Loom Pedals: Retooling Jacquard Weaving for Improvisational Design Workflows

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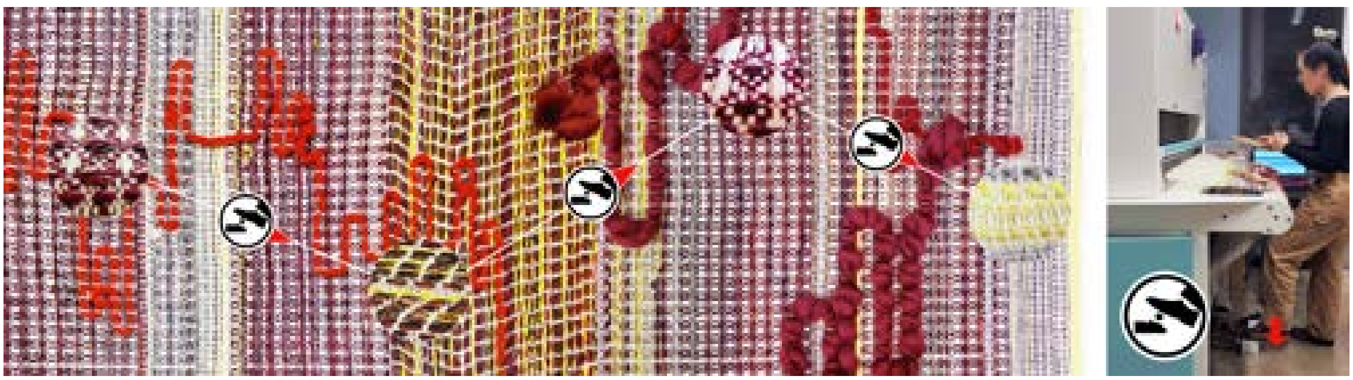

Figure 1: A large Jacquard weaving by one of the authors, woven (left to right) with the Loom Pedals prototype interface on a TC2 Digital Jacquard loom. At various points, the weaver stepped on a "Loom Pedal", triggering the design to change based on specific operations. Rather than modifying their design file in software, the user can playfully design the fabric at the loom with a sequence of Pedal steps. **Foot pedal icon by Daniel McDonald from the Noun Project.**

ABSTRACT

We present the Loom Pedals, an open-source hardware/software interface for enhancing a weaver's ability to create on-the-fly, improvised designs in Jacquard weaving. Learning from traditional handweaving and our own weaving experiences, we describe our process of designing, implementing, and using the prototype Loom Pedals system with a TC2 Digital Jacquard loom. The Loom Pedals include a set of modular, reconfigurable foot pedals which can be mapped to parametric Operations that generate and transform digital woven designs. Our novel interface integrates design and loom control, providing a customizable workflow for playful, improvisational Jacquard weaving. We conducted a formative evaluation of the prototype through autobiographical methods and collaboratively developed future Loom Pedals features. We contribute our prototype, design process, and conceptual reflections on weaving as a human-machine dialog between a weaver, the loom, and many other agents.

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CCS CONCEPTS

• **Human-centered computing** → **Interactive systems and tools**; • **Applied computing** → *Arts and humanities.*

KEYWORDS

Jacquard weaving, interactive fabrication, craft, design interfaces

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1 INTRODUCTION

Many researchers in HCI and other computing fields recognize that textile technologies formed the foundations of early computing.

History credits weaving with "the first computer", for the Jacquard loom of the first Industrial Revolution was the first widely-adopted technology to be programmed using punch-cards [23, 33, 64]. Fittingly, this legacy continues through the researchers who have brought Jacquard looms into their labs to weave prototypes for future e-textiles and wearables [11, 28]. Yet, the Jacquard loom is only a modern addition to the weaving family. When the first loom predates written language [7], weaving offers a far richer source of inspiration for future interactive technologies when we consider its entire history.

In this work, we challenge TEI researchers to look to older loom traditions as the community of textile-based HCI research grows. Most often, the complex weaving in HCI prototypes uses a particular model: the TC2 Digital Jacquard loom, one of the only prototype-scale Jacquard looms on the market. Jacquard looms may be able to weave designs that are infeasible on traditional wooden floor looms, but the reverse is also true: some things are easier to weave on floor looms.

Floor loom weavers can weave dramatically different pieces in a single setting, playfully combining frames of algebraically encoded patterns and sequences of footsteps to give rise to emergent outcomes. In contrast, Jacquard looms like the TC2 require the weaver to prepare a bitmap image (the modern punch-card format) that represents the entire fabric, and load it into the loom. The weaver weaves the file row-by-row, advancing through the predetermined design by pressing a foot pedal. Revisions to this process are costly: the weaver must leave the loom, return to design software, revise the bitmap, and re-load the new design before they can resume weaving. In an insightful deconstruction of the Jacquard-loom-as-computer narrative, Ellen Harlizius-Klück writes: "Jacquard's cards are the end of this story [of weavers' embodied algebra and computation], rather than its beginning, reducing the weaving from a coder of weaves, to an operator who had to step on a single [foot pedal] repeatedly" [34]. The current Jacquard workflow can be slow to iterate, which prevents rapid prototyping. More generally, it prevents a weaver from responding to their materials and exploring alternate possibilities, a key aspect of the creative process in traditional weaving which has enabled so much of its historical innovation.

Our work responds to the limitations of Jacquard weaving by designing an interface for a TC2 Digital Jacquard loom by learning from simpler looms—primarily floor looms, but also tapestry looms and other types. Implicitly, we also challenge how notions of "high tech" usually exclude historical textile knowledge, and marginalize innovations by those preserving handcraft traditions, particularly Indigenous communities and women [25, 57, 76].

In the following paper, we present the Loom Pedals system and our prototyping process as a case study in promoting improvisational, playful creativity in a design interface. We first contextualize our work with the history of loom design and review different types of traditional looms. Next, we describe our design process, the system implementation, and the new Jacquard weaving workflow which developed. We report on the formative evaluation we conducted amongst the authors as weavers, finding lessons for play and improvisation in weaving and refinements for the prototype. Finally, we conclude with future directions for the Loom Pedals as we continue to develop and explore the system with a broader community of weavers.

Our contribution consists of: the Loom Pedals prototype, source code, and bill of materials as an open-source project; the review of various loom mechanics as a resource for other interaction designers interested in weaving and craft; and the preliminary findings from our design inquiry. We hope that our experiences will inspire readers to also investigate weaving as both craft and technology – joining us in a web of warp and weft, humans and machines, digital and analog, histories and futures.

2 RELATED WORK

2.1 Weaving in Digital Fabrication

Textiles have been a rich domain for digital fabrication to explore, offering techniques, besides weaving, such as: knitting [50], crochet [61], spinning yarn [74, 83], and embroidery [39]. Technologists have used these techniques to create novel artifacts like soft robotics [47] and e-textile circuitry [66]. Using weaving, researchers have leveraged its complex, grid-based structures to create sensors [18, 68] and wearable devices [36, 84]. Its diversity of methodologies can even generate 3D objects, such as garments [51] and multi-layered folding shapes [49, 73].

From an HCI perspective, these works have renewed interest in textile crafts, by introducing traditional practices into the realm of computing research. Besides crafted items, researchers have also investigated craft processes themselves. Works like EscapeLoom [15], personal Jacquard weaving [6], and open-source DIY looms [1] consider the potential benefits of digital fabrication for making novel, accessible weaving tools. Furthermore, a growing domain of interactive fabrication and flexible fabrication leverages both the complex machinery of weaving, 3D printing, and other techniques, while recognizing the value of a human designer's participation in making [5, 29, 44, 85].

2.2 Textile Crafts in TEI/HCI

Weaving – as an embodied process, cultural practice, even political statement – has been a provocative action for many designers. In HCI, Fernaeus et al. investigated a mill with original, wooden Jacquard looms, dating back to the Industrial Revolution, and found design lessons for modern computers in the looms' longevity and historical uses [23]. A collaborative study conducted by Zhang et al. with communities of Malaysian Songket weavers offered insight into the innovation embedded in grassroots infrastructures and highlighted the value of tradition in this sociotechnical context [93]. Finally, Oogjes et al. reflected on the bodily experience of weaving as part of a human-machine-material ecological network [62], providing language for our own practices of noticing, thinking, and making.

We characterize these aforementioned works, or specific artifacts, as case studies that explore themes shared in this research. More broadly, we look to methodologies such as autobiographical design [16, 58], embodied interaction and somaesthetics [8, 37, 88], as well as embodied knowledge and craft-based inquiry [24, 26, 79] to immerse ourselves in our subjective experiences and to understand the role of weaving in generating our design. While our work does not directly engage with the sociopolitical dimensions of weaving, we

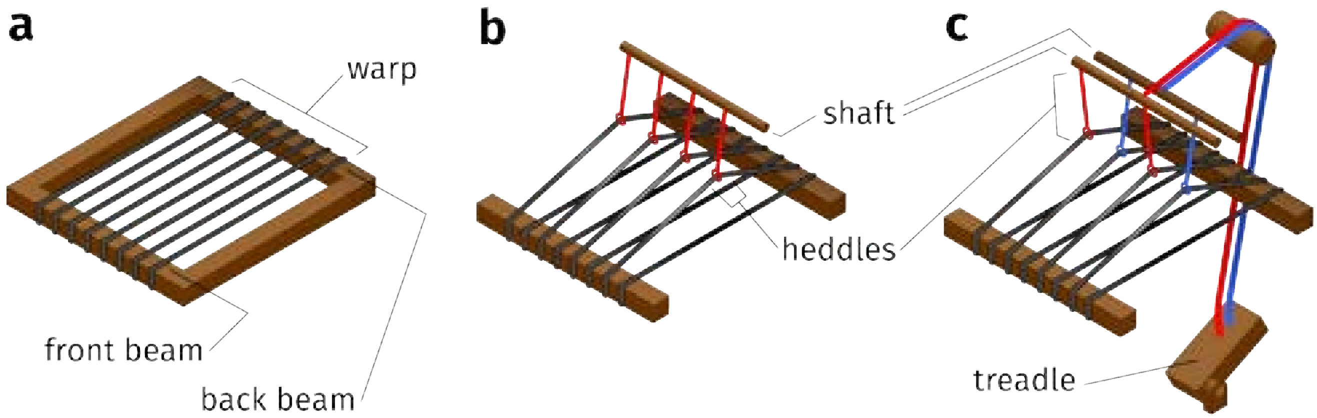

Figure 2: Simplified cartoons that illustrate each of the weaving hardware components discussed. (a) A loom that consists of a frame with two beams holding the back and front of the warp, equivalent to a tapestry loom. (b) A loom with one shaft that lifts half of the warps with one motion, using heddles around the selected warps, equivalent to rigid heddle looms and many backstrap looms. (c) A loom with two shafts, both tied to one treadle, which will lift the same shed as in (b). However, now it is possible to select which shafts are associated with the treadle, equivalent to shaft or frame looms.

strove to honor how crafts and textiles have been historically devalued as low-tech knowledge, and how textile traditions are vehicles of resilience and political resistance for Indigenous communities [25, 54]

2.3 Improvisation and Playfulness in Fabrication

As interest in digital fabrication has grown over the last several years, so too have discussions that explore how to integrate chance, playfulness, and otherwise improvisational experiences into the making process. Early projects in interactive fabrication, such as Constructable [56] and Protopiper [3], sought to enable improvisation by offering direct manipulation to the design in-progress, like using a laser pointer to modify a laser-cut design on-the-fly. Others frame improvisation as inviting various forces to participate in the design and creation process, augmenting the voices of the machine and/or materials. Threadsteading [4] and Exquisite Fabrication [31] show how playfulness can be applied literally as well, by integrating games into the making process.

Playfulness can also be subversive, because these projects prioritize unexpected outcomes, rather than conventional fabrication metrics like precision and throughput. For instance, Dew & Rosner's work in timber construction focused on living materialities as part of making, which meant the post-making process of the materials' decay became a factor as well [20]. Similarly, recent fabrication research has examined unmaking as a valuable kind of interaction [81], creating a dialogue between fabrication and sustainable design and materials. Overall, these projects frame improvisation as an interaction between humans and technology that can foster deep material engagement.

Our study participates in this larger conversation regarding play as it applies to looms, of many origins and uses, as a kind of human-machine cooperative interface of interest. It does so by augmenting these systems with hardware peripherals that are aimed at inviting playfulness and embracing improvisation within the traditionally rigid process of Jacquard weaving.

3 BACKGROUND: LOOM HARDWARE AND THE WEAVER'S DESIGN PROCESS

Our reasoning for modifying the existing Jacquard workflow relies on our prior experiences weaving on other types of looms, primarily on traditional floor looms (henceforth referred to as "shaft looms" for consistency). To provide readers with the same context, we will review the core mechanics of three types of looms (tapestry, shaft, and Jacquard) and compare how their hardware influences play and improvisation in weaving. We have also included a glossary of **key terms** in Appendix A.

3.1 Tapestry Looms

In general, **looms** are machines for weaving: interlacing sets of **yarns** to create fabric. The oldest and most fundamental loom mechanism is a frame that holds one set of yarns, the **warp**, in place, so that the weaver can interlace a perpendicular set of yarns, the **weft**, into the desired structure. Tapestry looms only require this basic frame (Fig. 2a), and thus, are sometimes called "frame looms". A tapestry weaver creates fabric by manually manipulating the weft and warp, often with their fingers and a large needle [52, 55]. In essence, a tapestry loom allows one to draw free-hand with yarn, creating different imagery and textures. Consequently, tapestry weaving tends to incorporate long loops, knotted fringe, twists, and other textured structures beyond strict over-and-under weaving [77]. The loom's simplicity imposes very few constraints on how the weaver's hands can move in and out to manipulate the yarns, encouraging these unusual techniques.

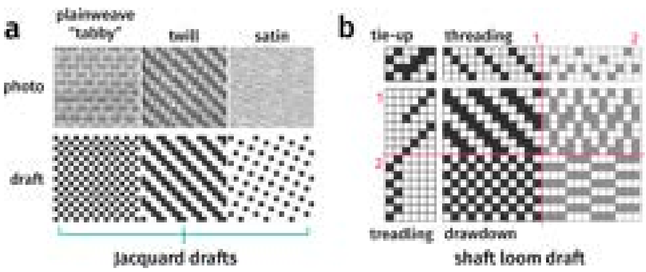

Figure 3: Weaving drafts and how they represent the cloth's structure as well as the fabrication method. (a) Comparisons of three common weave structures (plain weave, twill, and satin) in photos of the cloth, as well as their drafts. The drafts are formatted for Jacquard looms. (b) A draft for shaft looms that shows the additional sections required: threading, tie-up, and treadling. The upper-left section represents the same twill as the Jacquard draft. Alternative threading or treadling can dramatically alter the woven structure.

3.2 Shaft Looms

Shaft looms introduce two mechanisms to the basic frame. The first are **heddles**, grouped into sets which share common **shafts** [9], allowing the weaver to simultaneously lift a set of warps and quickly pass the weft through (Fig. 2b). The second are **treadles**, foot pedals which can lift multiple shafts (Fig. 2c). Both shaft loom and Jacquard weaving designs rely on such lifting mechanisms to interlace wefts over and under the warps in specific patterns. These patterns, represented by **drafts**, also denote different **woven structures** and fabric properties, as seen in Fig. 3.

Setting up a shaft loom (a.k.a. "warping") starts with **threading**, assigning each warp to one of the shafts [12, 63]. Threading a shaft loom is analogous to preparing a file for a Jacquard loom—these looms need configuration before they are ready to weave specific designs. Yet unlike a Jacquard weave file, a shaft loom's threading does not specify a particular pattern; rather, it provides a selection of related patterns. Weavers can choose their **tie-up** (how shafts are assigned to treadles) and their **treadling** (what order the treadles are pressed) to create variations on a structure [27, 41]. Shaft loom drafts are divided into four sections (Fig. 3b) to reflect how weavers can experiment with each configuration and iterate upon multiple designs using the same threading [40]. We briefly note that shaft loom weavers are also free to play with different yarns and materials, and integrate tapestry and hand techniques. However, merely discussing the loom mechanisms already illustrates how shaft looms give rise to complex fabrics and open a large field of creative possibilities for weavers to explore.

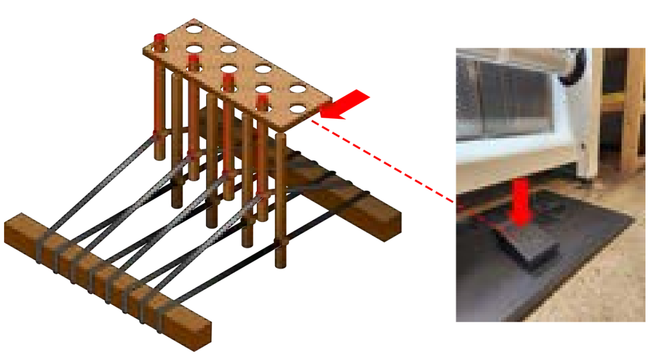

Figure 4: A simplified Jacquard loom. The Jacquard mechanism is an abstract, invisible component that can control each heddle individually. The loom uses a foot pedal (right) to advance the punch-card to the next row.

3.3 Jacquard Looms

Jacquard looms enable even greater complexity in woven fabrics by exchanging shafts and treadles for the **Jacquard mechanism**, which lowers and raises each yarn independently, rather than in fixed sets (illustrated in Fig. 4). A weaver executes a design on a Jacquard loom by loading the draft into a punch card, or a digital bitmap equivalent, then inserting the card into the machine to be read row-by-row [23] (Fig. 3). This system opens up a much larger possibility space for woven design, as the Jacquard loom can lift warps in any arbitrary pattern [35, 59]. While some Jacquard looms are entirely automated, others still require a weaver to physically insert the wefts. The TC2 is one such loom, which we will discuss in 4.2. At the loom, the weaver is free to change their weft materials, but they are still working within a predetermined design file. Jacquard drafts require much more planning and preparation compared to shaft looms. A draft needs to encode every **interlacement** into a pixel, and the weaver might spend hours creating a draft before they can weave anything [59, 78]. To change the draft, the weaver must swap a different file or redesign a new file, reload the draft, then resume weaving. This does not make improvisation impossible; but it does impose a significant time cost.

3.4 The Broader Space of Looms

While our design was most heavily inspired by the looms described above, it is worth noting that this history of loom design presents only a small subset of the mechanisms and equipment used for weaving. Looms such as warp-weighted looms and backstrap looms have been used longer than there is written history [67, 69]. They have encoded patterns in the body, song, and environment, and require collaboration amongst multiple parties [71, 86]. Some of these looms are portable, some are made with found materials; each brings its own unique approach to encoding and reproducing patterns. We believe this history can be of interest to the TEI community as it shows multiple modes of embodied creative processes among humans, machines, and materials in the computational process of weaving.

4 DESIGNING FOR IMPROVISATIONAL JACQUARD WEAVING

How can we bring improvisation into Jacquard weaving through the loom's user interface, and what experiences or possibilities emerge in designing such a system?

4.1 Improvisation and Play in Handweaving

In the context of weaving, improvisation is the ability to "jump on the loom and weave"—more formally, a weaver can start without a full plan or draft, and they are able to to change the design *at* the loom. Thus far, we have discussed how weavers design differently depending on the type of loom they use. In general, the more mechanically complex the loom, the more a weaver needs to plan their design in advance. Conversely, simpler looms such as tapestry looms offer more flexibility with planning a woven design. Shaft looms fall in the middle of this spectrum, allowing the weaver to alter their design by reconfiguring the loom, or simply their own actions. Even the set-up phase presents opportunities for improvisational play, as weavers can experiment with different colors and textures in the warp as they set up the loom [22]. Weavers start a design by "sampling", trying different ideas by weaving samples of potential designs. In the words of Amanda Rataj, a contemporary weaving instructor, "sampling is like making a sketch—you learn more about your materials…and how the finished textile behave…[But it] isn't all just about practical weaving knowledge—[it's] also about having fun and trying something I wouldn't typically make" [70]. Improvisation and play are crucial to a weaver's design process, often leading to unexpected discoveries.

With these facets of playful weaving in mind, our design prioritizes: *reconfigurability*, lowering the cost of making changes; and *modularity*, in the form of sampling functions that can quickly generate ideas.

4.2 The TC2: Existing Interface, Sampling Workflow, Frustration Points

In the decade since its release, the TC2 loom has accumulated a worldwide community of users, ranging from independent artists, to industry researchers, and academic institutions. The TC2's design process is typical for a Jacquard loom; designers use computer-aided design (CAD) software, e.g. Arahweave [21] or JacqCAD [38] to prepare their Jacquard draft. First, the designer creates a digital image file, then defines regions in the fabric corresponding to different features, and finally fills the regions with the desired weave structure [35]. Afterwards, the designer takes their file to the loom. TC2 users most commonly use Adobe Photoshop for their drafts, loading their weave structures as Photoshop Patterns [78]. At the loom, weavers can play with different materials, and can even apply hand techniques (e.g. tapestry and embellishments) within the emerging cloth to create effects that are impossible in fully-automated weaving. For this complex design possibility and creative freedom, the TC2 is popularly used for prototyping as well as art-making. However, weavers still need to endure the laborious cycle of preparing a file, sampling, and iterating. Furthermore, this workflow assumes that the weaver has already developed an idea enough to create the initial draft. In our own experiences, as well as anecdotally from other TC2 weavers, the sampling process is generally tedious and frustrating. Often, more time is spent in the editing software than at the loom. By separating the file design and fabrication phases, this workflow limits the weaver's ability to improvise, disrupting the generative relationship between designing and making in weaving.

4.3 Conceptualizing the Loom Pedals

4.3.1 Methods. We looked to craft-based design inquiries in HCI to guide our research, with a particular emphasis on "creating knowledge through deep, embodied engagement" [26]. This principle led us toward autobiographical design [16, 58], where our own embodied weaving experiences would shape the design of the Loom Pedals. Not ones to work in isolation, we sourced ideas from crafters and artists who spoke of their own embodied experiences with woven design: such as Harlizius-Klück's writing on the algebraic complexity of shaft looms. We also valued input from our own community of practitioners, which led us to seek their ideas through collaborative design [17, 53, 72].

4.3.2 Design Metaphors. Two metaphors emerged during the Loom Pedals' design process which helped clarify both improvisation and play in the prototype.

Weaving as Music: Musical concepts and practices directly informed several of our design choices. For example, we considered why improvisation felt easier when weaving on a shaft loom, and in doing so, developed a conceptual model of improvisational weaving. Treadles were key, as they provided a well-defined set of choices for the weaver. In the same way musical notes form chords and leitmotifs, treadles enable a woven pattern to emerge from treadling sequences. Similarly, musical effects pedals enable musicians to apply various effects while performing. If we wanted to improvise on a Jacquard loom, we reasoned that we would: 1) add more hardware inputs so users can edit their drafts on-the-fly while weaving; and 2) add these inputs as extra foot pedals, as this would build on existing pedals in Jacquard looms.

Weaving as Conversation: This work involved several fluid processes, in which multiple agents responded to one another. For one, weaving is a conversation between humans and machines. We note that we are not the first to investigate fabrication as a conversation between humans and the more-than-human [42, 43], such as the rhythmic movements of a weaver's body interacting with the loom's mechanisms while weaving. To improvise while weaving is to involve the design and the fabrication processes in a two-way conversation. Lastly, like any craft, weaving also brings humans in conversation with each other to exchange ideas and culture [2, 26]. We saw that our prototyping and evaluation process (Section 6) should likewise be part of a conversation, iteratively integrating feedback from multiple weavers.

5 LOOM PEDALS SYSTEM OVERVIEW

In this section, we briefly describe how the current Loom Pedals prototype blends the design and fabrication phases of Jacquard weaving.

5.1 Weaving with the Loom Pedals

The Loom Pedals system has three interactive components: the Pedals, the TC2 digital Jacquard loom, and the Draft Player—a software interface where users both control the loom and edit their designs. To accompany the following walkthrough, we also present an example workflow using the Loom Pedals in Fig. 5, documented while evaluating the system by weaving a large project.

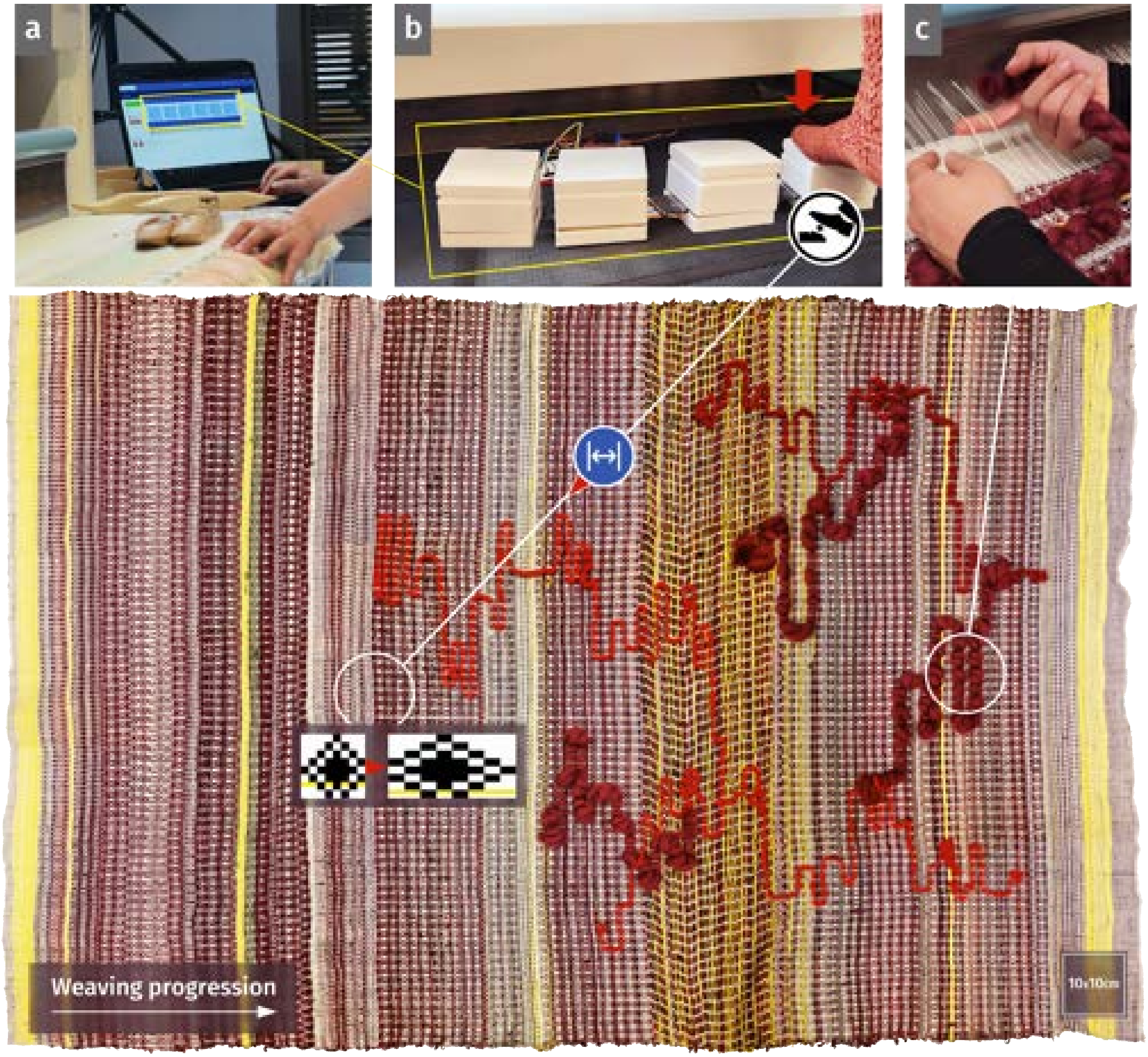

Figure 5: Key user interactions for the Loom Pedals weaving workflow. a) Before starting a weaving session, the user configures the number of connected Pedals and assigns Operations to each Pedal that control design edits and weaving progression. b) While weaving, they can step on a Pedal at any point to execute the assigned Operation. In this example, the user stepped on a Pedal that horizontally stretches the draft, and this moment of change is visible in the fabric (indicated). c) With these interactions delegated to their feet, the user is able to get more creative with their hands like a tapestry weaver, such as manually inserting a free-form accent yarn. **Foot pedal icon by Daniel McDonald from the Noun Project.**

To start weaving with the Loom Pedals, the weaver (user) first turns on the TC2, then connects to the Draft Player on their personal device. They plug in the desired number of Pedals, arrange the modules as desired, and prepare their yarns. In the Draft Player, they map Operations to each connected Pedal. When pressed, a Pedal triggers its associated Operation, which can apply a specific transformation to the design or switch to a different draft entirely. For instance, using the Loom Pedals, a weaver can: flip their draft, switch from satin to twill, activate or deactivate certain yarns in the design.

The Draft Player opens with a default plainweave draft, so the weaver could start weaving without preparing a file. They can also choose from some basic preset drafts, and they can still load a premade draft into the Draft Player. When the weaving starts, the

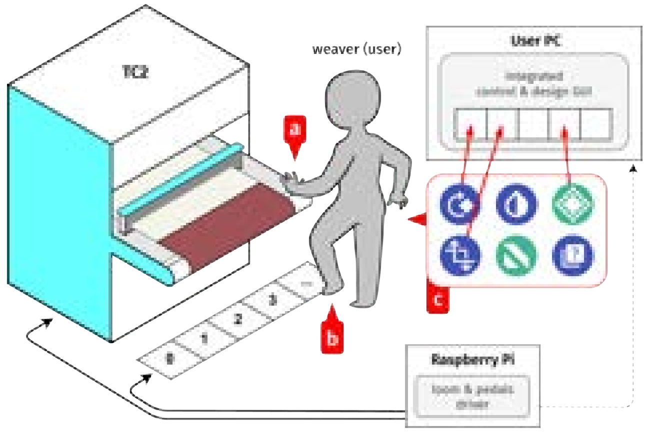

Figure 6: Diagram of the inter-device connections and user inputs in the Loom Pedals system. The elements are roughly arranged as they would appear in the physical world. a) User interactions on-the-loom during weaving. b) The Pi indexes the connected Pedals and monitors when the user steps on one. c) User-defined Operation mappings to the Pedals.

TC2 lifts the warps for the first row of the draft. Then, the weaver passes through their first weft and steps on the "forward" Pedal for the next row. From here, the weaver can continue row-by-row through the draft, or at any point, step on a different Pedal to change what they are weaving. The weaver now has a number of choices for spontaneously altering their design as it emerges through the weaving. The result is a more improvisational and playful kind of weaving, one which engages the weaver in a dialogue between themselves, the loom, and their own imagination.

5.2 Implementation

The Loom Pedals replace the existing TC2 interface with custom components. Besides the previously mentioned foot pedal, the TC2 relies on an external user device (e.g. a personal computer) to control the loom and send design files via WiFi. We re-implemented some functions of the driver software in Node.JS for a Raspberry Pi ("Pi"). The Pi also manages the connected Pedals and maintains a connection to the cloud-based design software. The user accesses the loom control functions through the Draft Player within the design software, as well as the Pedal configuration (see Fig. 6) In the version used for evaluation, the user still needs to bring a personal device to access the design GUI. In later iterations, we aim to consolidate the loom controls, Pedals hardware, and draft editing features to use a single device. All materials are publically available on GitHub[1].

To ensure flexibility in our modified TC2 workflow, weavers are able to add or remove Pedals and customize the functions according to their preferences. We designed each Pedal module to be reconfigurable and interchangeable. Each module can be connected in a chain, with only the first Pedal directly connected to the Pi. Through the wired connection, the Pi reads how many Pedals are in the chain, as well as the input state of each one. This design

[1]https://loompedals.github.io

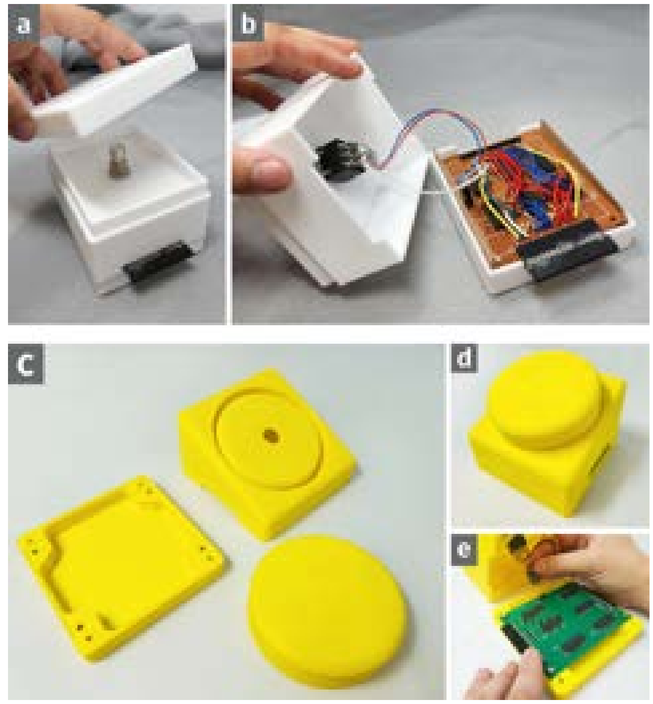

Figure 7: A single Pedal module and its physical enclosure. (a-b) an earlier iteration used for evaluation (Section 6) which established the enclosure's basic parts (c): a two-part base for the electronics, and a top plate covering the foot switch. d) In newer versions of the Pedal's physical design, the top plate is tilted for more comfortable stepping. e) The enclosure houses a PCB and includes slots on two of the sides for interconnects.

minimizes the effort required by the user to add or remove pedals, as they only need to (un)plug one end. Fig. 7 shows an earlier and a later version of the Pedal modules' enclosure and circuitry, showing our process of refining the physical design requirements. In particular, we realized that Pedals needed to be easily pressed and have a large top plate, as many weavers often work barefoot or in socks (ourselves included). As an aside, we intentionally show the earlier "handmade" Pedal circuitboard to pay homage to musicians who similarly build their own pedals "from scratch" [14]. The Pedals use 3PDT stomp switches, the same hardware that is commonly used in these musicians' DIY pedals.

While foot pedals remain our core interaction, we also note that the prototype establishes a template for connecting other types of physical inputs to the loom, such as hand-based buttons for accessibility or customization purposes. We have included further details on the Loom Pedals system in Appendix B.

5.3 User Interface: The Draft Player

For the Loom Pedals GUI, we built upon AdaCAD [19, 28], an open-source software tool[2] for designing weave drafts. AdaCAD's generative design approach was compatible with the Loom Pedals, using drafts as inputs and outputs for parameterized Operations.

[2]https://adacad.org/

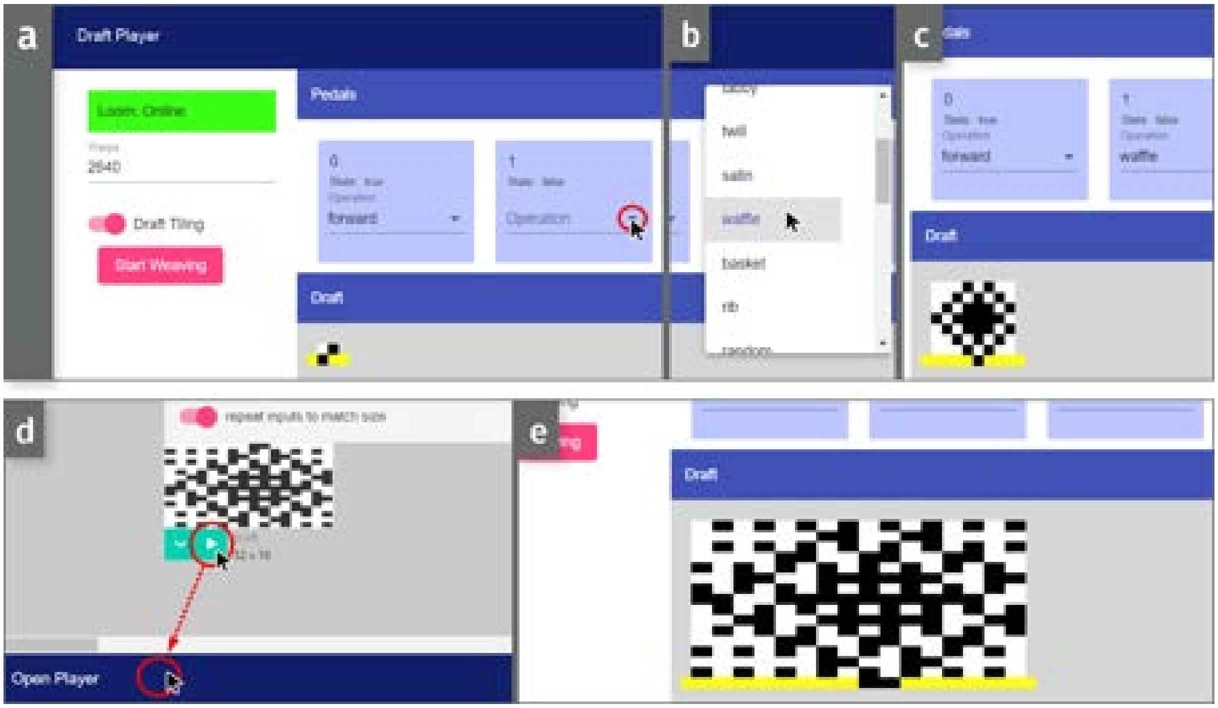

Figure 8: Overview of the Draft Player, the Loom Pedals' interface in AdaCAD. a) The Player will start with a default tabby draft, and the first connected Pedal is automatically mapped to "forward". b) Users can select an Operation to map to the Pedal. c) Any changes to the draft on the loom will be displayed, as well as the weaver's progress through the draft (yellow bar). d-e) Users can load a pre-made draft from the main AdaCaAD interface with a new "Play" button.

We created an AdaCAD extension which would allow users to map Pedal inputs as triggers for Operations. As a result, we gained access to a number of discrete transformations such as: flipping a design, swapping it for a random draft, or stretching/squashing a motif to adjust the aspect ratio. AdaCAD's main interface is called the "Draft Mixer", where users assemble a tree of drafts and Operation to generate large, complex designs from small building blocks. If the Draft Mixer interface could be described as "composing the score", then weaving a draft would be analogous to "playing the track". Thus, we named our extension the Draft Player.

Users can start directly in the Draft Player with one of the several basic building block drafts, as shown in Fig. 8a–c. However, if they have prepared a draft in the Mixer, they can transition to the Player by clicking the Play button on a selected draft node (Fig. 8d), which then loads the draft into the Player (Fig. 8e). The Draft Player will display the number of Loom Pedals currently connected and some basic loom configurations, such as the number of warps on the loom. Each Pedal displayed has an associated menu of Operations the user can map to it. Most are ported over from AdaCAD's existing Operations, with the exception of three Player-specific Operations which represent the user's progress through the draft: forward, reverse, and refresh. The first two Operations are equivalent to basic functions in the TC2 software that let a user progress forwards/backwards in a draft. Meanwhile, the refresh Operation lets a user repeat the current row of the draft without progressing.

6 FORMATIVE EVALUATION

As alluded to previously, we evaluated the Loom Pedals prototype while actively iterating upon the system's design. This *formative evaluation* was crucial for refining the prototype beyond basic functionality [75, 87]. While our study was informal and conducted amongst the authors, it revealed several considerations for conducting larger, more systematic user studies in the future. We will refer to individual authors with numbers (A1-A6) for brevity and consistency.

6.1 Timeline

The first author (A1, Wu) implemented a basic working version of the Loom Pedals prototype (white enclosures in Fig. 7) which was ready at the start of 2022. Over the course of the next 4 months, A1 recruited the other authors as both pilot participants and collaborators. Throughout the remainder of the year and up to present day, the authors remained in contact about the work, including one (A2, Corr) who worked with A1 during September - December 2022 to develop new features for the Loom Pedals.

6.2 Recruitment

Participants were recruited to gain insight into how the Loom Pedals might provoke new ideas for weavers, particularly ideas that would suggest features to add in order to accommodate a range of weaving practices. We recruited weavers who also had some knowledge of physical computing, coding, or digital fabrication,

Table 1: Comparison of the authors' weaving experiences and disciplinary backgrounds.

Author	TC2 exp?	background	yrs weaving
[A1] Wu	✓	engineering	5
[A2] Corr	×	design	0*
[A3] de Koninck	✓	textiles	12
[A4] Bowers	×	comp. sci	15
[A5] Gao	×	design	0*
[A6] Devendorf	✓	comp. sci	5

* Corr and Gao began learning to weave at the start of the collaboration.

to minimize the amount of onboarding necessary for understanding the Loom Pedals and modifying the prototype (see Table 1). Because of the collaborative research process, we agreed that the weavers would be recognized as co-authors. As this agreement did not involve anyone outside the weavers, we did not seek approval from an institutional review board.

6.3 Feedback Process and Testing

A1 conducted an initial meeting with each collaborator upon recruitment, scheduling one collaborative sampling session that lasted between 2 and 3 hours. These meetings had three parts: 1) a semi-structured interview, 2) a guided tutorial of the Loom Pedals interface followed by open weaving time, and 3) a reflective discussion of each other's weaving practices. The sessions were audio-recorded from beginning to end, then transcribed.

The interviews consisted of a few prepared questions targeting the author's use of weaving tools, their interest in the TC2/Loom Pedals, as well as their design processes. During the tutorial, A1 prompted the other author to preview several simple structures using different transformations, until they settled on a starting draft. With yarn in hand, we began weaving, allowing the collaborator to iterate on the loom for as long as they wanted. Once they finished, A1 asked them to share feedback regarding how they might use the Loom Pedals and what features would be helpful in implementing those uses.

A1 reviewed the transcripts, identifying key traits within each participant, such as: their relationship with improvisation while weaving, their use of reference materials, and how they learned new techniques. All authors documented their woven samples (Fig. 9, noting the physical actions taken during weaving and which Operations were most provocative.

To test the Loom Pedals' usability beyond sampling, A1 also an extended test of the Loom Pedals by using the prototype for a multi-day, large-scale weaving. Over the course of 5 days, they spent a total of 20 hours at the loom and avoided using premade design files. The process was recorded in multiple ways: a timelapse video, a screen recording of the Draft Player while weaving, and real-time videos of key moments e.g. when a special technique was used. The fabric shown in Figs. 1 and 5 is the result of this test.

After the sampling sessions, A2-A6 were involved with the prototype in varying degrees. A6 and A1 were able to schedule another sample-weaving session, while others were unable to find time to use the Loom Pedals again.

7 FINDINGS: IMPROVISATIONAL WEAVING WITH THE LOOM PEDALS

Through the sampling sessions and extended weaving test amongst the authors, we came to better understand the relationship between improvisation and weaving, and how the Loom Pedals might support novel Jacquard weaving. This section is organized around the key findings, highlighting individual narratives that support each one. We acknowledge that this work's autobiographical approach comes with its own limitations (e.g. generalizability), discussed by Desjardins & Ball [16]. As such, our claims are limited to a small set of viewpoints. However, we take our findings as a starting set of possible codes for future studies and thematic analyses that involve a broader community of weavers.

7.1 Interactions Felt Musical

Across the collaborative sessions, all of the authors referenced musical practices at least once. While not all of us had experience *making* music, we had all *heard* and *felt* music, making it an easy reference point. A2's experience with audio production inspired their Sequencer feature (see 8.1). A5 noted how the TC2 felt and behaved like a piano. A4, who has struggled with improvisation in weaving, compared (and contrasted) the experience to a live jazz performance.

During their extended text, A1 noted how improvising with the Loom Pedals recalled their experiences as an amateur musician. Like their past jam sessions with violins and drums, the weaving began with finding a base beat or motif. Following this initial discovery phase, A1 wove the rest of the piece in a cyclical process: starting with an idea, weaving different motifs based on that idea until one stood out, and repeating this new structure to complete the work.

7.2 Weavers Needed to Trust the Machine

We found that the musicality of weaving also reflects how weavers develop deep relationships with their tools, as musicians deeply relate to their instruments. The TC2 has undeniable agency when working with it, and its sheer physicality could intimidate new users (A2, 4, 5). However, A4 and A5 presented an interesting contrast when first encountering the TC2. When asked why they were intimidated, A5 replied, "because it is a machine...it is not my hands." For someone primarily experienced in hand tools, like sewing needles, using the TC2 meant surrendering a great deal of control on their part. On the other hand, A4 had learned to weave on shaft looms as a child, and was thus very comfortable with a loom controlling the warp. They explained, "I just get [the loom] threaded, then play with the patterns…the threading steers you to a cluster of [possibilities]." Framing this relationship between weaver and loom as *trust* reflects how the embodied process of handweaving builds familiarity and intimacy with one's tools.

As the lead developer on the prototype, A1 felt an additional layer of trust with the TC2. In weaving, knowing and trusting one's tools seems tightly intertwined with the ability to modify those tools. A4 shared how their weaving experience included "bolting on 2x4's [to existing looms]" and making looms from repurposed materials. In fact, "weaving hacks" are so common that large online communities have formed around sharing them [32]. Our experiences in hacking Jacquard weaving felt comparable to a musician building their

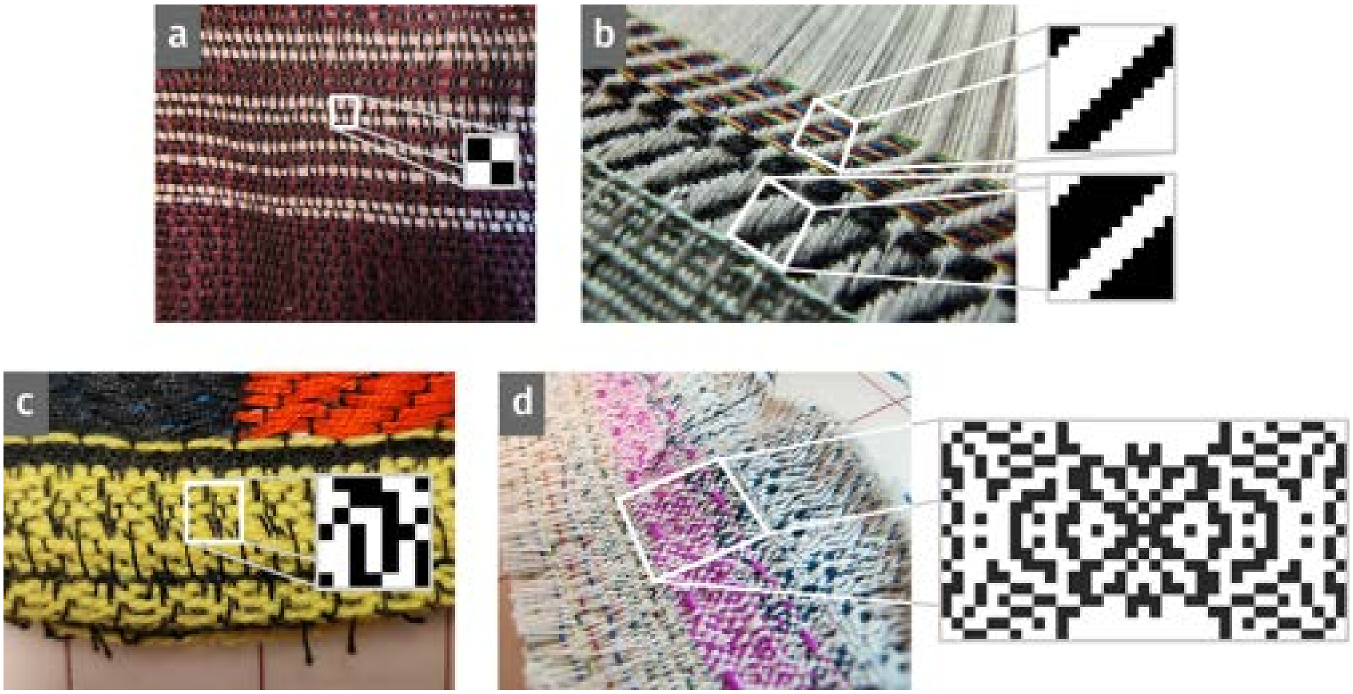

Figure 9: Selected samples woven by the authors with the Loom Pedals, and the draft used. a) A5's first try on the TC2, exploring tabby/plainweave and alternating colors. b) A large twill and its inverse woven by A1 and A6. c) A4's first try on the TC2 using the "random" Operation. d) A3's experiment with a "make symmetric" Operation to generate unique structures.

own synthesizer, situating this research within a larger culture of creative expression, improvisation, and reconfiguration [80].

7.3 The Pedals Inspired Happy Accidents

We theorize that this trust between weaver and loom further promotes improvisation by inviting "happy accidents". Most of the authors were not able to weave larger pieces partly because we worried about fitting the weaving into a larger project (A3, 4), or otherwise wasting time and materials (A2, 3, 4, 5). A1 was only able to overcome this inertia and planning paralysis by taking the extended weaving test as a personal challenge.

In one key moment, A1 accidentally reassigned a Pedal to generate a random draft structure and altered the design drastically. They decided to embrace the mistake as a "happy accident", and switched to a contrasting yarn to further highlight the change. Maintaining their improvisational momentum seemed to be an exercise in letting go of their desire for control, keeping the design open to external inputs. A2 picked the starting set of yarns for A1, and A6 later informed one experiment through an offhand comment about "squiggles". In the same way, mistakes and happy accidents can be seen as inputs from more-than-human voices.

7.4 Improvisation Required (Un)Learning

Through these reflections, we realized how instincts, emotions, and chance shaped the knowledge we embodied while weaving. Weaving is a repetitive activity, physically and cognitively. Through practicing this structured dance between themselves and their loom, a weaver's muscle memory not only includes their body, but their workspace as well. Consequently, those experienced with the TC2 (A1, 3, 5) had developed strong personal preferences for how they arranged their tools, prepared materials, and moved around the loom. On positioning their foot pedal, A3 said that they "preferred it to their right, near the [controller computer]" and would sometimes place a small dumbbell behind to prevent it from shifting. A1 differed, preferring the pedal "in the center of the loom, so [they] can shift side to side while weaving and avoid locking [their] knees." When A6 wove with the Loom Pedals, they repeatedly missed Pedal modules with their foot, as they instinctively stepped where they usually placed the TC2 pedal. Experience could help fluency, but could also hinder creativity and novelty. To illustrate, A3 compared hand knitting with weaving at the TC2: "I find knitting to be really improvisational for me because I know much less about it." Accustomed to the standard TC2 drafting workflow, they unconsciously resist changing their design while making it. "It's harder for me to get loose with [weaving] in the same way I do with knitting—add some stitches here, make this lumpy bit here." In contrast, as someone new to both knitting and weaving, A5's lack of experience allowed them to approach these crafts with a fearless curiosity. We cannot be certain these findings will apply to more weavers, but they suggest tensions in the Jacquard weaving process which the Loom Pedals prototype leaves unresolved.

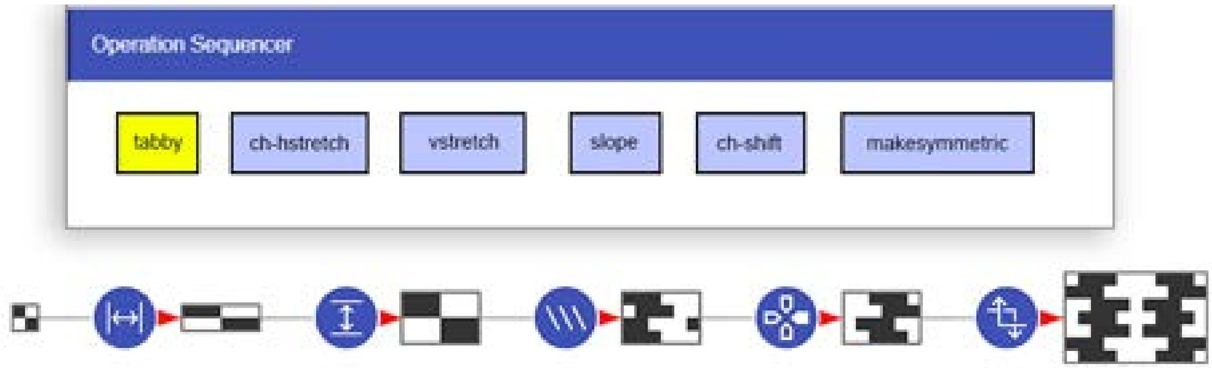

Figure 10: An example configuration for the Operation Sequencer, a new component in the Draft Player. (top) The Sequencer has been loaded with the following Operations to execute from left to right: tabby structure, (chain) horizontal stretch, vertical stretch, slope, (chain) shift right, make symmetric. The "hstretch" and "shift" stages are chained Operations to perform a single transformation multiple times. (bottom) The Draft Player output as the Sequencer progresses.

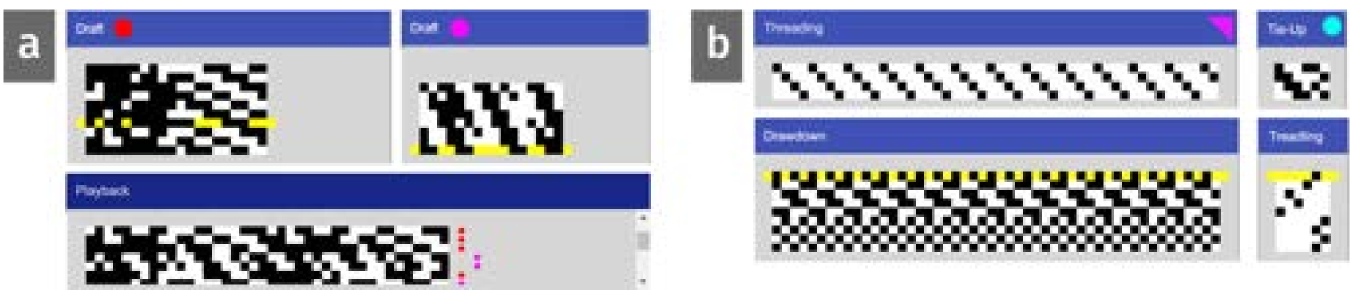

Figure 11: Key differences in the Draft Player in the Remixing and Treadle views. a) Remixing: Pedals are divided between the Drafts in the mix. The forward/reverse pedal for each Draft is highlighted in yellow. A "Playback" component has been added underneath the Drafts, which also indicates which Draft each row was selected from. b) Treadles: Pedals that are configured as Treadles are grouped and condensed into a separate component from the Pedals that execute Operations.

8 MAPPING FUTURE DIRECTIONS

Based on the above themes, we identified a number of possible features to expand the expressive range of the Loom Pedals. We present these ideas as a secondary set of findings, as the formative evaluation was intended to clarify how we could improve the prototype. The Loom Pedals are currently limited to fairly simple drafts, and we propose to expand the system's capabilities along three axes of weaver inputs: time-dependence, drafts, and physical inputs.

8.1 Time Inputs: the Operation Sequencer

A1 and A2 collaboratively developed a new "Sequencer" interface for the Draft Player, exploring how the Loom Pedals might continue to expand base AdaCAD Operations. Generating a draft while weaving, instead of using CAD software before weaving, introduces a time component to Jacquard drafts. When no longer confined to a static image, a legacy of the punch-card, we can reimagine Jacquard drafts as a sequence of dynamic Operation inputs. In Fig. 10, we show the Operation Sequencer interface component, which we designed to enable more complex Operation mappings to the Loom Pedals. Not only can the user chain together Operations to act as a single transformation, they can also add Operations to the Sequencer, a queue of Operations, to apply at certain time intervals.

8.2 Draft Inputs: Remixing and Emulating

Even with the Sequencer, the Loom Pedals interface can only handle one Jacquard draft at a time. However, the system can be modified to handle multiple drafts, treating each as a separate track to remix while weaving (Fig. 11a). The connected Pedals would be divided amongst the different drafts, each following a separate progression through set Operations. A new Playback component could record each row woven, highlighting when the weaver alternated between drafts.

We can also consider how the Loom Pedals might handle non-Jacquard drafts, such as shaft loom drafts (see Fig. 3). To use another technological analogy, we can turn the TC2 into a shaft loom emulator, as shown in Fig. 11b. The user would connect one Pedal per treadle. Additional Pedals could be connected to apply Operations during weaving. However, instead of applying the Operation to the drawdown, these Operations are applied to either the threading or tie-up, augmenting the flexibility of traditional shaft looms.

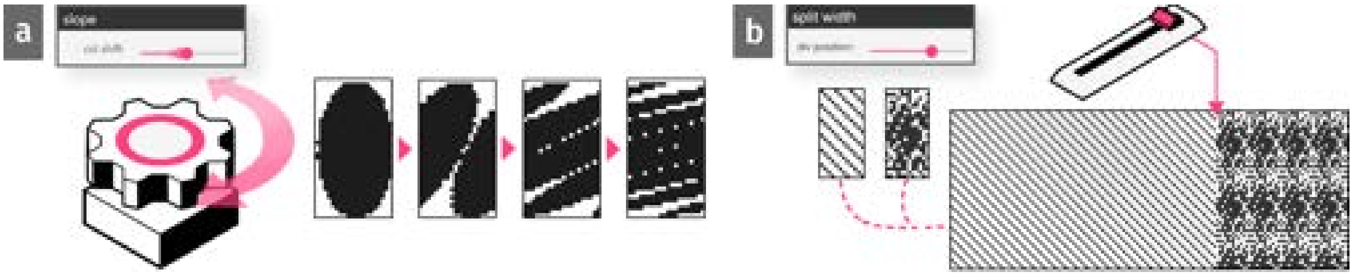

Figure 12: Two examples of weaving Operations that could be controlled with analog inputs. a) A knob that the weaver turns to adjust the "column shift" parameter of the Slope Operation. b) A slider that allows two different drafts to be woven side-by-side, where the slider's position corresponds to divisions in the weaving rows. Slider and gear icons by Lluisa Iborra from the Noun Project.

8.3 Physical Inputs: Sliders and Knobs

While our prototype only incorporates foot-controlled Pedals, we realized that hand-activated inputs would also fit into the rhythmic flow of weaving. For example, a user might prefer to press a button or keyboard to select an Operation. Beyond binary on/off inputs, we can also consider analog inputs like sliders and dials. In Fig. 12, we present two examples of how analog inputs can be combined with parameterized Operations to enable even more responsive draft editing. This feature draws upon our experiences with hand tools like crochet hooks and manual weaving techniques, as we found ourselves wanting a direct connection with the materials.

9 DISCUSSION

Looking back on our design and development process, we reflect on our original inquiry, the lessons learned, and how these insights will guide future development of the Loom Pedals. Primarily, we learned about the experience of improvising in the realm of textile craft, specifically weaving. Although, we focus our discussion on the unique facets of this project as they relate to broader discussions of improvisation and playful, creative interactions in the HCI community.

9.1 Playful Peripherals for Digital Fabrication

As discussed, one of our primary goals in designing the Loom Pedals was reimagining the Jacquard workflow in ways that invited playful improvisation. Besides the insights we gained in the context of weaving, we found connections to other works investigating playful improvisation in the HCI community, particularly in interactive digital fabrication.

As technologies such as 3D printers and laser cutters become increasingly accessible to the general populace, these machines have also become sites for exploring interactions with fabrication, physical materials, and data. [30, 90] Research projects often build bespoke machines, such as a wall-sized vertical plotter [13], or augment existing systems with new sensors and input modalities to enable novel interactions [60, 65, 82]. The Loom Pedals prototype does neither; it is a peripheral to an existing Jacquard Loom that expands one of the TC2's current input modalities. We highlight this fact to emphasize peripheral devices as an avenue for further design explorations in digital fabrication.

What would adding foot pedals to a 3D printer look like? What interactive mechanisms in printers might one draw out and exaggerate as a result? If foot-based interactions have distinct influences on the user's experience [89], how might playing with your feet, rather than twisting knobs or pushing buttons, free the hands for other forms of participation? How would this whole-body modality affect what users fabricate with the machine, whether for prototyping or creative expression? Peripheral devices may introduce novelty and playfulness to existing machines, unlocking unique interactions and design opportunities.

9.2 Learning from Historical Technologies

To close, we consider how our design process was informed by older forms of weaving. The Loom Pedals' design was heavily influenced by the design of shaft looms, and to a lesser extent, tapestry looms. Unlike most "dated" technologies, for example gramophones or cassette tapes, traditional looms are not considered obsolete to contemporary weavers and still see use alongside modern looms. Thus, we believe that the Loom Pedals presents a case study in how an interface can use history to inform its design and support the creative needs of its users, a case in which the existing technologies have a unique relationship with history.

In HCI, an ongoing research agenda is augmenting existing objects and spaces to enable connected interactivity [48, 92], including intimate contexts such as showering at home [45]. We note that nearly two decades ago, Wyche et al. called for researchers to sensitize themselves to past tools and cultural values in their design contexts, particularly when developing ubiquitous devices for the home [91]. Beyond the fact that textile crafts are often associated with home settings, designing for both of these domains can involve intimate, body-centered interactions. Generally, researchers understand that users of these augmented objects will be carrying over habits and associations in the form of embodied knowledge and cognition [46]. Thus, designing technology to sense and respond to these kinds of intuitions, such as how to hold horsehair for embroidery [24] or how weather can elicit sentimental responses [10], can enrich tangible interactive systems for users. In that sense, embodied knowledge is a kind of history inscribed into our bodies and communities, where past interactions with technology inform future behaviors. As such, historical technologies within our domain provide a wealth of possibilities for exploring new designs, rooted in older interactions.

By unlearning terms like outdated, obsolete, and low-tech, we can reexamine modern problems through the lens of past designs. Because a majority of shaft loom usage was pre-industrialization, their mechanics offered a unique take on improvisation, distinct from newer Jacquard looms. This distinction helped anchor our initial ideation for how to reimagine the TC2 workflow and it guided us throughout the design process, as a point of reference.

10 CONCLUSION

In summary, we began this paper by discussing the state of Jacquard weaving in textiles design and prototyping, and the limitations of the current workflow, as it relates to other types of weaving, particularly weaving on traditional shaft looms. We reviewed recent developments in HCI, where researchers have developed digital fabrication tools that make fabrication techniques and hardware more accessible, expressive, and collaborative. Given the related research in digital fabrication, we saw opportunities to design alternative hardware and software interfaces for Jacquard weaving that centered on playful improvisation, rather than meticulous planning. Our contribution consists of the documentation of our design and prototyping process, findings in the form of design lessons, and the resulting open-source interface to the TC2 digital Jacquard loom.

To review, the Loom Pedals are a hardware/software system of modular, interchangeable pedal inputs for the TC2, one of the few commercially-available models of Jacquard loom accessible to consumers. The customizable interface allows a weaver to place as many Pedals as desired, assign functions to them, which dynamically generate and transform drafts, then begin weaving an emergent design with little to no preparation. As a mixed group of experienced and novice Jacquard weavers, our own weaving practices informed this prototype. First, we implemented the core functionality, then collaborated amongst ourselves to design additional features for the Loom Pedals, to accommodate our varied weaving experiences. Reflecting on the process of designing and using the Loom Pedals, we found common themes that influenced improvisation and play in our weaving practices.

We present the collaboratively generated features as expansions to the Loom Pedals along three distinct axes of system inputs: draft inputs, physical inputs, and time-based inputs. Finally, we conclude with discussion points that relate to broader themes in our research community. We see the Loom Pedals as a system which brings the machine, design data, and human weaver into a direct dialogue with one another – a dynamic echoed in a world which increasingly links virtual and physical agents, as well as humans and the more-than-human.

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A GLOSSARY OF WEAVING TERMS

draft – binary encoding of a weaving pattern
heddle – a needle-like component used to raise and lower a single warp thread
interlacement – one crossing of a warp thread with a weft; one cell/pixel in a draft
Jacquard mechanism – a loom component which can independently control each heddle according to a punch-card program
loom – a machine used to weave fabric
shaft – a loom component which groups several heddles in order to raise a set of warps simultaneously
threading – the mapping of warps to shafts
tie-up – the mapping of shafts to treadles
treadle – a loom component that is connected to one or more shafts, raising them all when stepped on
treadling – the sequence in which a weaver steps on treadles
warp – a set of yarns set up in parallel, to prepare for weaving

weaving – the process of interlacing sets of yarns to create fabric
weft – a set of yarns that is interlaced with the warp after set-up
woven structure – a specific pattern of interlacements that achieves certain effects or characteristics in the fabric
yarn – long, flexible materials used in weaving

B SYSTEM COMPONENTS

The source files and assets for the Loom Pedals are divided into three components: hardware design, driver software, and design interface, each in a separate Git repository[3].

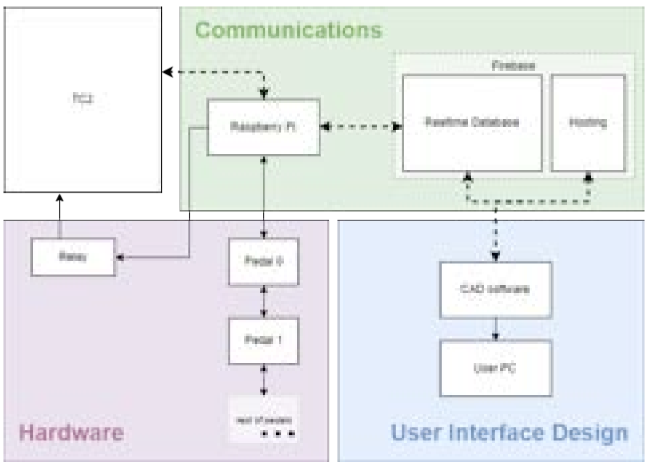

Figure 13: Overview of how the system components connect to the TC2 and with each other. Lines with only one arrowhead indicate one-way communication between components (output to input). Dashed lines represent wired communications (via TCP/IP or other networking protocols). Solid lines represent wired connections between components.

B.1 Hardware

The Loom Pedals are reconfigurable and interchangeable due to the digital logic circuit built around each Pedal module's physical switch. Each module can be connected in a chain, with only the first Pedal directly connected to the controller. Additionally, the controller receives a count of how many Pedals are in the chain, as well as the input state of each one. This design minimizes the effort required by the user to add or remove pedals, as they only need to (un)plug one end.

In addition to the Pedal modules, the hardware includes a power relay, also controlled by the Raspberry Pi, which connects to the TC2 in place of the existing foot pedal. This relay ensures that user inputs are correctly sent between the TC2 and the Pi.

The Pedal enclosures are divided into: a top panel for ease of stepping and a case to mount the switch, with the circuit board underneath (Fig. 7). The circuit boards include header connections on either side, so that the user can add/remove Pedals by physically attaching modules. The case also has openings on each side to enable these connections.

[3]Following these recommendations: https://www.oshwa.org/sharing-best-practices/

B.2 Driver

The Loom Pedals use both wired and wireless connections to communicate between the TC2 and the design software. The TC2 transmits data via TCP/IP over WiFi and takes foot pedal input from a physical port. The Raspberry Pi acts as an intermediary hub, managing both of these connections with its WiFi capability and GPIO pins, respectively. Furthermore, the Pi tracks all connected Pedals and facilitates a connection to the design software, which is a cloud-based web application. The routines for all of these communications are handled in a Node.JS application. We modeled the Pi, the TC2, and the design software as three separate, but tightly coordinated, state machines.

The TC2 has an established protocol for sending weaving data over TCP/IP. However, we had to define a unique protocol for the design software and the Pi to communicate in the cloud. To accomplish this, we created a set of nodes using a Firebase Realtime Database, which stores data as key-value nodes in a JSON, syncing rapidly-changing data across clients.