garnered more interest.

Participants also described the yarn view as a novel feature. While River, who had used Jacquard software, described views that allowed you to see a weave's structure as a cross-section, they had not seen anything specific for circuitry. As such, they had used Illustrator to document their circuitry in the past. Others, like Inara, also described working across platforms for weaving and platforms like Eagle and

Fritzing. The yarn view, for them, opened the door to many other features such as predicting total resistance, organizing messy traces, or highlighting all parts of the weave that were connected to ground. The yarn view also helped our beginning weaver, Zoe, understand the structures of double weaving by offering an alternate view of a double woven fabric. Throughout their interview, Zoe sought to reconcile the pattern draft and yarn views of double weave with their physical understanding of double weave as "two yarns are in the same row." With the yarn view's visualization, they were able to intuit the stitch as two yarns forming two distinct fabrics.

The experienced smart textiles weavers in our study described what we called warp connections as "tapestry" techniques that they and others often used when implementing smart textiles prototypes. River, specifically, described their attempts to insert segments into the warp in weaving projects. Yet, what most excited River about the connections feature was that is was something that is "able to combine what the machine can do and what [the weaver] can manually do into one [file] format." In their experiences with other CAD software they found that files often do not have "documentation information" built in, making it difficult to share human influences on a piece. This idea sparked more requests for "annotations" features that could help guide the implementation and communicate insights across the community.

6 REFLECTION

While it may seem counter-intuitive to some, many researchers describe and conceptualize the process of software development as "craft" [28, 43]. Our process of designing smart textiles and software for smart textiles in tandem illuminated the similarities of both processes. When crafting a woven fabric, a weaver may try several design ideas, repeatedly working, troubleshooting, and reworking. While developing AdaCAD, we would go through the same iterative process: code, debug, recompile. Observing both our designs and tools co-evolve, we realized that we, too, as weavers evolved and learned alongside the software.

When taken up in a design process, Agre describes how generative metaphors can help shape and scope designs towards specific ends and values [7]. As we reflected on this project, we found ourselves using the metaphor of "coproduction" to describe the relationships between materials, histories, weavers, and software. Building off Haraway's use of "coproduction" to describe the mutual shaping of categories and boundaries (e.g. software/hardware, human/machine), Devendorf and Rosner suggest that "coproduction" can also help designers rethink how technology is enrolled in relation to "traditional" or craft practices [15]. Specifically, they describe how coproduction places humans and nonhumans on more equal footing and treats designs as emergent from continuous evolution rather than bringing the new to bear on the old. In the following sections, we contextualize what we learned in our design processes through the lens of coproduction to describe practices we aim to support and provide the community with guiding principles for future designs.

Engaging Multiple Agencies in Weaving

The metaphor of coproduction can help designers account for yarns, tools, and human as creators of the production of a smart textile: Both the loom and AdaCAD acted as tools for designing the fabric. The loom provided parameters for the design of the patterning of the fabric and AdaCAD gave rise to the planning of circuit components. The yarns themselves played a role in the design as differences in thickness, texture, and tension would set additional parameters for the fabric, influencing stiffness, degree of insulation, and other properties. These variables change the way that the yarn interacts on the loom with the warp, so one pattern with two vastly different yarns would yield varying results. The user is connected in the production as a designer, as a mediator between the loom and yarn (running the shuttle across the warps), and as a vehicle to carry out instructions within the design (the connections). Each agency offers something to the production, no one more important than another because they all come together to engage mind and body as well as direct creativity.

This confluence of agencies makes improvisation a necessary (and constant) part of the creative process, as we saw in the responses of our participants who saw drafts as a guideline and not a rule. As in other crafts, it can be difficult to actually know how the design will behave until you begin to follow the instructions. For instance, Tim Ingold discusses craft in terms of the "sighted watchmaker" who certainly begins with a plan or design but constantly negotiates with materials in relation to that plan [22]. We learned that weaving, especially with "smart" materials, forces a degree of "following the materials" as properties are realized as much through the tactile pulling and pushing of yarns, as they are through the planning of the design. AdaCAD supported these improvisational patterns by offering itself as both a tool for designing as well as for recording and modification. Furthermore, its drafts delegated instructions to both machines and humans, placing humans and machines on more equal footing in the production process.

Seeing Value in Designing as a Beginner

To recall, all authors learned to weave while designing AdaCAD. We found our beginner perspective to be useful for becoming attuned to many agencies at play and decided how our software could participate. Consider a beginner's perspective on designing: because the materials (loom, yarn) are new, a beginner does not have any preconceived notions of how they will behave. Instead of trying to control them, the beginner follows the tools. They pick a draft, weave it, play with it, and troubleshoot as they learn how to communicate and negotiate with the loom and materials. After talking to more experienced weavers in the community, not just those working with smart textiles, we realized that both expert and beginner weavers alike use similar forms of improvisational action and adapt as they learn—planning, improvising, and documenting.

It is common for CAD tools in the craft domain to attempt to delegate the complex parts of craft to the technology, often by way of simulating a design that a tool might implement, with more or less user engagement. While all these tools require some iteration and planning, they are often premised on the ability to make beginners able to produce objects more like those experts have created previously. We believe that smart textiles will continue to require craft expertise for some time and thus, it should not be abstracted away. Coproduction, here, helps us see the value in designing for beginners, of all sorts, can help designers support the improvisational nature of weaving necessary to develop as a craftsperson.

Rich Historical Inclusion

A draft is a legacy format. Drafts and the ability to read drafts grants weavers at all expertise levels access to a long history of weaving encoded within the instructions [13]. The appearance of a draft has not changed much, placing AdaCAD at an accessible point for not only creating drafts, but also working from drafts created decades, if not centuries, earlier. Coproduction, here, helps us connect our present trends in technology to the histories from which it emerged. By supporting the legacy format of the draft, AdaCAD inherently supports accessibility for the existing weaving community while leveraging the community to be accessible to new users. It also puts "smart" material on the same field as traditional material used in weaving, which are smart in their own way.

7 FUTURE WORK AND LIMITATIONS

Our future work will tackle implementation challenges while balancing ideas of what could become of a tool like AdaCAD. The most pressing technical challenges include optimizing AdaCAD such that large weaves do not cause significant processing delays. Next, we plan to implement suggestions from our participants such as highlighting connected yarns, non-rectangular selection, predicting the total resistance of yarns, and adding implementation annotations. These improvements would give the user more control over designing irregular shapes and complex fabrics as well as built-in tools for documentation and sharing.

We envision building a community around the software, for instance, by adding improvements to the stitch library so people to share their custom stitches. Other users could then search and add these community-created stitches into their personal library. We want users to be able to share their complete designs, not just their drafts, with the community. Improved labeling, commenting, and annotation features will enable users to communicate their design choices and novel techniques. Beyond existing features, we are exploring plugins that will bring new design possibilities to woven smart textiles. One such idea would allow users to import datasets into drafts, creating novel data visualizations when woven into a fabric.

8 CONCLUSION

This paper presents detailed description of smart textiles weaving and the common techniques it employs. These techniques are supported in AdaCAD, a novel web-based software to realize woven smart textile drafts. We present woven prototypes and describe usage examples, structural elements, and realization of the design through AdaCAD's novel features. In the interviews we discovered themes around improvisation, community, and collaboration in smart weaving. We describe how the metaphor of craft coproduction that encapsulates these themes and can help future designers understand how drafting tools can be effectively enrolled in smart weaving practices. We discuss the way AdaCAD presents guidelines for others working with smart textiles: the negotiations between human and nonhuman agencies; thinking of users of all weaving levels and experience as beginners; and inclusion of weaving history and community.

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