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Reflecting on the Emerging Sample Making Practices in Digital Craftsmanship

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Doctoral dissertation

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Table of contents

Prologue

Designerly ways of working often do not get translated into designerly ways of knowing. Instead, for the purposes of publishing and knowledge sharing, design processes get cleaned up to convey clarity or objectivity. Presenting design research as a *hero's journey*, meaning presenting the final design as a reached goal and the process as a quest to success, may be a common way for researchers to deal with the high complexity of practice-based design research projects [9]. However, this way of documenting and disseminating knowledge is disconnected from actual designing experiences which limits the potential of grounding theory on practice and, consequently, the potential of theory impacting future practice. It also helps perpetuate false expectations for what can constitute theory, alienating practitioners from researchers.

My aim with this work was to be both a practitioner and a researcher. For this reason, this dissertation does not report a quest. Rather, this is a *traveler's journey*, an attempt of connecting theory and practice through the telling of a messy process that embraced serendipitous opportunities while *making* soft things *with* and through a digital embroidery machine. Insights from a series of explorations in this design space converged into the design approach of becoming travelers, proposed through this work.

1 The point of departure

Before I get into the details of this dissertation and research methodology, I first introduce my background and personal motivation for starting this work. I was personally motivated to explore curiosity as an instrument of design research and how such curiosity can play a role in connecting design theory and practice. Different authors and practitioners influenced this work. One of the earliest influences I can remember came from my early days as a product design student, when I read "*Uma introdução à história do design*" [11] (which can be translated to "An Introduction to the History of Design"). Cardoso was explicit about the title being a warning that this book was but one of the many ways of tying together historic events that lead to design becoming a discipline. This idea of history as a narrative curated by someone, and therefore not a definitive and objective account of facts, directly influenced how I discuss the way that design processes are typically reported within this dissertation. In this book, Cardoso also discusses early accounts of the division between conception and labor, which was a key milestone for industrialization and for the emergence of the design field. It was arguably in the production of *gobelins*, tapestry for wall decoration, that we first see the figure of the designer (who was in fact a painter), as someone who conceptualizes things and communicates their vision through a technical language for others (in this case, weavers) to execute. This rupture from making was characteristic of the classic industrial design process in which I was trained when I started to study product design. Based on methodologies proposed by Bernd Löbach [52] and Bruno Munari [59], I was taught design processes were equivalent to 'following a cake recipe': ingredients may vary, but the main steps are the same. In this, *making* was presented to me as something to be considered during the implementation phase of the design, when the concept and most important design decisions have already been made. In this kind of approach, form is imposed to the material [41] and the real implications of working with specific materials, machines or techniques have room to effectively inform the design phase of the project. Therefore, experiments are either successful or failures in relation to the decisions that have already been made. Then, I could relate to the theory disciplines such as Semiology, but not the practical design approach. Unfulfilled by this kind of approach, during my master program I sought to engage with theory and develop my practice differently, based on first-person perspective and material experimentation. Undertaking such approaches, combined with prior interest in textiles, took me to designing soft wearables. Eventually, the advantages of prototyping wearables through high-fidelity means of fabrication led me towards digital craftsmanship, meaning engaging in research through making with digital fabrication systems. These transitions are entangled with my involvement with the Wearable Senses lab [85], from which I have been part of since 2014.

Through my design practice, I have become ever more intrigued by the growing rekindling between HCI/design researchers and craftsmanship. This renewed interest in craftsmanship was largely enabled by the democratization of digital fabrication machines, made possible by patent expiration of technologies that had been in use for decades but were only accessible in an industrial context [6]. I first engaged with digital machine embroidery for the development of a Smart Sock, sensorized socks for continuous tracking of gait quality (detailed in chapter 3). At the time, the choice for this technique was justified by project requirements related to the reproducibility of the design (needed to create a comparable pair of socks as well as comparable versions of prototypes). By working closely from the capabilities of the digital machine embroidery in this project, I began to see the relationships between parts of socio-techno system as potential links of renegotiations towards new kinds of things and ways of designing them. Observing (and trying to decipher) how the machine operates, I could see new ideas unfold and use that to inform the design process. This way of *collaborating* with the machine, in which we both contribute towards the outcomes of the making process, became an inherent part of my practice, as I will explain in detail in chapter 2. In retrospect, the main factors that led me to this machine were the selection of equipment available at the lab combined with samples that were on display above the machine, that showed the potential of using digital machine embroidery to create self-supporting textiles. I only reflected on the importance of these combined factors later, through the process of this PhD research, and this realization has since become a key aspect of this work.

I believe the field of wearables contributed to expanding the range of digital fabrication machines used in digital craftsmanship. Equipment such as digital weaving looms and embroidery machines have more recently joined this umbrella, that used to only encompass 3D printers, milling machines and laser cutters. I also believe that this field significantly stimulated bridging goal-oriented and explorative practices in HCI and design research. The complexity of creating integrated garments in the high level of fidelity needed to dress a moving body required reaching to crafts and developing new techniques to create soft or textile alternatives to conventional electronics. Tacit knowledge gained a different weight in this field as an important aspect of creating artifacts, but this type of knowledge is still difficult to articulate, particularly in the publishing formats used by researchers to communicate their work. To bring both the field of wearables and digital craftsmanship to their next levels, there is a need to continuously develop approaches to design grounded in the possibilites of materials and fabrication techniques. This motivated me to investigate ways of reporting such work, to better understand the implications of desiging with and through digital fabrication machines, and consequently, how these machines change design practice.

1.1 Research methodology

> *"Why tell stories like this, when there are only more and more openings and no bottom lines? Because there are quite definite response-abilities that are strengthened in such stories. It is no longer news that corporations, farms, clinics, labs, homes, sciences, technologies and multispecies are entangled in multiscalar, multitemporal, multimaterial worlding; but the details matter. The details link actual beings to actual response-abilities."*
>
> *Donna Haraway [37]*

This PhD research project focused on crafting soft things and wearables as an area of application that allowed investigating how digital fabrication machines have been transforming design practice, and what is the role of sample making in design research and HCI. As digital craftsmanship is still an emerging field and sample making is a nuanced, rich and multifaceted process, the theoretical framing to engage in investigating it was based on research through design approach [23], in which theory emerges from situated design practice [28]. Research through design is a term adopted by design researchers from diverse fields of design to describe practice-based inquiry, not having a particular epistemological basis [18]. Like design practice, research through design is plural and has been subjected to various interpretations by researchers. A common understanding is that research through design employs design processes as a method of inquiry to wicked problems [77], and produces different kinds of theory for design, which can take form as conceptual frameworks, guiding philosophies, and design implications [21]. In other words, it generates knowledge through design activities that, in turn, can be applied in design practice. More specifically, this research was conducted through an emergence-friendly approach [29], meaning that it was an exploratory research that welcomed surprise and in which "methods, understandings, outputs, even overall topics are all left continually in play". This approach was supported by notions from feminist technoscience and posthumanist thinking that promote relationality [3, 36] and multiplicity in design practice [86].

The notion of *situated knowledges* [36] indicates that, rather than aspiring to universality and objectivity, what we generate through research is an entanglement of relations that can be rearranged through new negotiations. This relationality is well illustrated through the metaphor of the string figuring [37], in which a pair of hands holds and lets go of entangled string, forming a different figure at each turn. I find this metaphor particularly fitting to explain the negotiations that occur in digital craftsmanship, which I will unpack in chapter 2. With each turn, we entangle humans, machines, and materials into a sample. We then reflect on it and renegotiate possibilities for the next sample or experiment, forming a process of *itineration* [42] in which each step is both a development of the previous and preparation to the next. Building on the notion of situated knowledge, Ron Wakkary [86] proposed the concept of nomadic practices in which knowledge gained through design research is situated and pluralistic, thus without seeking universality or claiming domains to limit what can be viewed as design or knowledge. "Nomadic practices follow the something they design wherever they lead and, in this way, they traverse in parallel, almost always on the move [86]." Acknowledging the notion of situatedness made it so collaborations with other designers that co-inhabit the Wearable Senses Lab, the textile fabrication lab where this research was conducted, were allowed to emerge and organically grow into projects that became important contributions to the dissertation. My stance as a design researcher and view on samples were also informed by the notions of *diffraction* and *intra-action* [3] as well as *matters of care* [50]. *Intra-action*, proposed by Karen Barad, consists of the mutual constitution of objects and agencies. In other words, separate entities only come to exist through each other, meaning that *intra-actions* "do not produce absolute separations, but rather cut together-apart (one move)" [4]. Building on Bohr's two-slit diffraction experiment, Barad argues for a non-binary view on mattering [3, 4] that highly influenced my view on samples. Instead of a success or a failure, a sample contains several concrete qualities and possibilities. Under certain circumstances, a "failed" sample can open opportunities for new directions. Therefore, in this work I propose seeing them both within and outside the process in which they were created. This leads to a practice of caring for the things we make, as the potentials of a sample can be activated long after the end of a given project through

Figure A. Relation of publications that compose this dissertation and the perspectives used in the sample making processes they discuss

revisiting. *Matters of care* has been proposed by María Puig de la Bellacasa as an understanding that to care for things means remaining responsible for their becomings through a strong attachment and commitment [50]. Revisiting samples, and creating strategies that support revisiting, can be seen as practice of care in which designers remain responsible and open for the other opportunities that samples embody.

In this research, sample making was explored through mixed perspectives [84], mainly through situated first- and second-person perspectives by making "by myself" and in collaboration with others, but also through third-person perspective by analyzing the work and practice of others (Figure A). First-person research methods enable researchers to be part of the system object of study thus explore design contexts from within, which means relying on first-hand experience as a mode of knowing [12]. Through rich descriptions and reflective practice, the knowledge generated is rich, inspirational, and situated in material practice. In this process, I have approached first- and second-person perspectives through autoethnographic methods [20], in which I engaged in making and documenting my own processes with the overall aim to explore and unpack digital craftsmanship. Autoethnography is a method that has been adopted in research through design as it supports pinpointing "the mental connections that are generated subconsciously and make their way into the designed" [85]. In my research process, I used the documentation of the samples as tool to document my process of "thinking in making", capturing the flow of expectations (goals) and insights gained through first-person perspective in each experiment. Such documentation supported discussions and reflections with other design researchers (colleagues, co-authors and supervision team), addressing my developing understanding of samples and making processes in digital craftsmanship. These reflections, and consequently my emerging understanding of digital craftsmanship, were documented through journal and conference publications thematically focused on the different projects within this research process. This means that the knowledge gathering process can be followed from paper to paper as I arrived at a more nuanced stance. Making with others and observing the practice of others (second and third-person perspective, respectively) also served to compare techniques and ways of working, thus supporting the reflections on my own practice. Research through design approach based on first-person methods has been successfully applied in different PhD research projects carried out at the Wearable Senses lab, where this research was carried out, by Kristi Kuusk [49], Martijn ten Bhömer [7], Pauline van Dongen [17], Troy Nachtigall [60] and Angella Mackey [54].

1.2 Research questions

This research is presented through a collection of papers, each investigating different aspects of the design space of explorative *making with* digital fabrication machines. To stay true to a bottom up and exploratory approach, there was a deliberate choice for not using Research Questions to plan and evaluate studies. Rather, questions emerging from the work were seen as research directions, sometimes in the form of simple '*what ifs*' or practical questions and sometimes as more structured questions, that informed the work presented in this collection of papers. As such, these publications show the evolution of my understanding of digital craftsmanship, the knowledge embodied by samples, sample making practices, techniques for crafting interactive materials and wearables based on digital machine embroidery, and strategies for nurturing explorative making. This dissertation is an attempt of threading these publications together, using the following questions to inspire broader reflections on the findings of this work.

This research departed from the perception that parts of our design processes are obscured in the way of reporting our projects. Communicating our processes as *hero's journey* is done for the sake of clarity and to conform with the publication formats used by our research communities. As such, this dissertation first tries to unpack points of obscurity in digital craftsmanship.

> **What is obscured in the practice of digital craftsmanship and the ways in which we describe the practice?**

Through early studies, another point of obscurity identified is that in trying to explain the practice of digital craftsmanship (or digital making, or hybrid craft) by dissecting it into its separate and contradicting entities (hand vs machine, digital vs physical), we obscure how they come together. As an alternative, a focus on samples is proposed.

> **What is unique about the practice of sample making of digital craftsmanship that should be communicated?**

Through an intense, long-term engagement with sample making, it was possible to identify different aspects of the practice and reach an understanding of what makes sample making unique. Samples are not only the outcomes of making processes, but they also embody the full socio-technical system of production. Thus, understanding samples and how they are used in our processes supports unpacking digital craftsmanship through a relational way. Acknowledging this opens the opportunity to pursue strategies for explorative making.

Can a focus on samples help us devise systems for taking the road less travelled in our making processes?

Samples are embodiments of the questions we ask entangled with our making skills, materials used, settings and state of machines, and other environmental conditions. As such, they can answer other questions than the ones we asked which means that, in the context of research through digital craftsmanship, sample making entails being able to follow a number of these insights without eliminating the traces that could lead to other directions. These could be the detours worth returning to in another journey. For returning to samples (which I call revisiting), we need to devise documentation systems that put attention to difference and to the unexpected in our making processes. To this end, in this thesis I propose a documentation format as an instrument for reflecting in different levels – both on the level of process (the role in the journey), or collection of samples, and on the single sample and its opportunities (what was made and what it does).

What does a focus on sample making reveal about digital craftsmanship? How does it transform the practice?

A focus on sample making practices led me to propose *traveling* as a metaphor for explorative making. In this proposal, explorative making also means collaborative making, in which agency is decentered from the designer and the different entities of digital craftsmanship are all potential collaborators. As such, engaging with this approach revealed that the model of entities that participate of digital craftsmanship (designer, machine, software, material) can be expanded to include the whole community of the lab, the other machines in the space, and the samples of others. This allows for more cross-pollination of ideas and techniques. Samples are at the center of such collaborations both as records from past travels and as invitations for new journeys. It is unpredictable when or under which circumstances will a sample be revisited. If samples are to remain actionable for new journeys, their documentation and the archives (or libraries) where they are stored need to be lively. This demands that we transform our practices to think of our current designs as future legacies. Bringing this approach to the context of research through design, this approach opens opportunities to question what and where is the knowledge being created in digital craftsmanship. New ways of disseminating knowledge gained through making as well as new formats of publication need to be crafted to share the knowledge embodied on the physical outcomes of our sample making processes.

1.3 Summary

"Nothing is ever finished. The artifact is a way station, the way to something else. Maybe, to the next artifact to be made in a series."

Tim Ingold [42]

Keywords: digital craftsmanship; sample making; design journeys; revisiting; making as traveling; itineration; explorative making; fellow travelers; cohabiting timelines

The field of *digital craftsmanship* has been developing at the intersection between maker culture, crafts, HCI and design research. *Digital craftsmanship* entails the use of digital fabrication tools as expressive mediums [44]. To achieve this, practitioners seek to reconcile craftsmanship values, such as risk and respect for materials, with the limitations and possibilities offered by digital fabrication machines. In this, both digital and physical assets are seen as craft materials that can be configured in various ways to create a wide range of designs and kinds of design (materials, artifacts, fabrication machines, interactive fabrication systems). Examples of designs include programmable materials such as knitted space fabrics [1], personalized 3D printed shoes [61], new fabrication machines like a felting printer [40], and interactive workflows between fabrication systems and CAD environments [22]. While research in the field has been abundant, the focus of research has been mostly on the possible new outcomes such technologies enable and new forms of interaction with fabrication systems. In comparison, the practices emerging in this field, and the role of the samples created through them, are underexplored. To investigate how digital fabrication machines transform design practice, this PhD research project took a *research through design* approach [23] to reflect on sample making and what a focus on samples can reveal about the practices emerging in *digital craftsmanship*.

The growing interest in exploring the possibilities of engaging with digital fabrication machines has turned sample making into an emerging key area of design research. Commonly used in fields such as textile design, sample making has been introduced into design research and HCI as a form of prototyping that is directly linked to the materials, tools and techniques used. In the context of *digital craftsmanship*, sample making is a fast-paced process which investigates new materials, emerging technologies, and ways of working with and through digital fabrication machines. The knowledge produced through sample making is distributed across the whole socio-technical system of production. Therefore, each sample offers potential insights related to application, interaction, programming, skill, technique, machines, material, collaborators and so on. Appreciating the potentials of each sample is difficult, which is reflected in the reporting of such processes. The difficulty of reporting material-driven processes often leads design researchers to describe design journeys from the perspective of the final sample as a reached goal. To build a clear narrative of how a project is

successful, samples or experiments that directly contribute to this success are more carefully described in research publications while others are often unaccounted for [80] or summarized as part of an (early) exploratory phase. Rather than discarding such experiments, this dissertation proposes that we look at making as an activity akin to traveling by seeing such experiments and samples as opportunities of new journeys.

The present PhD research project embraced serendipitous opportunities and the complexities (and even messiness) of material-driven processes both as a way of working and as objects of investigation. To reflect on the emerging practices of sample making in digital craftsmanship, sample making was explored from mixed perspectives [84]. This meant engaging with making through first-person perspective, making in collaboration with others and analyzing the practices of others. All of which was based on collaborating with the capabilities of digital embroidery machines to explore new possibilities of creating (interactive) materials and research products. This focus on sample making enabled me to depart from a utilitarian approach to prototypes to question what the notions of *failure* and *exploration* mean in *digital craftsmanship*. As a result, this PhD dissertation contributes with a combination of technical solutions for crafting wearables and soft things based on digital machine embroidery, and a design approach for *digital craftsmanship* that proposes *traveling* as a metaphor for making.

Making as a traveler means welcoming detours of the main inquiry of a given research design project and making time to pursue them. In this, it is understood that while exploration is often used to indicate a phase of looking for a direction, the proposal of *making as travelers* is to shift the notion of exploration from "not knowing where we are headed" to embracing that "we are here". *Explorative making* is about nurturing practices that allow us appreciating what we have at hand and coming back to it within and outside design journeys. This dissertation presents and reflects on different strategies to support this practice. Among strategies, ways of documenting-while-making and archiving are explored as tools that allow documenting simultaneously the journey of material-driven processes (how each experiment led to the outcome), while also promoting a practice of considering each sample for their individual qualities and potentials through reflection. Ultimately, the body of work here presented should be seen as a provocation to stay in the thick of making while opening our processes to new interpretations and to each other, fostering permeability of ideas, cross-pollination, *turn taking*, and collaboration through our material samples.

1.3.1 Reading guide

In this first chapter, I presented the motivation and methodology for the research. In the following chapters, I present how my understanding of socio-technical systems of fabrication and sample making practices emerged and evolved throughout the project. This understanding informed the approach of becoming travelers as a way of making proposed by this dissertation. Each chapter is based on peer reviewed publications. This dissertation treats these publications as it treats its samples, acknowledging that this is one of the possible ways of supporting a story through this body of work. As such, their division in chapters (Figure B) and contextualization within the dissertation is seen as a form of annotation of the design work to draw out design theory [10]. The papers can be read both within and outside the narrative of this dissertation, letting them stand on their own as possible *loose ends* for other explorations and journeys.

To differentiate the papers from previously unpublished content, papers are presented in a double column format and include a citation box at the top of the first page. Some publications consist of pictorials, a format in which the visual components are considered an important part of the contribution. For this reason, the layouts of pictorials were preserved as close to the original as possible. Figure captioning is different between published (numbering, self-contained to papers) and unpublished content (letters, running throughout the dissertation).

Chapter 2

In chapter 2, I discuss my understanding of digital craftsmanship and my practice with digital machine embroidery. The point of departure for this reflection was revisiting past projects done in the lab through two publications

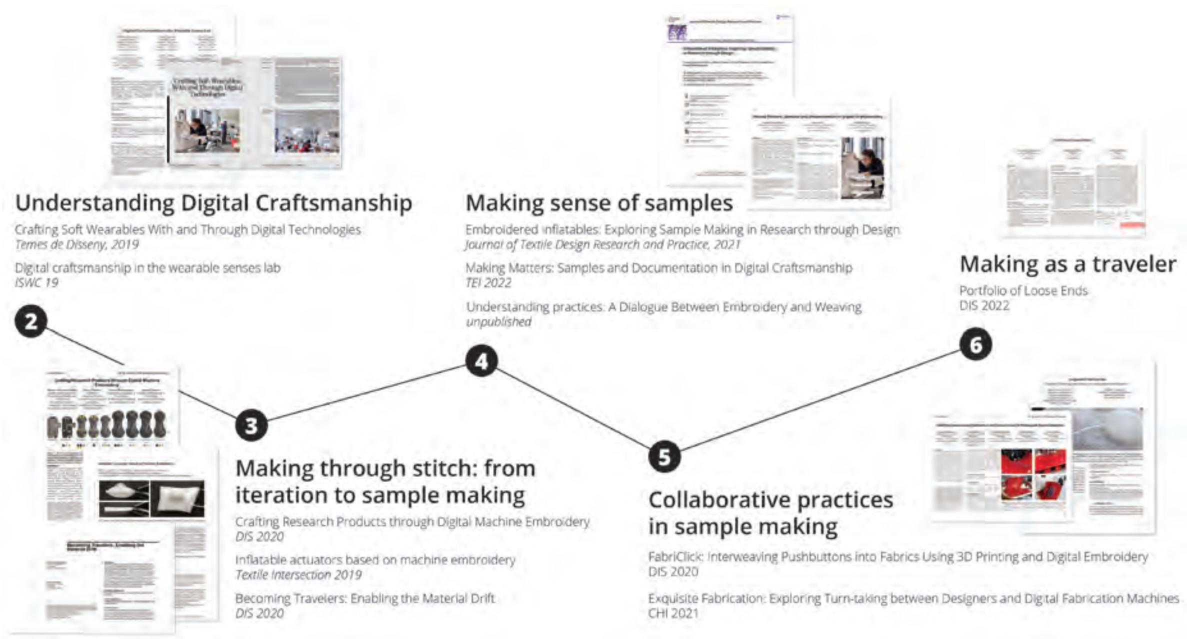

Figure B. Overview of chapters

"*Digital Craftsmanship in the Wearable Senses Lab*" and "*Crafting Soft Wearables, With and Through Digital Technologies*". This exercise of "looking back to look forward" provided the basis for discussing socio-technical systems and the attitude of makers engaging in explorative making.

Chapter 3

In chapter 3 I detail how I transitioned from iterative design (*hylomorphic* [41], top-down) to an *itinerative* (*non-hylomorphic* [41], emergent) process of sample making by looking at the material-driven design processes of three projects: *the Smart Sock, the Embroidered inflatables* and *Becoming Travelers*. The first two projects were longer developments that were discussed in the publications "*Crafting Research Products through Digital Machine Embroidery*" and "*Inflatable Actuators based on Machine Embroidery*", respectively. In both projects, the use of digital fabrication tools was core of the project but while the first was more goal-driven, the second allowed more emerging opportunities to inform and lead the design process. The third paper presented in this chapter, called "*Becoming Travelers: Enabling the Material Drift*", flips this transition into a performative approach to making and exploring. As the title gives away, this provocation is a key piece of this PhD research in which some of the possibilities of becoming travelers the basic attitudes that should be nurtured for supporting this practice were first identified.

Chapter 4

Chapter 4 further investigates sample making practices through two publications and an unpublished study. "*Embroidered Inflatables: Exploring Sample Making in Research through Design*" explores the potential of revisiting samples proposed at the end of chapter 3 through a creative session with a fashion tech design researcher in which we used the Embroidered Inflatables samples. Through this session, we found that ways of documenting and archiving are important for enabling viewing samples within projects and as research objects on their own. To look at other practices and understand how samples are currently used in the design process by designers in the field, two studies were conducted. One was an unpublished long-term study in which I put my practice in dialogue with that of a textile designer specialized in (digital) weaving using a documentation template for digital craftsmanship developed from my own documentation system of the embroidered inflatables as tool. This documentation format was further developed through her adoption of the template into her practice over time. The second study, presented in "*Making Matters: Samples and Documentation in Digital Craftsmanship*", investigated the work of other practitioners in the field through interviews conducted by Janne Spork, a master student who did her research semester within my project. These interviews gave insights on how samples are currently used within different practices and validated the importance of integrating documentation as extension of making to enable revisiting samples.

Chapter 5

As a parallel line of inquiry, the projects presented in Chapter 5 explored strategies to push the possibilities of collaborative practices by moving samples between machines. Rather than optimization, "*FabriClick: Interweaving Pushbuttons into Fabrics using 3D Printing and Digital Embroidery*" and "*Exquisite Fabrication: Exploring Turn-taking between Designers and Digital Fabrication Machines*" publications propose different strategies to add complexity of samples. These collaborations showed that the socio-techno system is more complex than we initially thought. Indirectly, the ideas, samples, people, and machines that inhabit the lab in a timeline rub off on each other. To tap into that potential, we need not only look backwards and forwards, but also to the sides. Together, the papers suggest ways of combining textile fabrication techniques and 3D through hardware, software, and strategies for nurturing an attitude for collaboration between designers and machines.

Chapter 6

In chapter 6, I expand the proposal of making as travelers by reflecting on the implication of putting this approach into practice. In the "*Portfolio of Loose Ends*" I explore how to communicate material-driven research in a multi-faceted manner by presenting the making of four samples through design memoirs, technical documentation and embedding the vector files into the pictorial. I reflect on the community of practice of the lab, on ways of traveling with fellow travelers, and on the role of documentation in explorative making.

Chapter 7

In Chapter 7, I conclude this dissertation with an overview of the research contributions and reflections on the concepts that emerged from this work.

2 Understanding Digital Craftsmanship

> *"If we consider machines as our own contraptions that embody us in extended and collaborative ways, rather than as tools of automation and semi-automation, what does it mean to make with, collaborate with, or become a machine? In which ways can we share autonomy rather than delegate automation? That is, in which ways can we make together rather than delegate the making to the machine?"*
>
> *Andersen et al. [2]*

Digital fabrication machines were first developed in an industrial context, thus their designs inherited notions like accuracy, optimization, and control that are important to engineering. The democratization of these machines after patents expired allowed for practitioners of many backgrounds to have first-hand experience with making [5] which prompted new bottom-up methodologies, such as *digital craftsmanship*. Inspired by expanded notions of craftsmanship, including Sennet's well known "desire to do a job well for its own sake" [79], design researchers in HCI have been developing new sorts of collaboration with machines, materials, and digital assets which opened up a design space for exploring emerging technologies and future manufacturing. This design space is very diverse in how engineering, craft and digital thinking are combined.

Researchers in the design space of digital making have, for example, focused on extending the range of additive technologies through new machines that enable the digitization of new fabrication processes or the use of different materials [38, 40, 51]. The development and characterization of (tunable) materials based on different digital fabrication machines and techniques [1, 34, 43, 57, 69, 90] has also been widely explored. Another approach used in this design space involves bringing experiential qualities of handicrafts into the interaction between designers and digital fabrication systems [22, 35, 58, 89]. Among other things, these seek for a less mediated fabrication process, facilitating the process of making design decisions-on-the-fly through direct manipulation of materials and processes.

This research is particularly interested in the approaches that more explicitly engage with the entanglements between humans, machines, materials, and environment. *Being the machine* [16], for example, is a system that guides users to follow instructions typically given to 3D printers. The aim of the system is to elicit reflections on agency and control in *hybrid making*. Iterative personalization [62] was proposed as a way to extend the notion of programming materials by considering the full lifetime of generated objects. In this system, the data from the use of objects created through generative design, in this case 3D printed shoes generated from the wearers data, serves as a starting point for new iterations of the design. Through an approach that also does not separate computation from the physical material, the *Ruta Loom* [68] engages the digital thinking of industrial jacquard weaving through embodied interaction. This handloom allows designers to physically program the woven structure of their textiles by changing the configuration of the shaft which contains pins that push down the warp yarns, emulating the way a jacquard loom would move individual yarns during the weaving process that allows programming complex textile structures. Both the *Hybrid Bricolage* [19] and the *Hybrid Basketry* [91] explore a complementary relationship between hand work and parametric design with digital tools to increase the complexity of the designed objects. While it is widely understood that digital tools and digital fabrication machines support generating complex objects that could not have been conceived otherwise, these two examples are interesting because they showcase how the opposite also stands. Both combine digital workflows and digital fabrication processes with handwork that cannot be (easily) automatized. The *Hybrid Bricolage* [19] presents a workflow for creating of three-dimensional objects based on honeycomb smocking technique (a hand embroidery technique based on fabric manipulation) through generative design and laser cutting, used to transfer the designs to the textile that will be hand finished. *Hybrid Basketry* [91] combines 3D printed structures with handweaving of reed, jute and canvas fibers in different degrees of investment between machine and hand work to create baskets. Nimkulrat and Oussoren [63] have also explored the combination of handicraft and digital tools. Their experience translating a coffee cup shaped object created through knotting into a 3D printed object first "revealed that the properties and characteristics of the handcrafted object were beyond the capacity of this digital tool" [63]. Their first experiment prompted an interesting process of exploration of the limitations and capabilities of 3D printing and other digital tools which resulted in considerations of the intra-relations between subjective decisions and tacit embodied knowledge of the maker, materials and techniques. Considering the role of the maker within the capabilities and limitations of digital tools, "digital processes presented challenges similar to those of craft materials and tools" [63].

The variety of the examples above shows that there are many possible ways to engage in digital making. Although I do not mean to categorize these, a rough division of these approaches in HCI could be between digital fabrication and digital craftsmanship. Digital fabrication is an umbrella for the approaches that lean more into engineering and material science. Digital craftsmanship, as the name may suggest, includes the approaches or practices that have borrowed notions through craft thinking from seminal work such as Sennet [79] and Pye [75] to explore and discuss materiality and making relations in HCI from other perspectives than engineering alone.

Digital craftsmanship is emerging as a form of research through design concerned with generating knowledge through *making with* digital fabrication

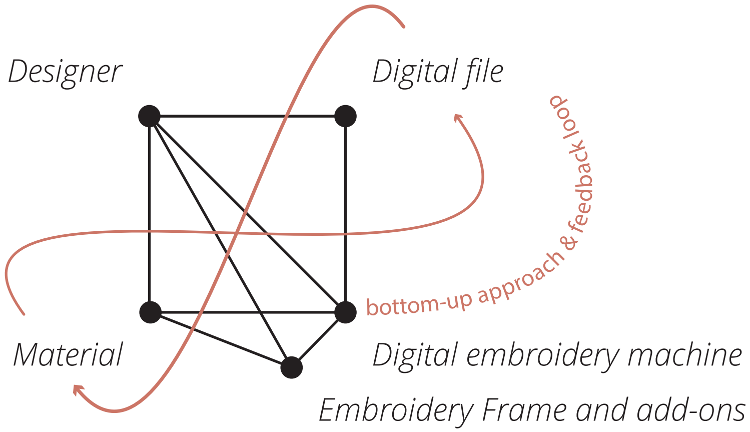

Figure C. Digital Craftsmanship consists of negotiations between all elements of the socio-techno system of production. The relational nature of digital craftsmanship makes it so that individual practices and aims of practitioners generating knowledge through sample making may vary greatly depending on their backgrounds and the digital fabrication systems they design with.

machines and other entities of socio-technical systems of production. As such, it shares a lot in common with neighboring fields like digital fabrication and material-driven design. Seeing that making is the main strategy used for this kind of research, samples are the most common kind of material outcome of design processes in this practice. As a bottom-up practice, making processes in *digital craftsmanship* are informed by a feedback loop between the physical samples and the digital files (Figure C). This loop is a big part of what allows such design processes to enter the realm of craft. Michael Nitsche and Anna Weisling [65], the computer can be used as "a tool that allows participants to shape and master its functionality in an as-immediate-as-possible encounter with the technology and material at hand". Similarly, David Pye [75] proposes that instead of separating craftsmanship from manufacturing through tools employed, we focus the sort of workmanship and the degree of risk involved. According to him, *workmanship of risk* means that "the quality of the result is not predetermined, but depends on the judgement, dexterity, and care which the maker exercises as he works. The essential idea is that the quality of the result is continually at risk during the process of making" [75]. Although machines and jigs lower the risks by increasing precision of reproducibility, their presence alone do not determine the degree of risk in the making process. In *digital craftsmanship*, allowing ideas that emerge during the sample making process to inform the design journey means that the whole process is always at risk.

In many occasions discussing this research, I was asked about what was *the digital* or *the craftsmanship* in this type of work. As this is both a diverse and emerging field, the terminology to describe a practice based on generating knowledge through *making with* and through digital machines is still being proposed and debated. This discussion matters because terminology carries values which can guide practice. While many practitioners in the fields of design research and HCI have been referring to it as *hybrid craft* [16, 26, 31, 92], others argue that the term *hybrid* overemphasizes the contrast between the concepts that form the *'hybrid'* (like digital and physical or hand- and machine-made) rather than how they come together. Laura Devendorf and Daniela Rosner [15], for example, question the use of the term *hybrid* as it describes the merger of distinct or contradictory entities and offer *coproduction* as an alternative metaphor for hybridity to draw attention to the tensions instead of the singularities of categories. Similarly, Troy Nachtigall [60] argues that "*hybrid craft* combines two disparate fields (one of these fields is always understood to be 'technology') in a multidisciplinary understanding. (...) *Digital craftsmanship* represents the interdisciplinary knowledge that comes from crafting with new technologies". Also adopting *digital craftsmanship* to describe their practice, Tobias Klein [46] suggests that *digital craftsmanship* consists of different entities merging into a new inseparable something through analogies like *syncretism* and *amalgamation*. Klein further pushes the idea of inseparability between digital and physical by comparing the process of 3D scanning to the concept of sublimation, the direct transition of phase from solid to gas without passing through liquid phase, in which the physical object dematerializes into "digital air" [46].

Variations of the term *digital craftsmanship* have also been proposed. Neri Oxman [70] used the term *digital ubiquitous craft* to describe material and fabrication-based design. As an attempt to highlight the creative collaborations and shared autonomy between humans and machines, Kristina Andersen et al. [2] propose the term *digital-crafts-machine-ship*. Maybe none of these terms perfectly describe the complexity of designing within socio-techno-systems of production which include digital assets, physical assets, and machines that share agency with humans. It could be called *digital-work-machine-man-ship*. It will probably end up being called something else as the field continues to develop. So, instead of arguing for yet another way to call it, this dissertation adopted *digital craftsmanship* to support keeping track of this development. My understanding of it is that while the *digital* in *digital craftsmanship* nods to the complexity of the socio-techno-systems of production; *craftsmanship* here refers to the commitment to the process of making through a deep understanding of the relationships between tools, materials, people, and ideas involved.

Beyond semantics, my aim in presenting the issue of terminology for the practice is to point out that we are still focusing more on dissecting it into separate entities than on what is unique about their coming together. As such, the interest of this dissertation is looking at how these multiple entities transform each other by being in relation. Therefore, when I say *making with* in this work, I turn to Donna Haraway's definition of the expression, meaning that different players, or *coproducers*, in more-than-human relations render each other capable of something new, *becoming-with* each other [37]. Ron Wakkary [86] has explored this notion in design research, arguing for *designing-with*. In the context of making with digital fabrication machines, what is observed is not the machine alone or the practice alone, but the activation of two '*becomings-with*'. This means the relations by which digital machines transform designers into digital crafters and by which the digital crafters transform the machines into experimental tools of making new things in new ways.

As a first step in the direction of exploring how the multiple entities that constitute *digital craftsmanship* are entangled and what else might be currently obscured in the way we describe this practice, this chapter will first look at the socio-technical system of production where I developed this research as a way of recognizing the situatedness of this type of work (section 2.1). Then, in section 2.2, I describe my own practice of *digital craftsmanship*.

2.1 The Wearable Senses Lab

> *"Constituencies are things- before- things that can be more fully expressed as gatherings before designing things. It is to gather those who are concerned, as well as the matters that cause their concerns, to debate and discuss designing something, without assuming or committing to the need for a designer of things, and then to debate and discuss what kind of designer the constituency wants."*
>
> *Ron Wakkary [86]*

In the previous section, examples of research in the design space of *making with* and through digital tools and fabrication machines demonstrated some of the numerous ways to engage in making and *digital craftsmanship*. From a posthuman perspective, this diversity of approaches is possible due to the relational nature of design, meaning we recognize whole socio-technical systems of production, and that their richness is embodied in the material outcomes of design processes. This means that to better understand both collective and individual practices, we should reflect on the socio-technical system of which we participate, this includes the relationships between the people, the work, the equipment and even the physical space where we work. This research happened within the context of the Wearable Senses lab (WS), of which I have been part of for the last eight years. Understanding that a designer is situated and formed within a particular constituency and that, consequently, whatever things designed are a product of such constituency [86], this section looks back at the evolution of the work done at our lab. I do this with the twofold intention of making my foundation as a designer explicit as well as to reflect on how *digital craftsmanship* has been developed within this socio-technical system of production.

The Wearable Senses lab is constituted by a prototyping space equipped with machinery to support the production of soft things (such as textile-based projects and smart wearables) and a community formed around it, composed by students, researchers, and occasional external partners. The lab has changed configuration many times over the years. The physical space moved buildings three times, new equipment was acquired, people joined and left, different work was created. As configurations change and new research directions emerged, research articles written in collaboration with different researchers active in the lab helped formalizing our shared position in HCI and design research at specific points in time. These publications supported documenting the evolution of the lab, its working culture, and its research direction. The first of such articles was "*Crafting a culture of prototyping*" [82], written in 2014, which discusses the role of prototyping in collaborative design processes of Smart Textile Services (STS). Prototypes are presented as both drivers of the process, capable of supporting shared ownership of ideas and of embodying the knowledge available in the project and in the lab. Prototyping through an iterative and hands-on approach was described as craft in the way makers become personally and emotionally attached to what they make and their experiences engaging with materials are strong motivators for design decisions. Another publication, "*Day in the lab: Wearable Senses, Department of Industrial Design, TU Eindhoven*" [83] adds to this view on prototyping culture by describing in more detail how the lab works, the organization of the lab and its infrastructure. Moreover, a commitment to a hands-on approach to design while nurturing a collaborative attitude between people in the lab was made explicit. Together, these two publications indicate that the lab community was focused on creating textile alternatives to hard components as well as exploring smart textiles and new interaction styles for close-to-the-body applications. By positioning the work done in the lab in the fashiontech field, the publication "*Towards a Next Wave of Wearable and Fashionable Interactions*" [81], published in 2017, sharpens this focus and previous commitments by leaning more towards fashion to achieve cultural relevance and social adoption.

To better understand our most current shared position in the field, an analysis of previous work done in the past years of the lab was done together with other researchers who have been part of the lab for many years. Although I had been a part of the lab as a student and as a researcher prior to this research, analyzing the body of work done in the lab supported me in situating my research. This analysis was used as basis for a journal article and a conference exhibition proposal (Figure D). The journal article, "*Crafting Soft Wearables, With and Through Digital Technologies*" (section 2.1.1), presents three levels of complexity regarding the manner designs relate to data in and around their own production to point at the vision the lab has for the future of wearables and soft things. In the exhibition "*Digital Craftsmanship in the Wearable Senses Lab*" (section 2.1.2), on the other hand, we formalize our understanding of digital craftsmanship and propose a format of documentation for future work. This documentation template emerged from my process of documenting the Embroidered Inflatables projects (chapter 3) and it continued to be developed throughout my research.

Altogether, these publications show how *digital craftsmanship* emerged within the lab as an extension of previous commitments with embodied practices, experimental and experiential design, and bottom-up methodologies for textile product-service-systems. The focus of the work at the lab progressively evolved from integrating components into textiles to explore close-to-the-body interaction towards exploring different kinds of engagement with (textile) production systems to rethink future manufacturing.

In the context of the present research, these publications particularly contributed with initiating a discussion on ways of documenting design work and proposing a practice of *looking-backwards-to-look-forward* that informed the strategies of nurturing the practices needed to engage in explorative making. This analysis also provided the basis for understanding my own practice (described in section 2.2) and reflecting on the possibilities of *designing with(in)* socio-technical systems, which lead to the approach of traveling proposed in this dissertation.

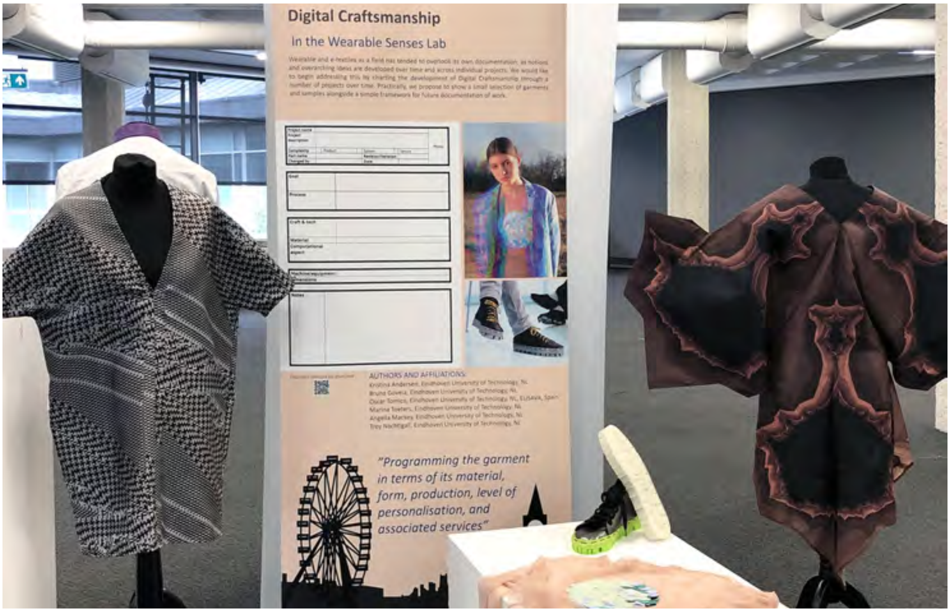

Figure D. The ISWC 2019 design exhibition included a selection of works created at the WS lab. It also included a proposal for documentation format which originated from my way of documenting the sample making process of the Embroidered Inflatables.

2.1.1 Crafting Soft Wearables, With and Through Digital Technologies

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Keywords

Composite Materials, Hybrid Crafts, Ultra-Personalization, Generative Design, Interaction Design, Dynamic Fabric, Digital Craftsmanship, Product Service Systems, Soft Wearables

ABSTRACT

As wearables and e-textiles enter into another hype cycle (Tomico et al. 2017), we find ourselves with the opportunity to reflect on the work that has been done and the work that remains to be done. In doing this, we hope to shed some light on the moment where we are now, the tools available to us, the materials in development and always central, the human body in all its complexity and unchanging biological functionality. The field of wearable soft things or soft wearables (Tomico and Wilde 2016) has developed from a niche concern to an increasingly well-documented area of research. As high-performing materials have become more widely available and our systems of making and production more sophisticated, we see wearable electronics projects emerge not only from the arts and fields of technology, but also from fashion, design and engineering. With the so-called 4th industrial revolution promising a much more flexible and automated factory work floor, we may soon see increasing levels of simple traditional electronics incorporated into soft things in our everyday lives (Andersen and Berzowska 2006).

In the Wearable Senses lab (Tomico et al. 2014), however, we believe that the future of soft wearables is now expanding to include programming, not just electronics and interactive behavior, but the programming of the whole garment in terms of its material, its shape, its manufacture, its level of personalization, associated services, and its direct relation to both its user and the social cultural and economic structures around it. In the following, we will provide an overview of projects created in the Wearable Senses lab in the last seven years. We know these projects intimately as we have seen them being built, tested, worn, analyzed and repaired. By looking through these projects we see three levels of complexity in the manner in which they each relate to the data in and around their own production and designs, namely, the product level, the system level and the service level.

Wearable Senses lab, Eindhoven University of Technology.

AT A PRODUCT LEVEL: DIGITAL MATERIAL PRODUCTION

The development of wearable technology is driven in part by the culture of “maker” DIY digital fabrication. Digital knitting, weaving and printing allow us to combine yarns, fibers or filaments with different material properties in different ways (structures) for each part of a garment. This expands the scope of design and production but also allows us to consider the craft aspects of innovative textile work. In the following examples, digital data is the main driver of each design:

In **Solemaker** (fig. 1), the shoe is designed based on a temporal data-composite created from the act of walking, either as a single footstep on a capacitive sensor or over the lifetime of wear and tear of a pair of shoes (Nachtigall et al. 2019).

In **Epic** (fig. 2), a thermogram from the body is combined with 3D body scan data to generate patterns based on algorithms to generate Voronoi diagrams with the Grasshopper plugin in Rhinoceros.

Shoemaker (fig. 3) developed a design tool and .gcode slicer with customizable surface textures and self-supporting structures, so support is no longer needed. In Zer Collection (fig. 4), three dimensional patterns in the shape of needle like fabrics were created by generative algorithms through the Grasshopper plugin to Rhinoceros.

Slow Analog Movement (fig. 5) used a binary mapping of black and white digital photos to the sewing direction of the embroidery to create a change in appearance depending on the point of view.

Fig. 1. Solemaker (2016). Troy Nachtigall, Bart Pruijmboom, Admar Schoonen, Henry Lin, and Loe Feijs. Solemaker is an interactive demonstrator for scanning, designing and manufacturing shoes. As an Ultra Personalized Product Service System, this process includes the scanning of feet, the design of the sole, the manufacturing of the sole, the manufacturing of the Upper. This is all coordinated via the solemaker.io website.

Fig. 2 Epic - Expression, performance, identity & control (2016). Kim Sauvé, Lisa Malou Smits, Liu Baisong. EPIC is meant for the amateur athlete who wishes to be able to express and control their performance. The skin temperature is measured and visualized by the color changing interface to give an organic data visualization when the body has warmed up (and is prepared for the exercise). The pattern on the sportswear becomes even more personalized through an algorithm that uses data from a thermogram to create a concentrated pattern at the thermal peak areas.

Fig. 3 Shoemaker (2017). Bart Pruijmboom. (Photo by Bart van Overbeeke)
Shoemaker is a set of generative 3D printable designs, with options for shaping the shoe, adding color, structures and textures, while insuring a good fit for any foot. Solemaker takes single piece production to the extreme. By means of unique patterns it is able to print the large overhangs with flexible materials without adding support material.

Fig. 4 ZER Collection (2017). Ane Castro Sudupe and Núria Costa Ginjaume. The Sweatshirt is one of the pieces designed by ZER Collection which features different uses of digital fabrication. The texture of the textile used to create the garment was generated through 3D printed dots.

Fig. 5 Slow Analog Movement (2018). Armando Rodriguez Perez, Elze Schers, Anne Lamers, and Evy Murraij. The Slow Analog Movement is the result of a design research that explored digital embroidery as means for concealing data on garments. The patterns created change in appearance depending on the light on the fabric and viewing angle.

AT A SYSTEM LEVEL: PERSONALIZED DESIGN PROCCESS

Algorithmic treatment of digital personal data allows the shape, design and finishing to be programmable and therefore modifiable in a way that maintains the identity of the designer while at the same time, matching the customer's identity, moving body and context of use. In the following examples, we see increasing levels of digital complexity on the designs.

In **This Fits Me** (fig. 6), a generative line pattern is projected on the digital version of the garment. By adjusting several variables in the generative algorithm, the customer can adjust the line pattern on the garment based on their personal preferences.

Fractal Art Fashion (fig. 7) laser engraves design patterns generated through recursive algorithms, applying tessellation theory and iterated functions systems to make fractals (Feijs and Toeters 2015).

Saiki (fig. 8) uses 15 measurement points of the customer and puts them into a parametric pattern in order to automatically generating G-codes ready for a 3D printer.

In **A Cellular Automaton for Pied-de-poule** (fig. 9), the generator of puppytooth patterns for the jacquard woven fabric is a one-dimensional automaton. It is possible to extend the automaton, which offers a rich playground for various types of semi-random yet pied-de-poule like behaviors (Feijs and Toeters 2017).

Fig. 6. This Fits Me (2014). Leonie Tenthof van Noorden in collaboration with Eunbi Kim. This Fits Me is a system that allows people to design unique and personalized fashion through 3D body scanning and generative algorithms. The system creates a virtual garment based on a 3D body scan of the customer. This customer can add a personal touch by customizing the generative design of the garment. This way, the garment fits the body as well as the customer's identity.

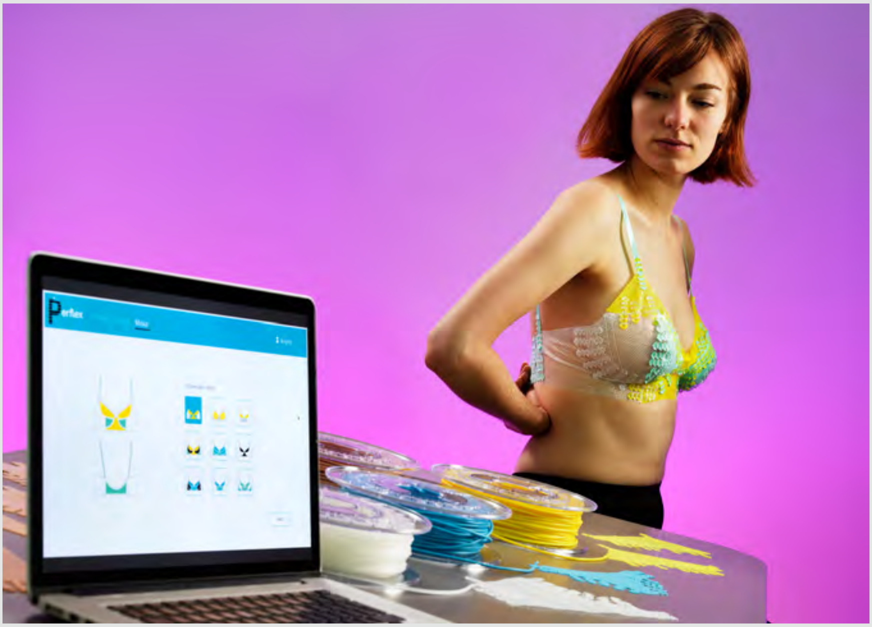

Fig. 8. Saiki (2017). Brigitte Kock. Saiki proposes a way to design a bra to fit the unique body shape of every individual customer with the use of 15 simple measurement points and a selection of parametric patterns. The design challenges the current practice of mass-produced products by large companies that provide 'one size fits most'. Saiki utilizes the possibilities of 3D printing and generative design to create a 'design that fits you'.

Fig. 7. Fractal Art Fashion (2015). Loe Feijs, and Marina Toeters. Fractal Art Fashion is a mini-collection of three attractive, high-tech fashionable garments based on the new fractal line pied-de-poule: a body stocking, a parka (coat) and a jacket. The patterns on the multilayer woven polyester fabric are laser engraved and created through algorithmic design.

Fig. 9. A Cellular Automaton for Pied-de-poule (Houndstooth) (2017). Loe Feijs, Marina Toeters With the use of the cellular automata theory, a more abstract pied-de-poule can be generated. The pattern was used to weave fabric from which garments are made.

AT A SERVICE LEVEL: END USER PROGRAMMING

By adding control systems integrated in the textile, we can use digital sensing and actuating capabilities to enhance its physical properties. In this way, "Self-programmed" behavior and functionality allow us to create new applications by programming the mapping between digital functionality and physical interaction. In the following examples, the complexity present in the designs continues to increase as the wearable is used and experienced by its owner.

Fig. 10. Tender (2012). Kristi Kuusk, Martijn ten Bhömer, Paula Kassenaar, TextielMuseum TextielLab Tilburg and Metatronics. Tender is a garment that reacts to stroking. It lights up separate pockets on the body according to how they have been in contact with the skin. By stroking the garment it is possible to 'move' the lighted part of the wearable. It can be used to gather light around the neck/chest area for reading, and hands area for the spotlight to find something in the dark or for other playful effects.

In **Tender**, the programmable electronics connected to capacitive sensors allows the LEDs (fig. 10) to react to the data transferred from the act of stroking the fabric against the wearer's skin.

Flow's (fig. 11) sequences of inflation and deflation of the air chambers are carried out by air pumps controlled through microcontrollers (Goveia and Tomico 2019).

Vigour (fig. 12) collects data about parameters related to movements of the upper body through the stretch of the knitted fabric sensors and sonifies them by means of a mobile application (ten Bhömer et al. 2015).

In **Issho** (fig. 13), textile-based touch sensors are connected to a microcontroller that turns on when it senses that the jacket is being worn. Phem (fig. 14) uses shimmering pastel-colored animated videos digitally composited onto fabrics in real-time via a chroma-key smartphone app (Mackey et al. 2019).

Fig. 11. Flow (2015). Bruna Goveia da Rocha. Flow is a wearable that includes six inflatable chambers that push against the body to cue fundamental joint movements of the wrist and forearm to foster learning physical activities, such as fencing. The integrated chambers and air ways in Flow operate as a material extension of the actuators responsible for the inflation, removing the air pumps from the area of actuation. Consequently, the wearable can be technically and materially sophisticated whilst remaining lightweight.

Fig. 12. Vigour (2016). Martijn ten Bhömer, Pauline van Dongen. (Photo by Joe Hammond)
Vigour is a piece of wearable technology for geriatric patients that would enable the physiotherapist to gain more insight in the patient's exercise and their progress. The garment can be worn all day and therefore gathers a lot of data. In addition to this, the garment can be worn when executing rehabilitation exercises and give feedback to the wearer by making a sound or optionally, also vibrate to encourage the wearer.

Fig. 13. Issho (2017). Pauline van Dongen, ItalDenim and with the support of Isabel Berentzen. Issho encourages the wearer to be present in the moment in an increasingly accelerating world in which our minds are often focused on future events. The jacket records social interactions (physical encounters and activity on smartphones) and is able to give feedback to the wearer using small vibration motors that exude the sensation of a gentle stroke on the upper back. Based on the wearer's behavior, the jacket responds to intimate touches to become a mediator of revived experiences in daily life.

Fig. 14. Angella Mackey.
Phem is a fashion brand concept for garments that use hybrid digital-physical fabrics. It can also be understood as a design exploration for fabrics that can be digitally animated, or fabrics that have the dynamic abilities of a computer screen.

LOOKING FORWARD AND BACKWARDS

Having worked alongside these projects for the past seven years has taught us that there is an increasingly complex and multifaceted field ahead of us. As e-textiles are partly absorbed into mainstream industrial production, the programmed garment is increasingly related to services. By designing smart textile things as a type of Product Service System (PSS), we have opened up the possibility of integrating the digital and the physical on various levels. As such, these devices can exist both as non-technological representations of a digital presence, and ultimately as forms owing their entire structure, presence and form to their digital identity. This broadening of what might constitute a wearable allows us to reconsider and redesign our current functionality, aesthetics, production, and design process (Nachtigall and Andersen 2018). We believe that the future of wearable soft things may still have technology physically embedded, but they may also be non-technical devices, where the technological innovation lies in how they are manufactured, the way they are personalized towards their users and uses and finally, in how they are related to product service systems throughout their use cycle.

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2.1.2 Digital Craftsmanship in the Wearable Senses Lab

Published as

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ABSTRACT
Wearable and e-textiles as a field has tended to overlook its own documentation, as notions and overarching ideas are developed over time and across individual projects. We would like to begin addressing this by charting the development of Digital Craftsmanship through a number of projects over time. Practically, we propose to show a small selection of garments and samples alongside a simple framework for future documentation of work.

KEYWORDS
Digital craftsmanship; documentation, theory development, soft wearables; interaction design; dynamic fabric.

1 INTRODUCTION
The field of wearable soft things or soft wearables has developed from a niche concern to an increasingly broad area of research [5, 9, 11, 19]. As high performing materials have become more widely available and our systems of making and production more sophisticated, we see wearable electronics projects emerge not only from the arts and fields of technology, but also from fashion, design and engineering. With the so-called 4th industrial revolution promising a much more flexible and automated factory work floor, we may soon see increasing levels of simple traditional electronics incorporated into soft things in our everyday lives [4].

We believe that the future of soft wearables is now broadening up to include programming, not just electronics and interactive behavior, but programming the whole garment in terms of its material, its form, its manufacture, its level of personalization, associated services, and its direct relation to both its user and the social, cultural and economic structures around it. In order for such complex frameworks to emerge, we need structures and terminologies not just to analyze past work but also to frame new projects and developments as they emerge.

2 DIGITAL CRAFTSMANSHIP
Over the last ten years, the notion of digital craftsmanship has developed through the building of our research projects and teaching in the lab. The term emerged as an attempt to describe the skill of expressing a designerly or artistic aim, manifested through soft physical materials, through a system underpinned by the digital material.

In our understanding, this digital material stretches from technological inspiration, technology envisioned in a project, technology required for execution, to technology for manufacture. Instead of considering the physical execution of an idea as the last and final step of a process, we wanted to allow material exploration, physical craftsmanship and skill to be central to our work with a set of materials that increasingly include digital material and notions.

This means that our projects increasingly combine programming, mathematics and material explorations, making use of crafting and open-ended making to imagine and craft new digital/physical objects. The digital often constitute the core material to be expressed through embodied objects ranging from the mundane to the complex; cardboard, recycling, fabric, embroidery, metal, printing and laser cutting etc. As a result, we are essentially working on material explorations of immaterial ideas in the context of post-human technology and new materialism [1, 14, 16].

In practice, this means that we consider digital assets design material, to be addressed and worked with in craft-like techniques, through hands-on making and sketching, moving through a number of computational design and manufacturing techniques all aimed at producing explorative designs of material/digital objects. All this is manifested through a very hands-on craft approach to working with machinery such as flexible substrate 3D printers, laser cutters (fabric, vinyl, leather etc.), digital embroidery, weaving and knitting. In this, our aim is to explicate our understanding of both machines and making towards a point, where we can make use of the technologies available to us as expressive mediums for craftsmanship.

3 DOCUMENTATION FRAMEWORK

To this end, we have focused on understanding and analyzing our own lab outcomes, what they explored, how they were expressed, and the extent to which they require a renewed understanding of the industrial work floor and its possibilities, as we work towards developing a renewed understanding of the roles of machines and aesthetics. These projects have already been documented in a number of publications on individual project level [2, 7, 8, 10, 12, 13, 17], but here we wanted to expand the scale, to be able to begin looking across projects over time.

In order to do this, we developed a simple framework, ilustrated in fig. 1. By looking through these projects we see three levels of complexity in the manner in which they each relate to the data in and around their own production and designs.

The three levels are the product level, the system level and the service level.

At a product level (digital material production), the development of wearable technology is driven in part by the culture of "maker" DIY digital fabrication. Digital knitting, weaving and printing allow us to combine yarns, fibers or filaments with different material properties in different ways (structures) for each part of a garment. This is widening the design and production space, but also allows us to consider the craft aspects of innovative textile work.

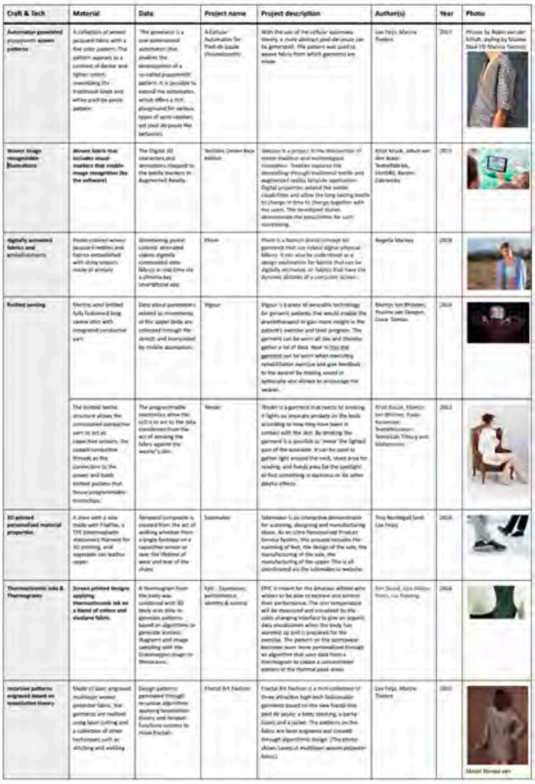

Figure 1. Part of an example page of documentation framework.

1. At a system level (personalized design process), algorithmic treatment of digital personal data allows the shape, design and finishing to be programmable and therefore modifiable in a way that still keeps the identity of the designer while the fitting to the customer's identity, moving body, and context of use. In the following examples, we see increasing levels of digital complexity in the designs.
2. At a service level (end user programming), we can use digital sensing and actuating capabilities to enhance its physical properties by adding control systems integrated in the textile. In this way "Self-programmed" behavior and functionality allow us to create new applications by programming the mapping between digital functionality and physical interaction. In the following examples, the complexity present in the designs continues to increase as the wearable is used and experienced by its owner.

As a crucial part of sharing and understanding this process, we believe that making the physical material available alongside the analysis of their context is a key component in allowing digital design and craftsmanship to develop a research culture for the future [3, 6, 15, 18].

4 EXAMPLES OF WORK

In the following figures (figure 2-5) we will show a number of project examples. We propose a selection of them for the exhibition.

5 PROPOSAL

For ISWC, we would like to propose an exhibit of garments and samples originating from our lab over a longer period of time. We will pick three examples, one from each of the categories mentioned above. These

Figure 2. Flow (2015). Bruna Goveia da Rocha. Flow is a wearable that includes six inflatable chambers that push against the body to cue fundamental joint movements of the wrist and forearm to foster learning physical activities, such as fencing. The integrated chambers and air ways in Flow operate as a material extension of the actuators responsible for the inflation; removing the air pumps from the area of actuation. [10]

Figure 3. Solemaker (2016). Troy Nachtigall (and Loe Feijs). Solemaker is an interactive demonstrator for scanning, designing and manufacturing shoes. As an Ultra Personalized Product Service System, this process includes the scanning of feet, the design of the sole, the manufacturing of the sole, the manufacturing of the Upper. [14]

Figure 4. A Cellular Automaton for Pied-de-poule (Houndstooth) (2017). Loe Feijs, Marina Toeters. With the use of the cellular automata theory, a more abstract pied- de-poule can be generated. The pattern was used to weave fabric from which garments are made. [8] Photo by Robin van der Schaft, styling by Maaike Staal (© Marina Toeters)

Figure 5. Phem (2018). Angella Mackey. Phem is a fashion brand concept for garments that use hybrid digital-physical fabrics. It can also be understood as a design exploration for fabrics that can be digitally animated, or fabrics that have the dynamic abilities of a computer screen. [12]

examples are all exhibition ready, but we will make the final selection when we have a better understanding of the space of the exhibition. Together these samples will illustrate and document past work at the lab, but also provide evidence of the process of developing the notion of digital craftsmanship and how we use this term and practice in the lab today.

6 REQUIREMENTS FOR EXHIBIT

Our garments and samples have no technical requirements, in the sense that they are stand alone. If possible, we would like to present at least one on a mannequin, but we can also have them on hangers or lying flat on a table. In addition to this, we would like to distribute our data sheet as seen in figure 1 as a proposal for the beginning of a future taxonomy of digital craftsmanship work.

7 VISION FOR THE FUTURE PAST

We are hoping that through showing not just examples of work at ISWC but also our simple framework for analysis, we can engage the community in conversation not only about what we have done, but also about what we may do next, how this fits with other work and communities and how we may document and share our experiences and knowledge.

8 CONCLUSION

We believe that the future of wearable soft things may still have technology physically embedded, but they may also be non-technical devices, where the technological innovation lies in how they are manufactured, the way they are personalized towards their users and uses, and finally in how they are related to product service systems throughout their use cycle. In order to build such visions of the future, we want to refine and evolve the notion of digital craftsmanship. Exhibiting at ISWC is a step towards doing this in conversation and collaboration with our wider wearable community.

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We would like to specially thank the authors of the works and all the staff, students and guests that have been collaborating with the lab over the years.

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2.2 My practice of digital craftsmanship

> *"Looking at a tool commonly gives a hint at the fabrication space in which it is applied, and this is even more so when seen among a collection of tools belonging to the same domain. The tool's physical appearance points at properties of the materials it is supposed to handle. The tool's size, manufacture, and functionality indicate producible forms and frame the possibilities for making."*
>
> *Irene Posch [74]*

My relationship with the digital embroidery machine started due to a combination of project requirements and the infrastructure available in the lab to create the prototypes for the AO Smart Sock project (the design process is detailed in 3.3). After the two interns working at the lab at the time introduced me to the basics of running the machine, I started gaining expertise on crafting soft things and *research products* through digital embroidery. By means of a technique called *chemical embroidery* [55], in which self-supporting embroidered textiles can be created by stitching on a water-soluble stabilizer, it is possible to deal with embroidery as a sort of additive technology. To inform my experimentation, I sought several sources about possible techniques to

Figure E. Me placing needles at the Brother PR1050x digital embroidery machine in the Wearable Senses Lab

Figure F. I had already explored variations of techniques by experiencing different tools for knitting in a project called "Crafts, Design and Motherhood" (six photos on the left). I later had an experience of the different implications of using an industrial knitting machine for the design process of the Smart Sock project (last two photos on the right).

learn the standard embroidery techniques and practices, as well as ways they have been appropriated by designers in the field of wearables and digital fabrication. These sources included embroidered samples hanging above the machine in the WS lab, scientific papers on wearables and digital fabrication, industrial machine companies' websites, video tutorials and the manual of the embroidery digitizing embroidery software. Indirect influences included the work of other practitioners in the lab, handicrafts, and other production techniques. As such, my experimentation processes are informed by *making with* the digital embroidery machine but also with other tools and embroidery techniques.

Exploring variations of a craft technique has been a way of becoming aware of the capabilities of different tools and creating sensibility to the relation between the material qualities of samples and their production process. I started to develop this practice prior to using digital fabrication machines, in a project that explored the crafting experience of knitting (Figure F). Later I applied a similar approach to silicone-casting to develop a technique to create Flow, a wearable designed to provide direction cues to the body through inflatable actuators [33]. When it came to embroidery, I engaged with the digital machine embroidery while also explored in parallel several other embroidery techniques such as tambour embroidery, needlework, free-motion embroidery, and punch needle.

In her reflections on craft productions, Nithikul Nimkurat emphasizes that a rhythmic interplay between bodily and thinking practices is established during making [64]. According to her, this enables her to move her consciousness from the act of making (what her hands are doing) to imagining future steps. In my experience, the same happens when working with digital fabrication machines. Making is a way of thinking and a mode of exploration. As one follows the rhythm of the machine translating digital files into sequences of action, they enter a process of designing with the machine and the new opportunities that emerge.

There are many ways of engaging with *digital craftsmanship*, such as focusing on (redesigning) the interaction with machines or on generative design. There are also different possible starting points for the process [70]. My practice of explorative *making with* the digital embroidery machine has been developed so far based on the understanding that while this machine is usually used for embellishments on textiles, what it does is interlocking two threads on a ground. It offers stability of the work through the embroidery frame, accuracy in the position of the needle, and freedom of routing. Understanding this was the basis for my collaborations with her, in which I asked what else could we make. Simple questions such as "what does it do?", "what is it usually used for?" and "what else can it be used for?" prompted a curious attitude towards materials and processes (Figure G). Because they are quite open questions, they can target machines but also the samples we make together. The order of the questions depends on the process.

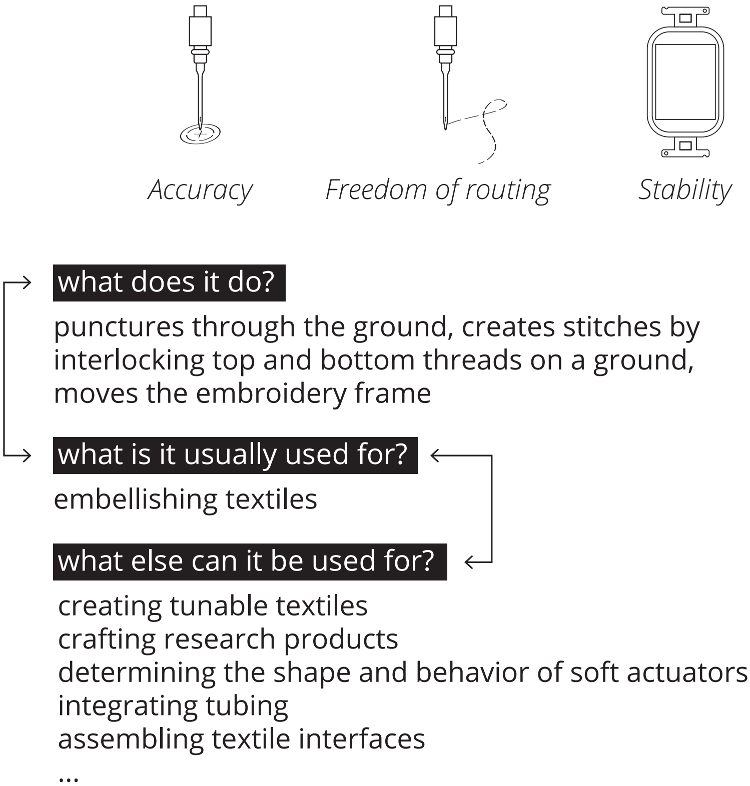

Figure G. Schematic of the questions that supported my collaboration with the digital embroidery machine. I started by asking "what it is usually used for" to collect clues about "what does it do". In turn, these questions help expand towards what else can it be used for. Over time, what it does became my usual departure point for new explorations.

3 Making through stitch: from iteration to sample making

"Design is what, for practical purposes, can be conveyed in words and by drawing: workmanship is what, for practical purposes, can not. In practice the designer hopes the workmanship will be good, but the workman decides whether it shall be good or not. On the workman's decision depends a great part of the quality of our environment."

David Pye [75]

In the previous chapter, I detailed how I developed my approach to designing with the digital machine embroidery. This approach was enabled by a transition from iterative process of design to seeing sample making as a process of *itineration* [41]. This also means a transition from a *hylomorphic* to a *non-hylomorphic* model of creation [41]. In other words, a shift from a top-down approach to design towards designing from a bottom-up approach, in which the designs emerge from the engagement with materials and fabrication techniques. In this chapter, I discuss how I went through this transition by looking at the material-driven design processes of three projects: the Smart Sock, the Embroidered Inflatables and Becoming Travelers.

The Smart Sock and the Embroidered Inflatables were discussed in the publications "*Crafting Research Products through Digital Machine Embroidery*" (section 3.2) and "*Inflatable Actuators based on Machine Embroidery*" (section 3.1), respectively. Comparing the processes of the two projects supported considering models of creation [41] and kinds of workmanship [75] in *digital craftsmanship*. The concept of models of creation is split between *hylomorphic*, in which the idea of a design precedes considerations about the fabrication, and *non-hylomorphic*, meaning the design emerges from the possibilities of materials and fabrication techniques in a bottom-up process [41]. As the samples generated through *digital craftsmanship* support a feedback loop to inform the making process, the model of creation is predominantly *non-hylomorphic*. The kind of workmanship, on the other hand, can range between *workmanship of certainty* or *workmanship of risk*, depending on whether the quality of the outcome is predetermined or not [75].

The Smart Sock was a goal-oriented project in which embroidery allowed creating integrated wearables in the form of *research products* [67], high fidelity prototypes, through a single fabrication machine. This process allowed recognizing a family of design elements that can be integrated through the same machine. To pursue its goal, the project started from a *hylomorphic* model, but it transitioned towards a more *non-hylomorphic* model once the digital machine embroidery entered the project. The reproducibility and accuracy of the technique allowed making specific changes to the designs. However, because the form factor and technology were developed together, the impact of these changes to the overall design was still considered. Due to their same high level of finish, rather than a prototype being compared to its predecessor, the research products created in the process are comparable among the whole collection, independent from the order of creation. In this, the accuracy of the technique was used to explore possibilities that would not have otherwise been allowed to emerge. Among other things, it was possible to explore how changes to the sewing direction and layering could cause stretch in a specific direction of the fabric. This was used to support a better fit around the toes and heel. Therefore, although the digital embroidery machine increased the level of certainty in the creation of each individual prototype, it can be argued that it also increased the level of workmanship of risk considering the complete design process.

The level of risk in the process of the Embroidered Inflatables was higher than in the Smart Sock. The intention of the project was to extend the family of (interactive) elements that could be integrated into *research products* through embroidery with the development of soft actuators. The versatility and freedom of routing offered by digital machine embroidery made it possible to combine materials (textile and silicone) and create inflatables whose shape as well as behavior were determined by the embroidery. The process, which was *non-hylomorphic* from the start, became increasingly more explorative. The second publication about this project (section 4.1) describes this intention as initially goal oriented. In retrospect, I see this more like a prompt than a goal. In a conversation with Christopher Frayling [24], Pye makes a distinction between a clear idea and a detailed one. According to him, “you must at every stage in making something have a clear idea of what you’re trying to do, even if you keep on changing the point of attack slightly as you go on” [24]. The series of the Embroidered Inflatables resulted from a clear idea of exploring the implications of digital machine embroidery to create soft actuators that evolved through collaborating with the machine. The questions that emerged through making and interacting with samples of each series informed and redirected the process of exploring this design space. These questions were captured through a process of documenting-while-making which supported reflecting both on the sample making process and individual samples. As result, it was possible to identify that each sample embodies different qualities and possibilities.

Reflecting on these two projects also allowed identifying samples as a specific kind of prototype that requires further investigation. Based on the Smart Sock and the Embroidered Inflatables as examples, samples in *digital craftsmanship* share important similarities with *research products*. Both kinds of prototype are made to have high level of finish, and they are evaluated based on what they really are and can do. The notion of relationality is equally important to them. However, this notion is considered differently in their evaluation since the research questions these two kinds of prototype seek to answer differ in nature. The high level of finish of research products makes it possible for these objects to blend into our everyday lives to support researching questions about human-technology relations over time [67]. The high level of finish of samples in digital craftsmanship, on the other hand, supports researching the *intra-action* [3] between entities of the socio-technical system of production. Understanding these entanglements allows, for example, identifying relevant variables to designing tunable materials. Unlike *research products*, the intended use of samples is more abstract which makes them especially suitable open for revisiting. Nonetheless, if the high fidelity of *research products* is used to evaluate the relation of properties to fabrication methods, research products can also be dealt with as samples. The stretch of the substrate of some of the *research products* of the Smart Sock, for example, was a point of departure to investigate which variables should be considered for tuning the behavior of the Embroidered Inflatables.

The third paper presented in this chapter, called "*Becoming Travelers: Enabling the Material Drift*" (section 3.3), was a response to the insight that a focus on samples and sample making could reveal different aspects of digital craftsmanship. Rather than thoroughly analyzing each of the embroidered designs to gather insights about the technique like in the other two projects, making served as a mode of thinking through our hands to reflect on making practices and the meaning of exploring. To support this reflection, the experiment had a component of documenting-while-making as each of the embroidered elements was marked by a tag to keep track of the concepts, and we followed up each of the two sessions with a discussion about our making experiences. Questions emerging from this discussion were also attached to the embroidery. The outcome of this process was a provocation to seek an approach to explorative making that could also support increasing sensibility needed to appreciate the things made in material-driven processes and to embrace detours in such processes. As the title gives away, this provocation is a key piece of this PhD research in which some of the possibilities of becoming travelers and the basic attitudes that should be nurtured for supporting this practice were first identified. The following chapters build on this provocation in two ways. Chapter 4 addresses sample making practices and the potential of samples created within one process leading to different directions. Chapters 5 and, especially, 6 deepen the exploration of the conditions of entering the *traveler's mindset* proposed by Becoming Travelers, supporting collaborative and explorative making.

The documentation of the Embroidered Inflatables sample making process and the embroidery files of the samples are accessible through a repository [32].

3.1 Inflatable Actuators Based on Machine Embroidery

Published as

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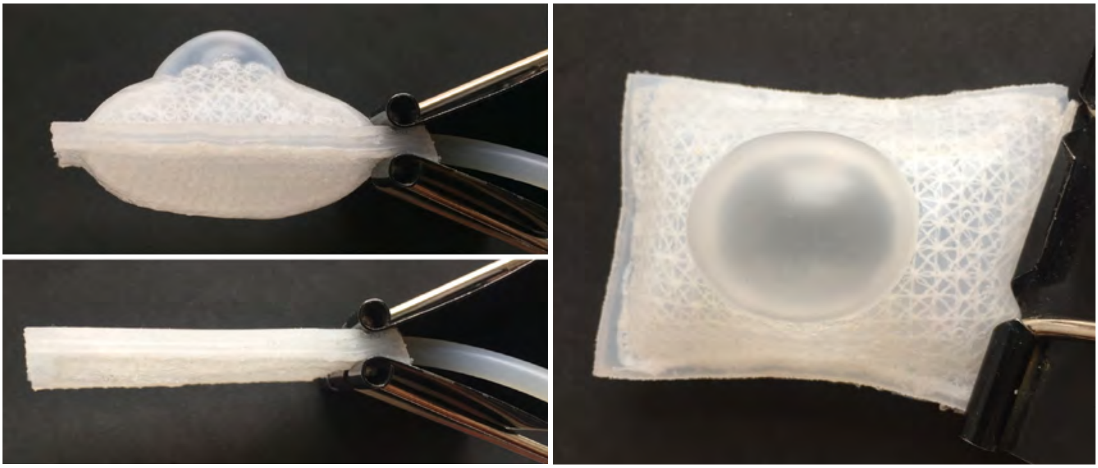

Fig. 1 Series 1 multi-state inflatable sample in relaxed state (bottom left) and actuated (top left and on right side). Sample made through two parts of embroidered substrate, a water-soluble sheet and silicone.

ABSTRACT

The growing interest in wearable technologies has prompted the development of new techniques for integrating electronics into garments, and more specifically to overcome the challenges interfacing hard and soft components. In comparison to sensors and leads, the textile-based or integrated solutions for actuation remain underexplored. Approaching materials as extensions of actuators, we investigate machine embroidery as means to integrate silicone-based inflatables into garments. Following a research through design methodology, we created inflatables whose design and behavior are determined by machine embroidered substrates. Our iterative process resulted in 24 samples, divided in five series, exploring distinct challenges: 1) sewing attributes to create properties of inflatables; 2) fit & support; 3) improving integration & resolution of complex shapes; 4) enlarging area of actuation; and 5) textile integration. We discuss the impact of different parameters to the fabrication and the interaction possibilities of soft actuators. We show how machine embroidery allows shifting the complexity of the designs away from the casting process, simplifying fabrication, while enabling the creation of a wide range of shapes and behaviors through layering of textile structures. Our work extends the possibilities of integrating different technologies into garments through a single manufacturing process. We contribute with the detailed description of our design process and reflections on designing inflatables by means of machine embroidery.

KEYWORDS
Research through design, soft actuation, digital fabrication, machine embroidery, technical embroidery

1 INTRODUCTION

Textile production techniques, such as knitting, weaving and embroidery have been widely employed for the creation of electronic friendly or electronic integrated wearable technologies (wearables). Embroidery, in particular, has shown the potential of supporting the design of interactive garments as it offers more freedom of routing than knitting or weaving [9] to create soft circuits [7, 14]. Moreover, it enables direct interconnections with conventional flexible electronics [9] and fabricating a variety of sensors.

While textile-based sensors have reached a higher level of maturity, having been integrated into commercial products such as smart garments for sports [8, 16], soft alternatives to actuators remains relatively unexplored. Usually, wearables are actuated through external mechanisms, such as motors, which restrain their wearability [3]. Among other forms of actuation, inflatable soft actuators (inflatables) are gaining interest for their use in a range of applications, such as navigation through tactile feedback [15] and augmented reality to create languages of feel effects [2]. Although the integration of air pumps into wearables still needs to be further explored for a completely unobtrusive user experience, inflatables can be produced through many techniques and materials, offering opportunities for customizing their form factor, material properties and dynamic behaviors. Additionally, the air pumps can be removed from the area of actuation [6]. This could be used to respect guidelines of wearability such as weight distribution or proxemics [18].

The challenges of integrating technology into garments include bulk/weight/stiffness, thermal and moisture management, flexibility/durability, sizing and fit, and device interface [4]. Additionally, the amount of manual work involved in realizing prototypes often makes it difficult to accurately reproduce them and compare variations/incremental changes. This is particularly an issue in contexts where high standards for reliability and safety are expected, such as in healthcare applications. Digital fabrication can support iterative design processes through highly reproducible prototypes by allowing designers to make isolated and precise changes per iteration. Specifically, digital machine embroidery can support such approaches while requiring a relatively low threshold of experience.

The present body of work builds upon earlier research on silicone-based inflatables for supporting tactile motion instructions [6], combining it with machine embroidery to develop reproducible textile integrated on-body applications. As such, we aim to contribute with new ways of using technical embroidery to develop soft wearables and textile interfaces [5, 12, 14]. The scope of this paper is limited to exploring how to fabricate silicone and embroidery-based inflatables (Fig. 1) to understand the implications of using machine embroidery for their fabrication and some of their actuation possibilities. We do so by reflecting on our research through design (RtD) process of five sample series of inflatables, culminating in three identified behaviors, which we refer to as interaction modes. To support our reflection about the reproducibility of the inflatables, the interaction mode designs were given to industrial design students, without prior experience with machine embroidery or casting, to be reproduced and implemented in their research projects within the context of physical rehabilitation.

2 INFLATABLE ACTUATION IN WEARABLES

While still relatively unexplored, inflatables have been gaining interest by designers of wearable applications due to their versatility and the possibility to conform to the body. Inflatables can be fabricated through a variety of processes and materials, both elastic and inelastic. The customization of the inflatable artifacts allows for creating simple to complex structures that behave in very specific ways.

AeroMorph [13], for example, presented a heat-sealing approach to fabricate inflatables made of different sheet materials coated in TPU (thermoplastic polyurethane) capable of curling, folding and changing texture. Polyurethane heat-sealed inflatables have also been adopted by The Force Jacket [2] to adapt a life-vest to support augmented reality experiences. Through 26 inflatables on the upper body, this wearable simulates a variety of sensations like feeling rain, being punched and being hugged. The WRAP [15] also explored the heat-sealing technique for creating inflatables made of plastic sheeting to propose an alternative to vibrotactile stimulation to avoid sensory adaptation in haptic applications. The low-profile switchback channels are used to enlarge the actuation area. As a demonstrator, these actuators were implemented into a wristband to guide movement through four points around the wrist. Rotation was indicated through a directional metaphor, in a similar approach to saltation via vibrotactile stimulation [11], having each actuator inflate and deflate in sequence.

Reporting similar material dynamic behaviors like the Aeromorph, PneUI [17] presented approaches to create soft composites both inelastic and elastic. For their inelastic actuators, plastic welding was used. For the elastic composites, materials of varying elasticities were embedded into silicone to control their behavior. The casting processes presented by PneUI include inserts to create dynamic textures and two- part 3D printed molds to cast silicone parts that are bonded together after cured to create air channel shapes. The difference in elasticities to control the behavior of inflatables was also explored to create self- sensing soft actuators based on machine embroidery [1]. Spiral patterns made of Kevlar fiber and optical fiber were embroidered on water-soluble film then embedded in silicone to control the shape of inflation and sense the deformation. Flow [6] used a 3D printed mold and 3D printed PVA inserts to cast silicone- based inflatables that provide users with tactile motion instructions to support motor learning. The wearable was entirely made in silicone which unified the process of form giving of the wearable with the design of the air pockets and paths. As an alternative to casting, the Self Assembly Lab [10] has explored additive technologies to develop liquid printed pneumatics which enable creating complex dynamically shape-changing structures.

While heat sealing enables the creation of textile-based inflatables, their integration into garments is limited by the inelasticity of air tight fabrics. Silicone-based inflatables, on the other hand, offer elasticity and work well for wearables designed for smaller areas of the body, such as the wrist or hand. For larger areas of the body such as the torso, however, crafting an entire wearable out of silicone presents challenges to fabrication and usability. Therefore, solutions for integrating silicone-based actuators with textiles are needed in order to broaden the range of applications of this form of actuation. By using chemical embroidery [12] to create a free-standing, lace-like substrate and by exploring the programmable nature of machine embroidery, we present a technique for integrating silicone-based

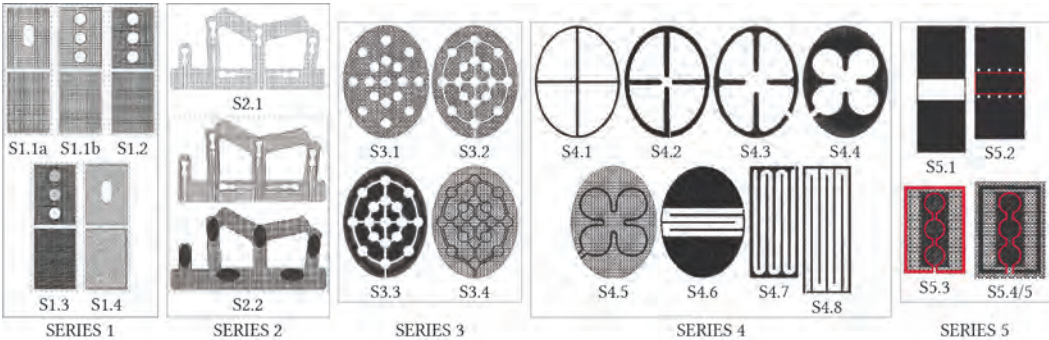

Fig. 2 Overview of the five-sample series. Each series of samples addressed different challenges: 1) sewing attributes to create properties of inflatables; 2) fit & support; 3) improving integration & resolution of complex shapes; 4) enlarging area of actuation; and 5) textile integration.

inflatable actuators into garments. Our approach considered three strategies facilitated by machine embroidery: *layering & manipulating the fabric character, component alignment*, and *shaping & construction*. In the next section, we describe how we explored designing inflatables through machine embroidery and reflect on our process.

3 DESIGN PROCESS OF THE EMBROIDERY-BASED INFLATABLES

We followed a research through design (RtD) to explore how to create inflatables through machine embroidery and, particularly, chemical embroidery. Chemical embroidery is a technique used to create machine-made lace. Designs are embroidered on a water-soluble film that, when dissolved, results in free- standing substrate [12]. Our explorations resulted in twenty-four designs, divided in five series of samples (Fig. 2) each addressing different challenges: 1) sewing attributes to create properties of inflatables; 2) fit & support; 3) improving integration & resolution of complex shapes; 4) enlarging area of actuation; and 5) textile integration.

The actuators were made through the combination of free-standing embroidered substrates and silicone (Ecoflex 00-30). They were designed using Adobe Illustrator and PE-Design 10 software. The fabrication process was carried out using semi-professional digital embroidery machines to sew the designs on water- soluble film, and acrylic laser-cut molds for casting. Apart from some short experiments with alternative materials such as monofilament and elastic thread, the samples were made entirely using conventional polyester embroidery threads. During the development of the sample series, the inflatables were manually actuated through syringes.

Different procedures were used to construct and cast the samples throughout the process resulting in different inflation dynamics. In some cases, like in Series 1, an additional layer of the water-soluble film was used in between substrates. Similar to the textures created through laser cut fabric described by PneUI [17], the difference in the properties of the embroidered textile and the silicone create the possibility of multi-state deformation. In other cases, like most samples in Series 4, the film used for the embroidery serves to create the air pockets, which means the actuator inflates to both sides. As a third construction possibility, samples have a support pad over which another piece of water-soluble film is sewn in the shape of the actuation area causing the inflation to be one sided. Based on the main learnings

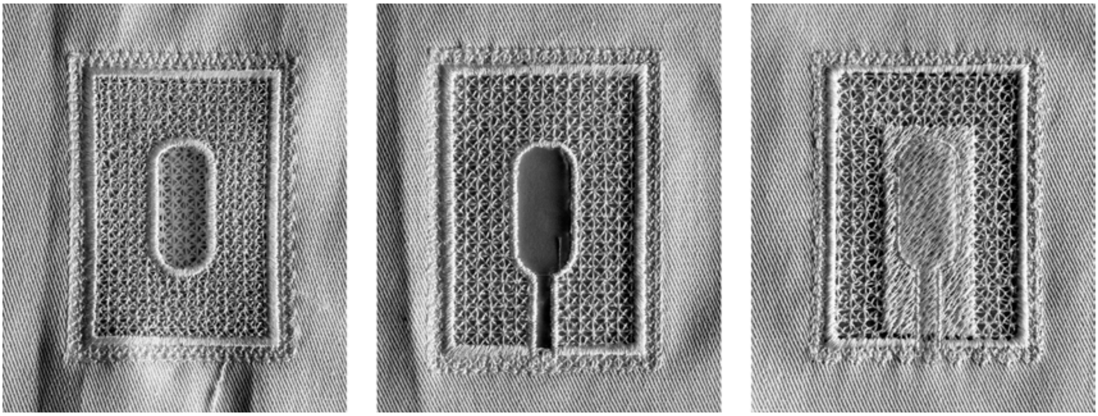

Fig. 3 Embroidered substrates of Interaction modes 1, 2 and 3 integrated into woven textile. Mode 1 is made from two embroidered parts. Mode 2 consists of a single embroidery part. Mode 3 is a single substrate sewn as layers that integrate a sheet of water-soluble film over the substrate and support pad.

from the sample series and these three observed actuation possibilities, a final set was made including three samples which we refer to as interaction modes (Fig. 3).

Below, we present our approach to designing inflatables through machine embroidery and reflect on the insights gained throughout sample series 1 to 5.

3.1 Embroidery-based inflatable sample series

Our approach to designing the sample series considered three strategies: layering & manipulating the fabric character, component alignment, and shaping & construction.

Layering & manipulating the fabric character, was the most relevant to this work. It pertains to defining the material properties of the substrate through sewing attributes and by sewing layers of different attributes on top of each other to manipulate the fabric character, globally or locally. We have explored this technique throughout all sample series. In Series 2 and 5 (Fig. 2), for example, we used layering to create support pads used to direct the inflation. We also used layering as a solution for avoiding stitch repetitions when sewing complex shapes (Fig. 4).

The second technique, *component alignment*, concerns the possibility of machine embroidery facilitating iterative

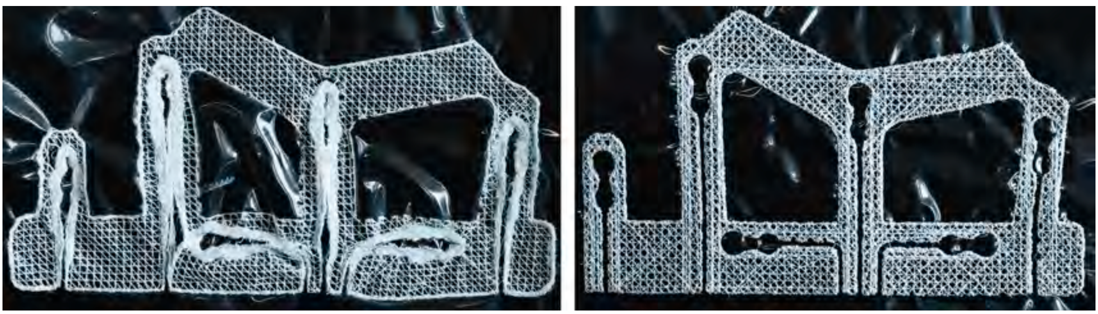

Fig. 4 Series 2 samples explored different sewing attributes to the same complex shape. As seen on the left, Net Fill Stitch causes excessive repetition of stitches to complete the design, deforming the outcome. On the left, the same shape was sewn as layers of Fill Stitch in two different directions that interlock.

design by enabling precise changes to be made to prototypes while the position of components (embroidered or embedded) is preserved. We used this technique in Series 2 in which we recreated in embroidery the design of Flow [6], a wrist worn soft wearable originally made of silicone only, which included six inflatables to push against the body. Between our two designs, the location of the six inflatables was preserved while we experimented with the sewing attributes of the substrate.

Finally, *shaping & construction*, relates to reducing the amount of manual labor in patterning, cutting and assembly of prototypes by designing complete wearables through embroidery. Entire wearable form factors or garment pieces can be shaped through the embroidered substrate as in Series 2. We focused mainly on the construction of samples and integration to fabric. In Series 5, for instance, we created a technique for integrating the inflatables into fabrics through cutwork needle. This opens up possibilities to increase the accuracy of reproducing the actuators as well as the way they are integrated into garments.

3.2 Reflections on designing embroidery-based inflatables throughout iterative series

Based on our experience, we reflected on the design implications of fabricating inflatables through machine embroidery. Together with the approach presented in section 3.1, the following points can serve as design guidelines to explore this fabrication technique:

- **Material properties:** the type of thread used to embroider effected the casting process more than it influenced the actuation. In Series 1, for example, we recreated the samples made of polyester in monofilament to compare the outcomes. While the deformation of actuators was equivalent, the casting process of the monofilament substrates was more challenging. The substrate did not absorb the silicone and tended to curl in the mold during casting, resulting in bubbles in the silicone. Rather than achieving different properties through the thread, we explored variable material properties of the substrate through layering. Layering enables the creation of variable material properties on the substrate, including creating support pads that direct the inflation to one side. This could be explored to support fit around the body through areas of variable flexibility/stretch.

- **Deformation:** we explored different factors that influence the actuation. In multi-state actuators (e.g. Series 1), for instance, the sewing direction had greater impact in deforming the actuator (pocket stretchiness) than small variations of density/spacing of the sew region types of embroidery. Size impacted the homogeneity of actuation. While multiple chambers allow for enlarging the actuation area of the inflatables, their actuation is gradual. For a homogeneous inflation of this kind of structure, multiple input points are likely to work better than one.of digital complexity in the designs.

- **Integration:** open structured substrates allow for the silicone to flow to both sides of the embroidery during casting, creating a better bond between materials. Round edges further support the robustness of the actuators as they reduce the chances of breakage between embroidery and silicone through air pressure. This is particularly pertinent for actuators that use thin walls for enlarging the actuation area through compartmentalization. Employing cut-outwork needles creates a smooth integration of the inflatables into fabrics. Overlapping the substrate and the textile edge allows for a robust connection that works both for woven and knitted fabrics.

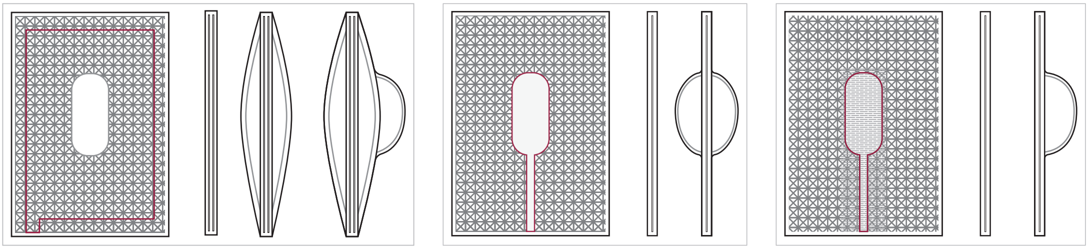

Fig. 5 Front views of Interaction Modes 1, 2 and 3, accompanied by their side views in neutral and actuated states. The red markings correspond to the water-soluble film that creates the actuators. M1 is a multi-state inflatable, M2 inflates symmetrically and M3 inflates unilaterally.

- **Accuracy:** we observed accuracy in two instances. The first was the accurate translation of the design into embroidery. Excessive repetition of stitches can deform the embroidery or tear the water-soluble film. When sewing complex shapes, multiple layers of low-density Fill Stitch in various directions work better than Net Fill Stitch for achieving a flexible result. If flexibility is not a priority, a single layer of dense Fill stitch can be used. Alternatively, the outline of complex shapes can be sewn over a new sheet of water-soluble film on the substrate. The result is one-sided inflation. The second instance of accuracy related to using the embroidery frame throughout the various stages of fabrication. This improved the reproducibility of samples and allowed for combining techniques like cutout needle work or washing off the stabilizer for layering.

4 FABRICATION PROCESS

Reflecting on Series 1 to 5, we discern three actuation behaviors which we refer to as interaction modes 1, 2 and 3. The modes are defined by the deformation of the actuators (Fig. 5), consequence of their construction and the substrate structure.

The actuators are integrated by machine embroidery in woven fabrics through cutwork needles. The cutwork needles consist of four blades, each at a different angle, that are installed in the embroidery machine in place of regular needles. The blades punch through the fabric to cut it out. Using this technique allowed us to keep the fabric hooped through most of the fabrication process, supporting the reproducibility of samples. For casting locally, laser cut acrylic hoops were attached to the fabric. Another acrylic piece closed the bottom of the mold.

Below, we present the three modes, their fabrication and the experiences of students implementing them in their projects.

4.1 Mode 1

Mode 1 is made by embroidering two separate parts and a sheet of water-soluble film (Fig. 6). The top part is integrated into fabric and the second part is a free-standing substrate used as backing for the actuators. As seen on Figure 5, this actuator is a multi-state inflatable. It begins to inflate as a pillow until the cut-out shape on the embroidery starts to protrude.

4.2 Mode 2

Mode 2 is a double-sided inflation of the negative space in the embroidered substrate. The fabrication (Fig. 7) requires only one layer of embroidery. The most delicate part of the process is that, unlike the other two modes, the film used to create the inflatable pocket is the same as the one used for embroidering the substrate. This means that for a better interface with the silicone, parts of the film need to be carefully washed away from the substrate without dissolving the center part of the sample. Another downside of this mode is that, based on the experiences of Series 2 and 3, we could not create a complex-shaped actuator that remains as flexible.

4.3 Mode 3

Mode 3 was created by layering a dense support pad over the substrate then adding a layer of water-soluble film to create the active area. This construction enables directing the inflation to one side only, which can be used to

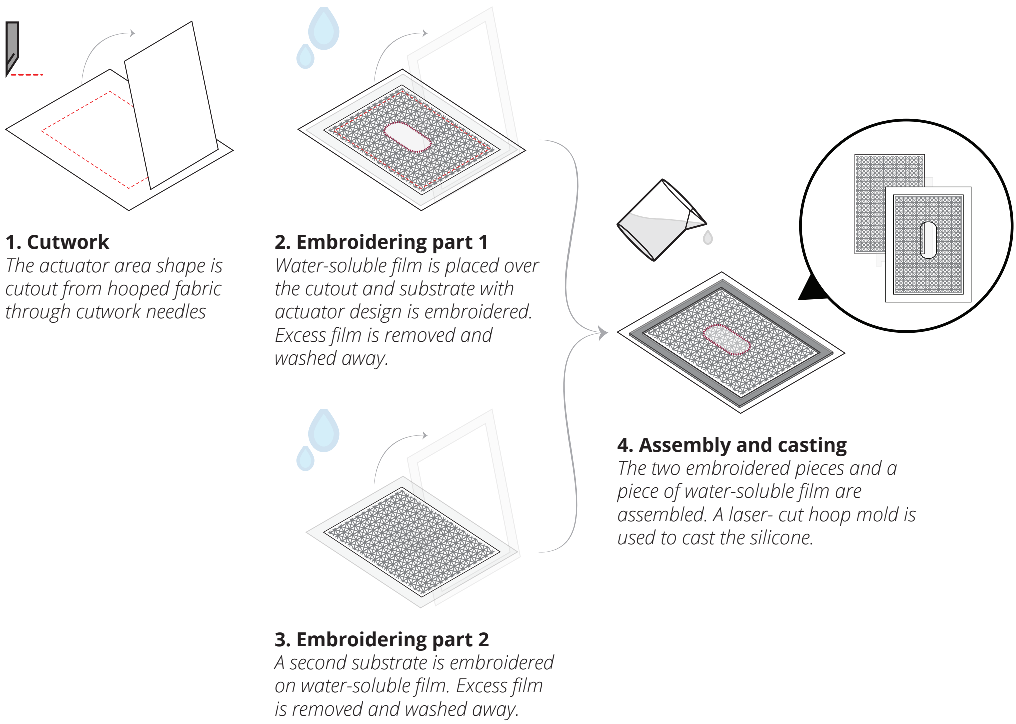

Fig. 6 Mode 1 fabrication process. Two embroidered substrates are sewn separately, then assembled on the hoop-mold with a piece of water-soluble film in between parts.

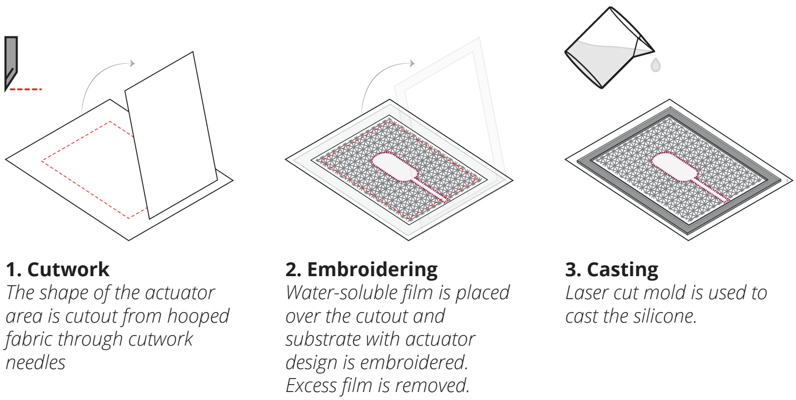

Fig. 7 Mode 2 fabrication process. The substrate is embroidered as a single part containing a negative space with the shape of the inflatable.

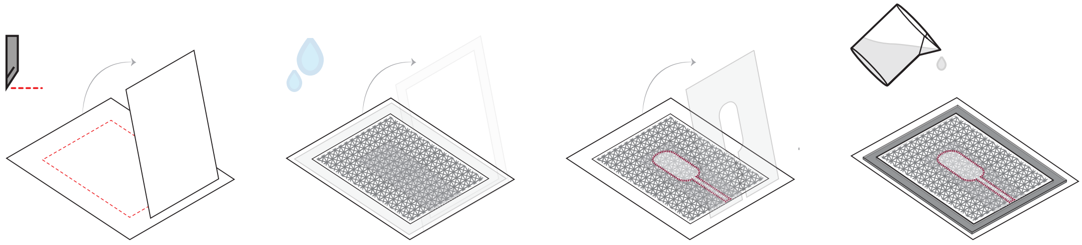

Fig. 8 Mode 3 fabrication process. The embroidery process is divided in two parts. First the substrate and support pad are sewn in layers. The water-soluble film is washed away before another piece of water-soluble film is integrated by sewing the outline of the actuator shape.

implement directional cues in garments. The fabrication process requires washing off the sample, still on the embroidery frame, after step 2 (Fig. 8), then bringing the frame back to the machine to finalize sewing the actuation area. This way, the silicone can flow to both sides of the substrate, without dissolving the middle.

4.4 Case studies: interaction modes reproduced by design students

To begin to assess the reproducibility of the inflatables, we offered the designs of the interaction modes to one master and four bachelor and industrial design students. They had no prior experience with machine embroidery or casting. Their assignment was to reproduce the three modes and to explore possible applications in the context of physical rehabilitation as case studies for their research semester. They were given the freedom to use the inflatables in their projects as they saw fit, including how to actuate them.

For reproducing the samples, students received the embroidery files and the laser cut molds. The process was explained through an introduction workshop in which we reproduced mode 1 as an example, so all techniques could be demonstrated. A follow-up session addressed questions about the fabrication process and their research directions.

The four bachelor students worked as a group to examine the potential of correcting back posture through inflatables by comparing the three modes in three wearing locations. They actuated them manually. The second project, conducted by the master student, tested the use of mode 3 to provide directional cues on four trigger muscles involved in activating the arm to support physical physiotherapy. The inflatables were actuated through air pressure pumps and valves, controlled by a microcontroller. Combined, the students reproduced a total of 26 working samples for their studies, which involved twenty participants each.

At the end of their projects, we conducted a final group session to collect their experiences while reproducing the interaction modes for their studies. In this session, the students related that they struggled with the amount of novel information they received during the introduction session which, according to one of them, “made it hard to visualize the whole process”. Thus, when they began to reproduce the samples, two parts of the process were misunderstood. The first was how to continue the embroidery process for fabricating mode 3 after washing off the water-soluble film (step 3, Fig. 8). The other involved understanding that the second embroidered part used in mode 1 was meant for all modes. They only realized this was a mistake while casting their first batch of samples.

When it came to learning about how to reproduce the substrates, one of the students said that “starting the process of embroidery was somewhat time consuming at first [and] it took us a day just to learn how to use the machine” but that it became easier with experience. The process of casting, on the other hand, was troublesome as they found it difficult to reproduce the same pressure on the mold as well as pouring equal amounts of silicone onto each sample. Also detrimental to the accuracy of reproducing actuators was the attachment of the air tubes to the samples. They glued them together, resulting in some samples being bulkier than others, depending on the amount of glue used.

The feedback given by the students suggests that, on the whole, replicating the process is easy, provided that novel information is presented through a hands-on experience. The number of samples they reproduced corroborates with our assumption that machine embroidery requires a low threshold of experience from designers. The difficulties they reported regarding casting and making the connection between actuators and air tubes are relevant for future work.

5 CONCLUSION

Following a RtD approach, we explored the possibilities of designing soft inflatable actuators by combining machine embroidered substrates and silicone. Our samples explored how to integrate embroidery-based inflatables into textiles and how to design complete form factors. We contribute with an approach to machine embroidery, several lessons learned through our process and a detailed description of the fabrication process of our interaction modes. The techniques we presented extend the possibilities of designing interactive garments and soft interfaces through machine embroidery. Our reflections offer guidelines for design and open up research questions about potential applications and automatizing the production process of inflatable actuators based on digital machine embroidery. In our work, we dealt with complex shapes through layering pre-programmed sewn region fills in different directions, thus avoiding excessive repetition of stitches.

Design students without previous experience with embroidery or casting reproduced our designs and incorporated them in their research projects. Through their feedback, we found that the potential of scalability and accuracy of the current method of fabrication of the actuators is reduced by the casting procedure. Therefore, further exploration of the casting process is needed. Keeping the samples on the embroidery frame during the different stages of production supported accurate layering and allowed techniques and materials to be combined during the process. One way we envision improving the accurate reproducibility of the final outcome is to keep the fabrics hooped in the embroidery frame until the end of the fabrication.

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3.2 Crafting Research Products through Digital Machine Embroidery

Published as

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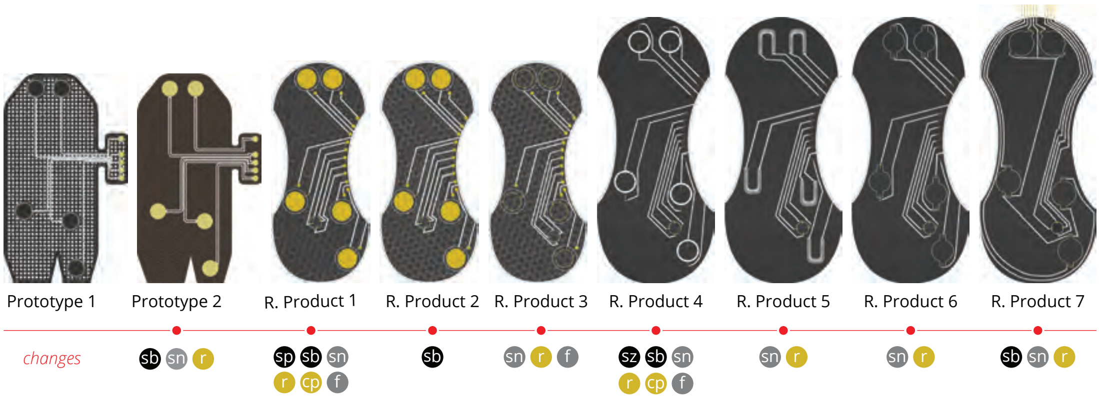

Figure 1. Overview of embroidery designs of the sensorized soles prototypes and research products for a smart sock. Machine embroidery allowed making precise alterations between designs while certain elements, such as relative sensor alignment could be preserved to facilitate comparisons and carrying through early design decisions across proofs of concept, prototypes and research products. Changes included, as marked above: substrate size (sz), substrate shape (sp), substrate attributes (sb), pressure sensor construction (sn), routing of conductive traces (r), contact pads (cp), the design of the flex PCB containing accelerometer (f).

ABSTRACT
Wearables combine practical and conceptual challenges related to electronics, clothing and interaction design. Research through design in this area is commonly done iteratively through prototypes of increasing levels of fidelity, often relying on manual fabrication. However, manual fabrication presents challenges when comparing prototypes due to their varying levels of realization and the inaccuracy of reproductions. We discuss how using digital machine embroidery, combined with chemical embroidery technique, supports fabricating consistent high-fidelity prototypes for soft wearables in the form of research products. Our approach involves creating the textile substrate together with integrating and embedding electronic components through a unified process whilst keeping high control over alterations between prototypes. We illustrate this approach through the design process of the Smart Sock, a sensorized sock for rehabilitation. We detail the challenges behind our process and reflect on the opportunities emerging from using digital machine and chemical embroidery techniques combined to craft research products.

AUTHOR KEYWORDS
Digital machine embroidery; soft wearables; Research Products; e-textiles; textile sensors; digital fabrication

INTRODUCTION

Textiles serve us in many ways that include cultural, aesthetic and functional purposes. In the form of clothing, textiles can elicit an intimate relationship with users, regardless of their sense of fashion [35], cultivating personal meanings and social functions [9]. Integrating electronics and interactive technology in garments can potentially help capitalize upon the inherent qualities of textiles to enable a wide range of on-body applications and interaction possibilities. In the field of healthcare, for example, wearables offer opportunities for continuous and unobtrusive monitoring of patients in everyday living which can improve their quality of life [3,14]. This potential has attracted many HCI researchers into the field of wearables and, especially, soft wearables.

Soft wearables are typically designed in an iterative process that explores material properties, progressively integrating sensing and interaction functionality [35]. Creating them is complex as it requires overcoming challenges related to electronics and wearability together with specific challenges pertaining to the application context [36]. Such combined challenges include comfort, unobtrusiveness, flexibility, stretchability, robustness of the connections between hard and soft electronics, or the reliability of the data outputs. To address these concerns, interaction design researchers are called to apply techniques and develop skills that are outside their traditional range, including selecting technologies that are or can become wearable, fabricating hybrid materials and designing garments. While examples of interesting design research concepts and applications abound, there is little guidance for interaction design researchers as to how to realize such prototypes in a high level of detail. This is in stark contrast to the effort needed to realize the prototypes and learning or developing the techniques needed to effectively integrate technology into garments within an iterative design process [31,32].

Using ready-made garments as a base for prototyping and toolkits including sewable ready-made components, such as the LillyPad Arduino [7], is an approach often adopted by developers of various backgrounds entering this area, as it lowers the threshold of fabrication skills needed to experiment with wearable concepts [32]. The level of fidelity of the prototypes of such concepts, however, is hindered by the restrictions imposed by these off-the-shelf solutions and the amount of manual work required for constructing prototypes. Next to being time consuming, relying largely on manual fabrication can also result in successive prototypes differing in more ways than intended, hampering comparisons between them. This can pose obstacles to the design process of creating soft wearables and it can be problematic when the design researcher needs to make the transition from a one-of-a-kind proof of concept to a design for scalable production. For this, we need to develop guidance, systematize and disseminate knowledge for how to make the best use of relevant fabrication techniques to support iterative processes of soft wearables in the form of research products (finished products designed for research [27,28]).

Integrating machine-logic into the project development can not only mean increasing the accuracy and reproducibility of prototypes through automation, it can also be used to support and inform the design research process [29]. The high level of fidelity of research products allows evaluating them for what they are rather than what they can potentially become [28]. This is particularly interesting for wearables as the conditions in which they will be tested (e.g. on curved and moving bodies) demands a higher level of fidelity in terms of aesthetics and material properties than other kinds of prototypes might require. The Project Jacquard [34], for example, considered the complete production chain of garments to create touch-sensitive textiles through weaving in industrial scale. Various other digital fabrication methods have already been explored for creating textile-based research products. The Hybrid Bricolage [11] blends hand and digital crafting through laser cutting patterns into fabric to achieve high quality smocking effects on soft objects that are finished by hand. Lea Albaugh et. al [2] used digital machine knitting to create soft actuated objects through tendons. The approach allows rapidly fabricating finished products that are breathable, lightweight and soft to the touch.

We have chosen digital machine embroidery for its versatility. Digital machine embroidery has been used in many applications as means to create soft circuitry [33], different types of sensors [1,24,26], actuators [8,12,16], heating elements [5], resistors [17] as well as for interconnections with electronic components [4,22]. We argue that digital machine embroidery can also enable the fabrication of reproducible prototypes, supporting highly iterative processes while remaining a low entry fabrication technique for non-textile experts. During the development process, variables of the design can be isolated and precise changes can be made both for optimization but also as a means of exploring alternative solutions. The stability granted by the embroidery frame and the accurate positioning of the needle allows for appliqué techniques, such as integrating pre-cut materials [38], that can be used to create or embed interactive components during the sewing process. Furthermore, the use of chemical embroidery technique (embroidering on water-soluble stabilizer), allows creating a free-standing embroidered substrate. This technique, which is commonly used to create machine-made lace, has been used in HCI for creating inflatable actuators [16] and on-skin interfaces [19] but is still underexplored in the context of wearables. In our work, this technique enabled us fabricating the textile substrate in the shape of parts of the wearable and integrating technology through the same process, which further reduced the burden of constructing garments.

In this paper, we illustrate our approach through the design process of the Smart Sock, a sensorized sock for rehabilitation. By focusing on textile practice, we aim to develop and encode the knowledge involved in designing and fabricating our proofs of concept, prototypes and, more importantly, research products in a way that other design researchers can apply it. To achieve this, we will first explain the context of the project and our research through design process. Then, we will detail our approach to digital machine embroidery through the design elements used throughout the project (Figure 1). Lastly, we contribute with reflections on the implications of the techniques we used and, especially, on how digital machine embroidery can be beneficial for the development research products for soft wearable applications.

THE CASE OF THE SMART SOCK

We present a research through design (RtD) exploration of digital machine embroidery in supporting the process of crafting research products. Our approach builds on known techniques used to integrate technology into soft wearables through digital machine embroidery to deal with the challenges of designing reproducible soft wearables for healthcare. Through the case of the Smart Sock, we articulate a number of challenges and illustrate

Figure 2. Inside of the sole of the second proof of concept. Conductive traces were embroidered on cotton fabric to allow for soldering the FSR sensors in fixed positions. The cotton was attached to an off-the-shelf hallux sock.

how our approach can support forming a design language through embroidered design elements. Before detailing these, we first introduce the broader research context and design process of the Smart Sock project.

Research context and Approach

The work presented in this paper was part of a bigger research effort that aimed to develop solutions for the recovery of trauma patients with surgically treated fractures of the lower extremities through early weight-bearing. The project was developed between 2015 and 2017 by a multidisciplinary team that included a movement scientist, surgeons, physiotherapists, data scientists, engineers and industrial designers.

The sock was designed to measure several parameters related to weight division, unwinding of the foot and indicators of overload which are typically evaluated in clinical practice. The assessment of the quality of gait was determined by comparing the affected limb to the healthy one as baseline. Early explorations using conventional pressure sensors concluded that five pressure sensors and an accelerometer/gyroscope were the most essential sensors to be integrated into a textile-based prototype. As the system would compare the pressure sensors of the sock of the affected foot to each other as well as with their pairs on the sock on the healthy one, the reproducibility of the design and sensor alignment were essential for the development of the algorithms. Thus, rather than designing technology and form factor separately, our approach to crafting research products was inspired by a postphenomenological approach to wearable technology [10], in which technology is treated as a material, and the notion of wearable composition [15], in which the design of components evolves together with the wearable. Even to explore alternative sensor constructions, sensor samples were integrated onto the embroidered substrate and, with few exceptions, into the wearable form factor to account for the many aspects that can affect sensor performance when testing on a tabletop and on the body. In this paper, we focus on the use of digital machine embroidery as the primary fabrication tool throughout the design process of the wearable.

Design process

The design research process was hands-on and highly paced, resulting in two proofs of concept, two prototypes and seven research products in a period of a year and a half. The proofs of concept were constructed with off-the shelf Force Sensing Resistor (FSR) sensors embedded on off-the-shelf hallux socks as a starting point. These had the purpose of determining the number and location of pressure sensors required under the foot as well as to collect data for initiating the algorithm development.

The number of sensors and corresponding conductive traces motivated the transition towards integrated textile solutions. Embroidery offered the advantage of accommodating the large number of conductive traces while creating a thin wearable that could withstand the stress

Figure 3. Sole of the second proof of concept. Embroidered pads were used to prevent the off-the-shelf pressure sensors from bending. Photo credit: Scott Delbressine

of the movement and weight of the body. Embroidery was first introduced in the project to substitute conventional wires with conductive yarn in the second proof of concept (figure 2) and to reduce the amount of manual work in placing the sensors into the ready-made sock. Additionally, embroidered patches were used as support pads for the FSR sensors to prevent them from folding (figure 3). Based on these, we started exploring how to unify the fabrication process of the sensors and the wearable form factor through two prototypes. The prototypes consisted of embroidered substrates in the shape of the sole, integrated or embedded pressure sensors, conductive traces and insulation layer (zigzag stitch, also known as couching stitch, sewn over conductive traces to protect them) through embroidery. In the prototypes we consider to be research products, two additional embroidered parts were used to form a ballerina sock, enabling them to be worn as finished products.

The process of developing prototypes towards research products and using them to collect data for developing or for validating the algorithms continued throughout the project. While the proofs of concept were used to initiate the process of development of algorithms, research products were tested each in conditions of gradually increasing complexity: 1) testing sensors on a table bench (static testing), 2) testing sensors on the body while on a treadmill (dynamic testing under controlled conditions) and 3) testing sensors on the body during walking (dynamic testing under semi-controlled conditions). As non-medical devices, collecting data from patients through our prototypes was not possible, thus healthy individuals performed the different types of pathological walk patterns that the system should be able to identify to assess the quality of gait.

The final wearable, research product 7, included the five textile pressure sensors and an accelerometer positioned near the toe. The flex PCB containing the accelerometer (Figure 4) was designed to be embroidery friendly, its contact pads were wide and double sided to improve the robustness of the interconnections.

Figure 4. Detail of research product 7. The flexible PCB containing the accelerometer/gyroscope was designed to be embroidery friendly. The contact pads of the PCB were double-sided and wide to increase contact with conducive traces.

RESEARCH THROUGH DESIGN OF SOFT WEARABLES THROUGH DIGITAL MACHINE EMBROIDERY

Soft wearables explore solutions to replace conventional electronics with soft or textile alternatives to offer on-body interactive possibilities while preserving textile character of the garments. As not all electronic components can be substituted by textile or other flexible alternatives, it remains necessary to interconnect hard and soft materials. Approaches to interconnecting electronics and conductive yarns include soldering, gluing, crimping and embroidery [23]. Embroidery offers the advantage of creating textile wiring and interconnections [25] and allows the use of different kinds of yarn and finishes (insulated and non-insulated). For these reasons, digital machine embroidery has become a popular way of integrating conductive yarns to soft wearables that allows for more freedom of routing of the conductive thread than knitting and weaving [25]. Researchers have also engaged in creating means for practitioners of varying levels of expertise to engage with digital machine embroidery to fabricate textile-based circuits and interfaces. The system presented in Sketch & Stitch [18], for example, allows users to create circuits through drawing directly on the fabric and using stickers as placeholders for electronic components. The colors in the drawing and stickers are recognized by a scanner and then converted into embroidery elements such as conductive traces, bridges (crossings of conductive traces), sensors and insulation. The system allows users to reach high quality outcomes without the need for programming. Although pre-set elements can support speedy explorations, the lack of freedom of making alterations on stitch level restraints the opportunities of such a technique. The Textile Interface Swatchbook [13,37] proposes the use of interactive swatches created through embroidery to allow designers to experiment the feel and interactive possibilities of interfaces as inspiration for designing new ones. The embroidered elements used in the swatches also included embroidered sensors, conductive traces and insulation as well as raised embroidery, used to guide the fingers of users. To be experienced, the swatches need to be connected to a binder containing the electronics in its spine.

We combined techniques found in such examples with chemical embroidery, which means that the designs were sewn on a water-soluble stabilizer, to create the free-standing textile substrates in shape of the soles onto which components and circuitry were embroidered, fashioning garment parts in a single fabrication method.

In our RtD process, the use of digital machine embroidery was a strong tool for crafting soft wearables not only for the freedom but also for the stability provided by the embroidery frame, which allowed us to manually intervene in the process without compromising reproducibility.

Machine embroidery made our iterative process fast paced and allowed for high control over small alterations between prototypes and research products. Furthermore, contrary to a common assertion that knitting and weaving enable conductive yarn integration during fabric production while embroidery enables it as a post-treatment for a ready-made fabric [18,25], the textile substrate and conductive elements of our prototypes and research products were fabricated through the same process. Through this approach, it was possible to explore material qualities of the embroidery, including layering embroidered elements of varied sewing attributes to add functions to the substrate locally. These included protecting the interconnections with the flex PCB through a support pad and using the programmable nature of machine embroidery to create stretchable substrates to support fit to the body.

Embroidery techniques and design elements

We based our RtD process on techniques and examples of previous work in the field. In this section, we describe the elements used in our process to consolidate knowledge on the possibilities of employing digital machine embroidery to develop soft wearables and soft applications. Our prototypes and research products were composed from different embroidered elements: substrate, support pads, placeholders, conductive traces, contact pads, sensor components and insulation. The designs were programmed in an embroidery digitizing software (PE-Design 10) and embroidered by a digital machine embroidery (Brother PR655) using conventional embroidery threads on a thick water-soluble stabilizer (Gunold Solvy 80).

Substrate

To reduce the number of steps needed to fabricate the prototypes, we explored embroidering free-standing substrates, used as a base for the soles (figure 5). This way, the final shapes of the prototype parts were determined completely through embroidery. Furthermore, it was possible to determine and explore its material properties. Different sewing attributes influenced the material properties of the embroidery, such as the use of underlay stitching (layer of stitches under the embroidered design, typically used for stability and support), density and sewing direction. In research products 2 and 3 (figure 5b), for example, the substrate of the sole could stretch in the length of the foot. The two other substrate parts used to turn the soles into ballerina socks stretched in the other direction, allowing them to conform to the heel and toes.

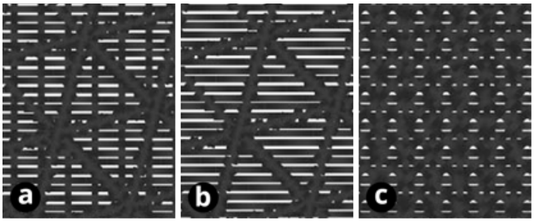

Figure 5. Substrates of research product 1 (a), research products 2 and 3 (b), and research products 4, 5, 6 and 7 (c). Sewing attributes were used to control the properties of the textile. The absence of underlay stitching (vertical lines seen in A) in substrate B, for example, enabled the sole to stretch.

Support pads

During test-wearing of our prototypes, preventing the connections to the PCB from getting loose due to friction between the different materials was a challenge. In research product 7, this issue was solved by sewing an additional layer of dense fill stitch over the substrate to serve as a support pad to the component (figure 6). The support pad prevented the PCB from bending, keeping connections tight. A support pad was also used in prototype 1 to create a flat surface for the pressure sensors as the substrate was textured. In a different use of the technique, the Textile Interface Swatchbook [13] used support pads as base for elevating embroidered sensors to highlight tactile features.

Placeholders

In conventional embroidery, adding extra layers of textiles or other materials to

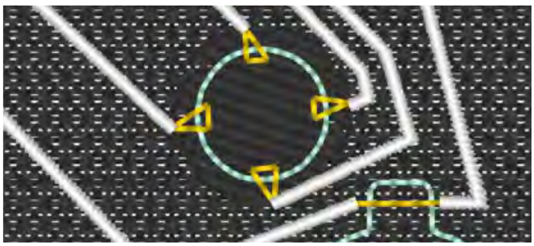

Figure 6. Detail of research product 7 showcasing part of the conductive traces under insulation zigzag stitch exposed and placeholders (blue markings) for attaching sensors.

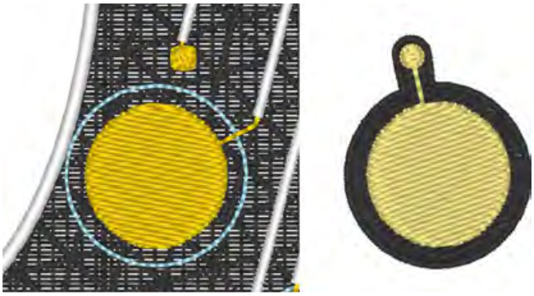

Figure 7. Detail of an electrode integrated on the sole of the research product 1 (left) and its corresponding top electrode (right), sewn as a free-standing patch. Eeontex was embedded in between them to form the pressure sensor.

the embroidery can be used to create embellishments known as appliqués. It is common to make them by placing a larger piece of material than the final appliqué onto the frame, stitch it down then cut away the excess material. The edges can be covered by a zigzag stitch for a neat finish. In some cases, appliqués are pre-cut or ready-made, such as when integrating electronic components onto the embroidery, thus their positioning onto the frame should be accurate. Creating placeholders by sewing placement lines onto the substrate supports aligning the contact areas of components with the conductive traces [22]. In our project, placeholders marked the position of components such as the flex PCB or pre-assembled textile pressure sensors (see blue markings on figures 6 and 7).

Sensor construction

Manually integrating sensors into the garment can be challenging. In the prototype 2 and research products 1 and 2, we fixed the position of pressure sensors by embroidering conductive yarn as the electrodes to construct the sensors (figure 7). Pressure sensitive textile (EeonTex) was embedded in between electrodes. The electrode sewn directly on the substrate was embroidered as part of the traces which also helped keeping the prototypes thin and connections robust. The other main challenges related to sensors in this project were range and drifting. Later prototypes explored various alternative sensor constructions that included conductive textile in place of the embroidered electrodes (research products 3, 4, 6 and 7), the pressure sensitive fabric alone (research product 5), or pre-assembled sensors using conductive textile as electrodes (research products 6 and 7) or. In terms of integration, research product 5 was the most successful as its sensor was the simplest, requiring the least manual work.

Conductive traces & interconnections

Flexibility and robustness of the interconnections in soft wearables are challenges that can be solved in various ways. For our project, keeping them thin was also very important to prevent discomfort from stepping on thick interconnections or components. Conductive yarn (Shieldex 110/34 dtex 2 Ply HC+B) was used to embroider the conductive traces. Permanent interconnections were used to embed the flexible substrate with the accelerometer to keep the thinnest profile possible [25]. In this technique, the needle stitched through the PCB without pre-drilled holes to ensure a more robust connection [22].

Contact pads

Assembling the prototypes with the electronics of the control unit was time consuming in the early phase of the project. For the second proof of concept, we embedded pin headers into the sock to allow detaching the control unit, which enabled the subsequent prototypes to be rapidly fabricated and tested by using the same electronics. Sewing contact pads from conductive yarns can match the contact pads of conventional electronics [33]. In prototypes 1 and 2, we used this approach to connect the traces to electronics through conductive snap buttons that could be

Figure 8. Detail of research product 3. The contact pads facilitated the temporary connection to electronics or multimeters through testing clips.

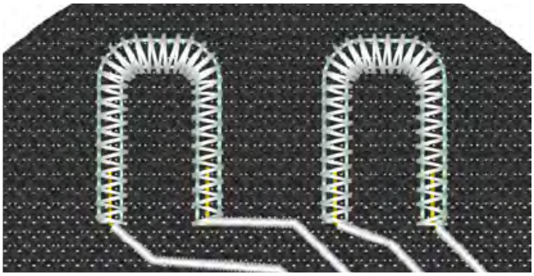

Figure 10. Detail of research product 5 showcasing the zigzag stitch sewn over the U shape pressure sensors made of Eeontex.

soldered to conventional wires. In research products 1, 2 and 3 of the embroidered prototypes, we used embroidered contact pads to facilitate connecting conductive traces to electronics through alligator clips during the testing process (figure 8). From research product 4 onwards, we used Pomona Minigrabber® test clips instead. Those clips feature small hooks that allowed us to make tight connections with traces without having to use large contact pads.

Insulation

Non-conductive yarn sewn over non-insulated conductive traces can be used to insulate them [6,13,33]. In the case of the sock, the non-conductive yarn was sewn as a zigzag stitch (stitch width 1,2 mm and density 4,5 line/mm) over the conductive traces which allowed a close proximity between them without causing issues

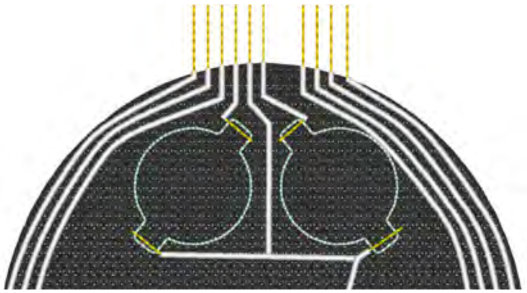

Figure 9. Detail of research product 7 showcasing part of the conductive traces under insulation zigzag stitch exposed and placeholders (blue markings) for attaching sensors.

(figure 9). Furthermore, to avoid fraying, the entry and exit points of the embroidered paths that made the conductive traces was edited so that their ends were tucked under the insulation.

Integrated sensors

Although placeholders support aligning external materials to the embroidery, their exact position can still vary. Stitching through the Eeontex could thus mean that each sensor is pre-loaded differently. To avoid this issue, we integrated sensors by stitching through the conductive electrodes. In the case of research product 5, the sensor was made of the Eeontex only. A zigzag stitch was then used to embed the U shape sensor (figure 10). By using the stitch width wider than the shape, the machine did not stitch through the sensor. Instead, it wrapped the shape and allowed the pre-load to be even in all sensors.

IMPLICATIONS OF USING DIGITAL MACHINE EMBROIDERY IN CRAFTING RESEARCH PRODUCTS

In this section, we distill some lessons learned through addressing the challenges and opportunities presented in the previous section. While some of the embroidery techniques used to craft our prototypes are not new as such, knowledge about them is scattered in the literature and coupled to specific embroidered elements. In the section that follows, we organize these techniques and compare them to examples in the literature thus providing a comprehensive resource for design researchers wishing to use embroidery as a means of crafting research products.

Sensor alignment

For the sock, ensuring that the sensor readings for both feet could be comparable was key. Therefore, sensor alignment was the main challenge in the project that motivated the use of digital machine embroidery. The importance of preserving the relative distance between sensors is not exclusive to our application. For example, applications that measure muscle activation [20] or that compare different segments of the body for movement analysis, also require sensors to be applied to specific areas of the body, making sensor alignment an important aspect of the system design.

By making use of digital machine embroidery to fabricate research products it was possible to preserve sensor alignment during our process while making incremental changes in the design in order to a) optimize them, b) explore their aesthetic and material properties, c) include new components and d) investigate the performance of various sensor designs.

Regarding optimization, small but accurate adjustments like changing the sewing attributes of elements were made possible through digital machine embroidery. Although of lesser impact to the design, changing the stitch type of contact pads at the end of conductive traces between research products 2 and 3, for example, avoided damaging the conductive yarn when connecting/disconnecting testing clips, facilitating evaluations. Another example was moving the entry and exit points of embroidered paths of conductive traces to tuck their ends under the insulation. This improved the finish of the embroidery, prevented fraying and, consequently, avoided the risk of potential contact between traces. More substantial changes to the shape or the material properties of the substrate and other embroidered elements were also possible while preserving sensor alignment. For instance, while the shape of prototype 2 was conceived to match the sole of the hallux sock used in the proof of concepts, the shape was changed to a ballerina sock when moving towards research products. The ballerina socks also integrated the flexible PCB into the sole of the wearable, which in later versions changed location so it would not be positioned under the ball of the foot. These alterations did not interfere with the relative position of the sensors or other design features we wished to preserve. Finally, our approach allowed exploring different sensor designs through an integrated solution, that enabled testing them statically on a tabletop and dynamically on the body, in more or less controlled circumstances.

Layering & manipulating fabric character

Most of the time, early prototyping of wearables uses off-the-shelf fabrics which means that the material properties of the final design are based on those of the fabric of choice. Through the use of chemical embroidery, we saw the opportunity of creating our own material through layering embroidered designs. This resulted in a seamless integration of elements. In the course of the project, we explored how to create free-standing embroidered substrates to form wearables. This involved exploring how material properties of the substrate could be changed through variations in the sewing attributes and through layering. Note that, in our process, we do not mean layering as the multilayer soft circuits described by Orth and Post [33]. We mean layers of embroidery sewn directly on top of each other during

Figure 11. The ballerina sock form factor of the research products was created via chemical embroidery. It was composed by three parts: the sole, upper toes and heel.

fabrication. That does not mean we restrict our view to the creation of the substrate as, arguably, the embroidered electrodes together with conductive traces as well as insulation elements can be seen as layers and affect the material properties of the wearable. Examples from the bridge layers from Sketch & Stitch [18] or the layered sensor construction to make EMG sensors [21] show how this approach can be taken further into crafting complex soft circuits and textile sensors.

The attributes we explored were mostly the kind of fill stitch, the use of underlay stitching, the sewing direction and the density/spacing of the fill. In research product 1, for instance, the substrate is formed by two layers sewn on top of each other. The first layer was a low-density fill stitch (with underlay stitching) to keep the form and structure of the final material stable after washing away the stabilizer. The second was a Zigzag Net Fill Stitch sewn in 45o angle. The result is flexible but stable in shape as the sewn lines of the first layer prevent stretch. Research product 2 has practically the same sewing attributes, with the exception of not having underlay stitching on the first layer. This difference was enough to make the structure stretchable in one direction. The

Figure 12. Size difference between research products 2 (top) and 7 (bottom). The relative distance between components was preserved while resizing the substrate shape.

same sewing attributes were used to craft the two pieces used to turn the soles into ballerina socks from research product 1 onwards (figure 11). For the sake of keeping the distance between the sensors fixed, the substrate used in prototypes 6, 7, 8 and 9 was composed by a denser structure made from one layer of running stitch without underlay stitching and a layer of net fill stitch. In research product 7, we also explored layering to change properties locally. Relatively dense fill stitch (4,5 line/mm) support pads were sewn over the substrate to protect the flexible PCB and its interconnections.

Although it was not the focus of our project, we also briefly explored how yarn can affect the material properties by embroidering versions of the substrates in cotton or silk in place of the polyester used throughout the project. Both result in much softer substrates, cotton having a more course texture than silk. After washing, the materials relax differently resulting in different overall dimensions and texture. Polyester seemed to remain the truest to the original design in terms of its dimensions. Further explorations of the effects of sewing attributes as well as yarn choices in the material properties of substrates should be done to extend the understanding of how to design them.

Shaping & Construction

Exploring chemical embroidery technique for creating the substrate of the soft wearable presents the opportunity to reduce the amount of manual work in the assembly of the research products. Rather than embroidering soft circuits on fabric, cutting patterns and sewing them together to form the wearable, the final shapes are already produced by the embroidery machine. Similar to 3D printers and other digital fabrication machines, however, the trade-off for these benefits is the work-envelope. The maximum size of a part that can be fabricated is determined by the machine [30]. The embroidery machine we used in our project has a maximum area of 200x300 mm. Thus, repositioning the stabilizer would be needed to embroider larger parts, hindering the precision of the final piece.

If we were not limited by the size of the embroidery machine, it would have been possible to further explore shaping the full wearable through one step, rather than in three separate parts. Regardless, the technique allowed us to scale the shape of the sole while preserving the sensor dimensions and their relative position (Figure 12). We explored this due to the fact that, for collecting more data, the population of individuals available required a larger size than the size of the previous prototypes. This process of enlarging the soles was done manually through the embroidery digitizing software. Nonetheless, it was possible to keep the relative alignment and placement of the sensors through their center. The precision and workflow of such alterations could be further improved in the future through generative design.

CONCLUSION

The contribution of this paper is to propose a path of developing and fabricating soft wearables in the form of research products by means of digital machine embroidery. Adopting machine-logic into the design process has shown to resolve some substantial challenges that design researchers face in developing soft wearables. Specifically, it allowed for accurately reproducing prototype elements, providing a higher level of control over design alterations between research products when compared to the traditional approach where electronics are integrated manually in garments. This advantage could be gained while at the same time offering substantial flexibility and high level of fidelity regarding the material and aesthetic properties of the prototypes. We exemplified this approach in the context of the Smart Sock, where our prototyping techniques enabled combining concerns and solutions from different disciplinary perspectives into a series of research products, prototypes of equal levels of fidelity and realization. Our experience showed that digital machine embroidery can be a fruitful driver for innovation for designing soft wearables. Specifically, our work shows promise in further exploring how to design the material qualities and properties of free-standing embroidered substrates, opening up opportunities to research end-to-end fabrication of wearable research products through digital machine embroidery. Future steps could include moving further towards a design language of digital embroidery through software packages to handle scalability of designs and to manipulate material properties of the embroidered substrates and elements.

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3.3 Becoming Travelers: Enabling the Material Drift

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ABSTRACT

Materially driven research can often feel like a long series of failed experiments, which ends with us telling only the story of how we succeeded. We propose engaging with the making experience as travelers, losing ourselves in the making while preserving the outcomes of each experiment.

In doing so, we might be able to on one hand document this iterative journey as a research outcome in itself and, on the other, identify the roads not travelled as opportunities and starting points for new projects. We present an open- ended exploration that led us to articulating the possibilities of becoming travelers in the design process.

AUTHOR KEYWORDS

Research through design; Ways of drifting; Digital Craftsmanship

INTRODUCTION

As designers and makers, we conduct our research in deeply materially driven processes. Our outcomes are complex meetings between intention and artefact, material and skill, accidents and opportunities, – and also, we cannot help but desire that they are insightful, well executed and beautiful. As a result, it is easy to consider our making processes as a series of failed experiments or imperfectly executed ideas, and the sheer volume of documentation can be overwhelming.

Traditionally, the designer will keep going until "something works" or time runs out, and then retrace a path backwards that makes sense of the sample we have deemed successful. In such a process, we tend to self-evaluate harshly in the making process and are often left with a large amount of "failures" at the end. In recognizing this tendency in HCI, Heinzel et. al [5] proposes reconsidering concepts and prototypes that were considered failures at the time of their making. To put it simply, to work against our tendency to edit out knowledge that does not fit in the current narrative of a project.

We would like to propose applying this perspective in the making process of new things, recognizing that "in design research and in particular the professional practice of design, drifting or pursuing alternative opportunities in the vicinity of one's work is an embedded way of arriving at relevant and high quality work" [7].

In the following, we describe an embroidery exploration and the reflections on this process in order to identify the "failures" and missed opportunities through what we call the travelers mindset. We see this as a first step towards proposing a system for analyzing samples both within and outside their contexts of creation. Our aim is to look at the things we make, beyond the expectation of what is successful for a specific project. With that, we hope to create grounds for an exploitative design approach grounded in the opportunities of failure.

We believe this process can be seen in the context of a broader shift away from the positioning of the designer as a holder of solutions towards the emerging image of a practitioner who lingers within the problematic in order to expose the invisible structures, possibilities and complexities.

LOSING OURSELVES IN THE MAKING

"...to be lost is to be fully present, and to be fully present is to be capable ofbeing in uncertainty andmystery. And one does not get lost but loses oneself, with the implication that it is a conscious choice, a chosen surrender..." — Rebecca Solnit, A Field Guide to Getting Lost [9]

We brought the question of how to drift-through-making (while capturing opportunities for new starting points) to two hand embroidery sessions. To explore the experience of creative drifting, we focused on hand-embroidery, unusual material and and open-ended goals. As we worked we were systematic in our documentation and reflection, but deliberately abstained from any conversation about what a particular pattern might be "good for". Instead we simply let each sample follow the next. At the end of each session, we analyzed the collection of embroidered elements and discussed emergent patterns.

Session 1 - different designs

In the first session, the focus was to create a mindset of making, without (pre) determining success or failure. Our chosen tools were wooden embroidery hoops and needles. As for materials, we semi-curated a selection of threads and beads from what we already had at hand.

We deliberately used an open mesh as a non-traditional base fabric for hand embroidery to elicit new techniques. Although there was no goal to be achieved, we felt the need to decide on a place to start, so we each embroidered a marking of the center. We started by aiming for variety: volume, color, bump, pattern. In time, the materials themselves started to inspire us

Figure 1. We stitched label to each embroidery of session 1 with a corresponding concept.

Figure 2. We finished the session by reflecting on the process and attaching questions to the hoops. These were: "When did you know what you were going to make?", "When did you see what you were making?", "How did one thing follow the next?, and "What were the stages?"

Figure 3. For the second session, we choose 'hiding interlacing' as starting point.

to do different things and we each took our own path into the making. Next to each embroidery, we stitched in tags relating to the concepts that inspired them (figure 1). We wrapped up by discussing what had happened in the process and came up with questions about the process, which we also stitched into the hoops (figure 2).

The things we made remained attached to the context of their making. Each of the embroidered pieces informs what to look for in the next one by contrast. What if we isolate one and try to understand what is in its nature?

Session 2 - variations of a design
For the second session, we explored how to drift from an existing starting point. We chose one embroidery design from session 1, "hiding interlacing" (figure 3). We changed the base material from the mesh to a woven strip but the selection of threads remained the same as the first session. The format of the ribbon created a more structured way of forwarding qualities from one embroidery to the next (figure 4) forcing a linear progression and in turn making us see each design in its own timeline. This time, we did not tag each of them, but we still noted down insights from the overall experience and attached them to the ribbons.

We ended the session by selecting yarns to create a small embroidery kit to go (figure 5). These kits were executed on our respective train journeys that form part of our work commute.

WHAT HAPPENED HERE

Throughout these making sessions, we experimented with both limiting and opening up the possibilities by making hard decisions about materials and soft intentions about the aims. The final outcome was a set of making materials for travelling in the recognition of the experience of this process. It felt like

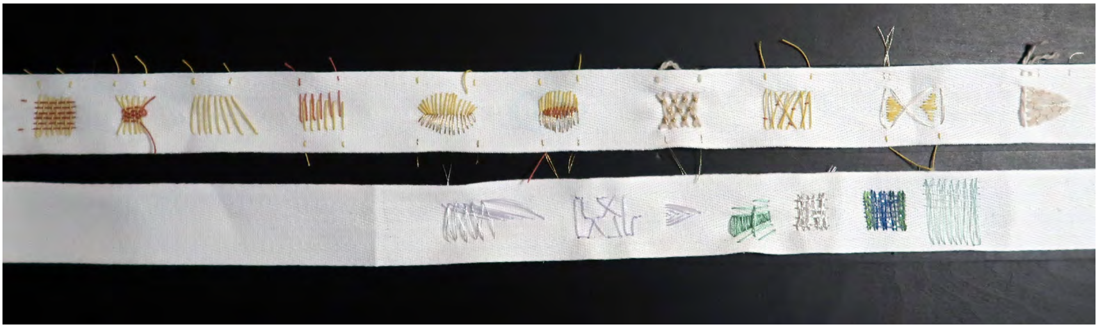

Figure 4. For the second session, we choose 'hiding interlacing' as starting point.

travelling, and it led us to questions to be asked of the things we make as travelers. What do I see? What else could I do? Is this finished? More importantly, it led us to an understanding of the circumstances needed to enter into a traveler's mindset:

- *Create time to make things* – this may sound obvious and silly, but the first three things you make will likely be boring. The following three might border on the edge of the obvious, after which you might get to something unexpected.

- *Collaborate (with people, with ideas, with tools and with materials)* – create a sensibility and critical eye to appreciate and identify what was done. Describe things and move on. Look over each others shoulders. It is also important to allow ideas to be forwarded from sample/ medium/person to sample/medium to medium/person.

- *Be systematic* – drifting meaningfully may require us to identify qualities and opportunities as we go. By just observing what we see, we allow the journey to be recorded without evaluation. Formalizing the rules of engagement not to enshrine processes but in order to potentially break or change them in the future [3].

MAKING AS DRIFTING

By setting simple rules and saying yes to challenges, we are committed to taking a performative approach to making and exploring [1, 2]. Colloquially the first rule of performance is to pick an act, execute it with absolute conviction and continue beyond a reasonable time. In a similar manner, we simply start somewhere and continue, picking challenges and new starting points as we go. This is of course similar to the first rule of brainstorming: Yes and...? [8]

THE OTHER PLACES

"the traveller who is lost should not ask themselves 'where am I?' but 'where are the other places?'" — Alfred North Whitehead, Process and Reality [11]

Throughout this process, it has been our observed experience that making is more akin to travelling than finding solutions or executing a task. As a result we would like to propose an extrapolation of the Whitehead call-for-other-places, into a mantra for wayfaring, allowing us to consider the discovery of new things as a mode of adventurous designerly travel. In retrospect, this of course echoes Tim Ingold's notion of itineration where each "every step is a development of the one before and a preparation for the one following" [6].

We believe that by extension, the finding of new things also means looking at old things with new perspectives. In this sense, we can travel both forward and backwards [4]. The making techniques we use are ancient and

Figure 4. For the second session, we choose 'hiding interlacing' as starting point.

well established, and as we travel with our embroideries on public transport, fellow travellers will occasionally reach over and examine our degree of craftsmanship, turn the cloth over, and approve or sigh. But while such standards of craftsmanship and traditions are close to our hearts and upbringings, with this text we would like to suggest a different manner of crafting for exploration.

This may mean accepting the failure of craftsmanship, using the wrong materials, changing our minds as we go and generally staying with the knowledge that we will eventually get lost. So far, we have never seen a "detour we did not like the look of" [10]. However, the detour means nothing, if we are not able to return to it, to ask: Can we come back here, later? In other words, can this detour be the starting point of another journey?

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4 Making sense of sample making

"[In cat's cradling, at least] two pairs of hands are needed, and in each successive step one is 'passive', offering the result of its previous operation, a string entanglement, for the other to operate, only to become active again at the next stop when the other presents the new entanglement but it can also be said that each time the passive pair is the one that holds, and is held by the entanglement, only to let it go when the other one takes the relay."

Donna Haraway [37]

The previous chapter identified samples as a specific type of high-fidelity prototype that have their interactive qualities and material properties intrinsically connected to their production. This chapter builds on this insight to investigate what is unique about sample making through three studies. As a collection, these studies bring forth aspects that are common in the everyday practice of *digital craftsmanship* but that are often omitted from research publications in the area, such as how samples that remain on sight on the walls of a studio become able to cross project lines and inform new directions. They also propose strategies that have the twofold intention of bringing transparency to the reporting of such practices as well as to promote higher intra-activity in practice-based research.

The first study, published in "*Embroidered Inflatables: Exploring Sample Making in Research through Design*" (section 4.1), was a creative session with Pauline van Dongen, a design researcher specialized in a fashion tech. In this session, we revisited the Embroidered Inflatable samples to explore the implications of designing from sample. This experience showed that the ways we document our work and archive the resulting samples have significant implications in supporting designers to tap into the generative potential of samples. The second study, unpublished, was a longitudinal study in which I put my making practice in dialogue with the practice of a textile designer specialized in (digital) weaving, Milou Voorwinden (section 4.2). This dialogue was enabled by using a documentation form template for digital craftsmanship as tool for reflection. This version of the form expands the one proposed in chapter 2 by incorporating more from my own documentation system of the Embroidered Inflatables. Through her adoption and adaptation of this form over the course of a year, we could begin to unpack her practice. In turn, this supported my reflections on how different craft techniques and machines configure our practices, thus affect our making processes and, consequently, impact knowledge production in practice-based research. Lastly, the third study, published in "*Making Matters: Samples and Documentation in Digital Craftsmanship*" (section 4.3). This study was done in collaboration with the master student Janne Spork, who conducted a set of semi-structured interviews with practitioners who engage with different digital crafts. While most published research in this area use samples to demonstrate techniques and interactive possibilities, this study aimed to reflect on how they are currently used in the design process. Therefore, this third study built on the insights from the previous two to inquire how these other practitioners handle samples within their processes.

Among other things, the third study supported identifying two types of roles taken by the designers interviewed, the researcher and the practitioner. The designers shifted between these two roles, which led to a reflection on how these two roles, or stances, can clash or contribute to each other. Seeing digital craftsmanship as a form of research through design, in which knowledge is generated through making, researchers will also need shift between the two stances. In my experience of emergence-led research, these two stances had to be negotiated, but they complement each other. As a practitioner, I followed a process of itineration, allowing insights that emerged from sample making in each project to (re)direct the research. As a researcher, I proposed the rigorous documentation of samples as a form of documentation of my autoethnographic process. This documentation extended the possibilities of both roles by keeping opportunities open for revisiting. The avoidance of reproducibility that practitioners might need or resort to was not part of my ethos. Rather, the documentation of samples meant to support practice through a notion of "designing from" which requires a relational understanding of each sample and making.

The three studies helped unpack how the process of *itineration* works in the practice of sample making in *digital craftsmanship*. In *Making Matters*, we describe the sample making process in four main activities: making, documenting, evaluating, and archiving. The latter three are inherently part of the *itinerative* way designers engage with *digital craftsmanship*. Building on Ingold's analogy to walking [41], the material sample can be seen to be akin to the stance phase of the gait cycle, when the foot is in contact with the ground. In the making process, this sample is a moment of stabilisation or, if we move back to the cat's cradle metaphor [37], a string entanglement of machine, designer, and material. Documenting, evaluating, and archiving are part of swing phase of walking, when the foot swings to move the body forward. Insights from these activities drive the process, informing the design of new samples or experiments. If we allow ourselves to keep on following insights and emerging ideas, the sample making process does not have a clear end. So, when do we stop walking? When discussing this with colleagues in a writing retreat, Pei-Ying Lin jokingly pointed out that the answer was simple: "when the deadline says so". I think this is true when thinking of projects, but not as much true for the practice of *digital craftsmanship*. By reflecting on both the practice of Milou as a weaver and my own experiences of sample making through embroidery, I suggest that a project is a cycle of making for the designer practicing *digital craftsmanship*. Insights and opportunities that emerge in the process linger with the designer as the next ideas to experiment with. These new journeys can be (partly) embodied in surprisingly interesting "failures" within the project or marked as annotations in sketchbooks or alike. Through the *revisiting* of the Embroidered Inflatables samples in the first study, it became apparent that the ways we document our work and archive the resulting samples have significant implications in supporting designers to tap into the generative potential of samples. An attention to sample making and how we document our designs opens the opportunity to encourage different forms of knowledge generation and dissemination, grounded on our real making experiences and the relational nature of samples.

Figure H. Spontaneous discussion about samples turned into an exercise of appreciating and regrouping samples based on different parameters. The value of samples as outcomes of making processes goes beyond narrating a journey chronologically. If we throw all samples on a table and examine what they are and do – as we did here –, they can tell different stories. From left to right: Lan Ge, Kristina Andersen, Milou Voorwinden, Suzanne Oude Hengel and Rosanne Bal.

By reflecting after the fact of making, we can see the things we did or did not do in relation to that specific process and whatever outcomes were considered as its final results. By reflecting-while-making and focusing on what was done, the samples, we also identify gaps in our making processes that open the space for making other things that are outside of our expectations. In other words, a focus on samples supports finding *the road less travelled*. To better explain how this can happen, it is important to look at how samples can gain agency in the making process. Karen Barad described the mutual constitution of objects and agencies within phenomena as *intra-action* [3]. While interaction assumes prior existence of distinct entities, *intra-action* means these presumed separate entities only come to exist through each other. When examining a physical sample made though digital machine embroidery, code cannot be isolated from structure or the yarn or the tension of the machine. This research proposes that analyzing a sample is an exercise of seeing "what's at hand" by unpacking the intra-actions between the entities, the entanglements embodied by the sample. This kind of analysis distributes agency with the material, which in turn unlocks the potential of a sample pointing to new directions of travel. To fulfill this potential, new strategies are needed to follow a number of these insights without eliminating the traces that could take us to other directions.

4.1 Embroidered Inflatables: Exploring Sample Making in Research through Design

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ABSTRACT

This paper reflects on the experience of sample making to develop interactive materials. Sample making is a way to explore possibilities related to different materials techniques. In recent years design research has put an increasing emphasis on making as a mode of exploration, which in turn has made such exploration an increasingly popular and effective design research approach. However, sample making is a messy and complex process that is hard to document and communicate. To mitigate this, design researchers typically report their journeys from the perspective of their success, retroactively editing out or reducing the accounts of experiments that did not directly contribute to their goal. Although it is a useful way of contextualizing a design process, it can contribute to a loss of richness and complexity of the work done along the way. Samples can be seen as instantiations of socio-techno systems of production, which means that they can be looked at from different perspectives and can potentially become the starting points of new design explorations. In recognition of this quality, we aim to investigate ways that samples can be appropriated in future journeys. To do so, we analyzed and reflected on the sample making process of the Embroidered Inflatables as a design case. The project resulted in 27 samples that explored distinct challenges related to designing actuators for soft wearables through the combination of silicone casting and embroidery techniques. To explore the potential of sample appropriation, we invited a fashion designer to a creative session that analyzed these samples from her personal perspective to identify new design directions. We detail the design process, reflect on our sample making experience and present strategies to support us in the process of reevaluating and appropriating samples.

KEYWORDS

Research through Design; sample making; design process; materials; embroidery; soft actuators

1 INTRODUCTION

The design research community is currently engaged in a process of creating a broader context for Research Through Design (RtD), beyond the well-established frameworks for HCI and user-centered design (Redström and Heather 2019). This broader context for RtD is supported through a series of concepts coming from different streams of thought in science and technology studies (STS) and philosophy, which share the interest in re-examining the relationship between humans and the material world from the perspective of the role of tools (Frauenberger 2020). Concepts like troubling design processes (Haraway 2016), correspondences (Ingold 2017) and radical interrelations (de la Bellacasa 2017) are opening new possibilities for design. In practice-led design research, we see similar ideas being articulated through digital craft (Oxman 2007), material assemblages (Wiberg et al. 2013), infrastructuring (Ehn 2008), intentional drifting (Krogh and Koskinen 2020) and traveling (Goveia da Rocha and Andersen 2020). They differ from user-centered design tradition in the way they embrace the full complexities involved in the act of making and designing, allowing a number of concerns and considerations to co-exist and take part in a common design space.

For decades, materiality of interaction has gained focus and interest in design research. Design researchers have begun to shift from metaphor-centered interaction design towards direct forms of interaction through material and their properties (Wiberg 2018). At the same time, the growing adoption of digital fabrication methods has opened up opportunities for more design researchers to explore design practices that are materially driven. By designing from the capabilities of digital fabrication machines, it is possible to transition towards a more integrated approach to designing with and through technology, which expands our views on the relationships between designers, machines and materials as well as between the physical and the digital (Nachtigall 2019).

Approaches based on material exploration allow the development of designs grounded in the real possibilities emerging from interacting with fabrication systems. As a part of this exploration, we are able to metaphorically stand next to the machines and materials we work with to ask them "what if?" and "what else?" (Andersen et al. 2019). In doing so, we emphasize the roles that machines and materials play in introducing opportunities, create intimacy with the making process, facilitate detours and, ultimately, develop different kinds of knowledge. The process is rich and multifaceted, and as a result it is difficult to document and communicate. This is in part due to the high number of samples or artifacts created in materially driven processes and the tendency to focus on final outcomes rather than in the details of how we got there (Krogh, Markussen, and Bang 2015). As a result, this type of design research is often reported from the perspective of how certain experiments led to the reaching of a specific goal (Goveia da Rocha and Andersen 2020). Experiments that do not directly contribute to this "success" are usually unaccounted for or collectively summarized as part of an exploratory phase that mainly serves to provide the reader with a rationalization of the process and evidence of the quality of its outcome. This can create a gap between the reporting of design research and the actual experienced design practice (Scrivener 2000), but perhaps more importantly, it can be seen as a limiting and wasteful practice, as samples or prototypes are treated as a means to an end rather than valued in their own right for the potentially intricate relations that they embody.

By recognizing that the experiments we make may answer more questions than the ones we asked through their making, we join a broader discussion about drifting in design (Krogh, Markussen, and Bang 2015; Krogh and Koskinen 2020) and craftsmanship (Andersen et al. 2019) to consider the role of making samples in Research through Design. More specifically, we reflect on whether we can consider these samples research objects separated from their original context. As a guiding line through the discussion in this text, we will look at the sample making process of the Embroidered Inflatables project, which allowed drifting and complexity throughout the sample making process. In this project, we engaged in a materially driven exploration, making use of state-of-the-art digital machine embroidery combined with silicone casting to create inflatables. Beyond the making experience, in this paper we explore the use of interactive material samples and their appropriation in design processes as a means to draw an outline of the complexities that samples embody. In doing so, we address the community of design researchers and makers engaged with material driven research and digital craftsmanship, and contribute a practical design case of the Embroidered Inflatables, an exploration of the possibility of considering samples research objects in a manner that is in part separated from their original context and a set of strategies to facilitate the revisiting of samples. As such, we aim to open up opportunities of appropriating the samples of Research through Design projects in other design journeys. In the following , we make use of the travelers metaphor (Goveia da Rocha and Andersen 2020) to look back at the Embroidered Inflatable samples as previous places that could be revisited and be appropriated as the starting points of other journeys.

1.1 The previous places

In this paper, we embrace the search for these other places (Goveia da Rocha and Andersen 2020) and aim to articulate how samples that may have been seen as failures within a design journey (van Dongen et al. 2019) can be seen as outcomes on their own terms. In other words, we aim to demonstrate that "failed" samples can be actionable (Rutkowska, Sleeswijk Visser, and Lamas 2019) as new starting points for other journeys. To demonstrate this approach, we build on two previous projects: Flow (Goveia da Rocha and Tomico 2019) and, mainly, the Embroidered Inflatables project (Goveia da Rocha et al. 2019), both aimed at investigating actuation in soft wearables.

Flow was a wearable artifact, made entirely of cast silicone, that aimed at supporting the learning of physical activities through directional cues given by elastic inflatables that push against the body. This one-sided behavior of the inflatables was achieved through a difference in the thickness of its walls, allowing them to push against the body to communicate the direction of movement to the user. The limitations of the fabrication technique were the bulkiness needed to create this asymmetrical inflation and size. Casting entire garments made of silicone alone is not convenient to fabricate or a comfortable solution to wear, limiting the application possibilities of the technique.

As a follow-up of Flow, the Embroidered Inflatables project was started to explore if the one-sided behavior of the inflatables could be achieved through a combination of silicone and a textile production technique to integrate elastic inflatable actuators in soft wearables. Inspired by techniques that use mesh to reinforce silicone or other materials, we opted to combine casting with chemical embroidery. Chemical embroidery (Mecnika et al. 2015) is a technique, typically used to create machine-made lace, that uses a water-soluble stabilizer to create self-supporting embroidery. Through this technique, we were able to take advantage of the accuracy and freedom of routing of digital machine embroidery to program the properties of this lace-like embroidered substrate and, in addition, to determine the shape and behavior of the inflatables.

By revisiting the analysis of these two works, we aim to unpack some of the opportunities that sample making offer beyond abstractions of the lessons learned. In the following sections, we articulate how samples may outlive the context of specific design journeys.

1.2 Old samples, new starting points

Our initial motivation was to recreate the specific behavior of the inflatables in Flow through a hybrid technique that combined a textile production technique and silicone casting. Nonetheless, we were open to explore emergent questions and ideas. As a result, we created 24 samples that explored different challenges: 1) sewing attributes to create properties of inflatables; 2) fit & support; 3) improving integration and resolution of complex shapes; 4) enlarging area of actuation; and 5) textile integration. From these samples, we identified three actuation behaviors, based on which we created three extra samples that we called Interaction Modes.

In the first account of this project (Goveia da Rocha et al. 2019), we presented the complete set of sample series generated in our project, including the Interaction Modes, together with lessons learned throughout the process of creating them. In the following, we propose a way that these samples may be seen to contribute beyond the traditional notion of lessons learned or guidelines.

By analyzing and reflecting on the design process, we observed how a goal-oriented approach could be combined with a more explorative process. Each sample can be seen to stand on its own and answer more questions than it was designed to answer. As such, samples can be seen as instantiations of a socio-technical system of production, and this view allowed us to look at them from different perspectives of the system, such as the interactive qualities of the material outcomes, the design of the digital assets or the experienced collaboration with the machines.

In the following, we present the design process of the Embroidered Inflatables project. Then, we detail findings from a session with a fashion tech design researcher, in which the sample series was used to identify opportunities and qualities that could be forwarded to the design of interactive garments. This session supported the reflection on strategies that can support us in making samples actionable beyond their original contexts of creation, such as how to store/display and document them, presented in section 4. Based on this framing of samples, the following sections provide: 1) the description of the process of making samples by means of digital machine embroidery; 2) a reflection on how to support appropriation of samples as starting points for new journeys.

Our intention is to support our community in finding ways to acknowledge, produce and share knowledge about our material sample work. We hope this is a way towards a more explicit exchange of material knowledge across projects and design researchers.

2 CASE STUDY: EMBROIDERED INFLATABLES

As a design case, we look into the sample making process of the Embroidered Inflatables project. This project was developed in the context of investigating actuation in wearables (Markopoulos et al. 2020). Through this project, we were able to experience a highly paced process of making samples. The samples were executed on the same level of finish and explored different parts of the design space of creating inflatables based on digital machine embroidery. The variety in the collection of samples and their equal level of finish contributed for us to continue to revisit these samples for the purposes of advancing the project towards designing soft wearables based on inflatables, as well as in different contexts and discussions. Looking at them from the proposition of designing as travelers (Goveia da Rocha and Andersen 2020), we gained a new understanding of the potential role of samples in Research through Design. More than steps towards a goal or failures, samples have the potential of taking us to other places by answering different questions than the ones that originated them.

Before discussing our approach to samples (in section 3), we first present the specific challenges we aimed to address through our design process by introducing the context of existing work in actuation in wearables and techniques for creating inflatables.

2.1 Actuation in wearables and textile production techniques

From self-expression to health monitoring, (soft) wearable technologies can open up many opportunities of bringing technology close to the body in engaging and unobtrusive ways. The challenges of integrating technology into garments include bulk/weight/stiffness, thermal and moisture management, flexibility/ durability, sizing and fit, and device interface (Dunne, Ashdown, and Smyth 2005). Textile production techniques, such as knitting, weaving and embroidery have been widely employed for the creation of electronic friendly or electronic integrated wearable technologies (wearables) to overcome such challenges. Embroidery, in particular, has shown the potential of supporting the design of interactive garments as it offers more freedom of routing than knitting or weaving (Linz et al. 2008) to create soft circuits (Post et al. 2000; Hamdan, Voelker, and Borchers 2018) and it requires a relatively low threshold of experience. Moreover, it enables direct interconnections with conventional flexible electronics (Linz et al. 2008) and fabricating a variety of sensors (Linz, Gourmelon, and Langereis 2007; Aigner et al. 2020).

While textile-based sensors have reached a higher level of maturity, having been integrated into commercial products such as smart garments for sports ("Hexoskin" 2019; "Sensoria Fitness" 2019), soft alternatives to actuators remain relatively unexplored. Usually, wearables are actuated through external mechanisms, such as motors, which restrain their wearability (Du et al. 2018). Among other forms of actuation, inflatables have been gaining the interest of designers of wearable applications due to their versatility and the possibility to conform to the body. Although the integration of air pumps into wearables still needs to be further explored for a completely unobtrusive user experience, inflatables can be produced through many techniques and materials, offering opportunities for customizing their form factor, material properties and dynamic behaviors. Additionally, the air pumps can be removed from the area of actuation (Goveia da Rocha and Tomico 2019). This could be used to respect guidelines of wearability such as weight distribution or proxemics (Zeagler and Clint 2017).

Inflatables can be fabricated through a variety of processes and materials, both elastic and inelastic. The customization of the inflatable artifacts allows for creating simple to complex structures that behave in very specific ways. AeroMorph (Ou et al. 2018), for example, presented a heat-sealing approach that enabled the fabrication of inflatables made of different sheet materials coated in TPU (thermoplastic polyurethane) that are capable of curling, folding and changing texture. Polyurethane heat-sealed inflatables have also been adopted by The Force Jacket (Delazio et al. 2018) to support augmented reality experiences. The WRAP project (Raitor et al. 2017) also explored the heat-sealing technique to propose an alternative to vibrotactile stimulation in order to avoid sensory adaptation in haptic applications. The low-profile switchback channels are used to enlarge the actuation area. These actuators were implemented into a wristband to guide movement through directional metaphors by actuating four points around the wrist.

Reporting similar material dynamic behaviors as the Aeromorph, PneUI (Yao et al. 2013) presented approaches to create soft composites, both inelastic and elastic. For their inelastic actuators, plastic welding was used. For the elastic composites, materials of varying elasticities were embedded into silicone to control their behavior. The difference in elasticities to control the behavior of inflatables was also explored to create self-sensing soft actuators based on machine embroidery (Ceron et al. 2018). Spiral patterns made of Kevlar fiber and optical fiber were embroidered on water-soluble film, then embedded in silicone to control the shape of inflation and sense the deformation. The project Flow (Goveia da Rocha and Tomico 2019) used a 3D printed mold and 3D printed PVA inserts to cast silicone-based inflatables that provide users with tactile motion instructions to support motor learning. The wearable was entirely made in silicone, which unified the process of form giving of the wearable with the design of the air pockets and paths.

While heat sealing enables the creation of textile-based inflatables, their integration into garments is limited by the inelasticity of airtight fabrics. Silicone-based inflatables, on the other hand, offer elasticity and work well for wearables designed for smaller areas of the body, such as the wrist/hand. For larger areas of the body such as the torso, however, crafting an entire wearable out of silicone presents challenges to fabrication and wearability. Therefore, solutions for integrating silicone-based actuators with textiles are needed in order to broaden the range of applications of this form of actuation. Chemical embroidery (Mecnika et al. 2015), the technique of embroidering on water-soluble film used by Ceron at al. to embed Kevlar and optical fibers in silicone (Ceron et al. 2018), was also used to create sensorized soft wearables as research products (Goveia da Rocha et al. 2020). In the Embroidered Inflatables project, we built on these techniques to develop reproducible textile-integrated and highly customizable inflatables for on-body applications. As such, we aimed to contribute with new ways of using digital machine embroidery to develop soft wearables and textile interfaces (Post et al. 2000; Gilliland et al. 2010; Mecnika et al. 2015).

For details about the fabrication techniques used in the project and implications of designing inflatables based on embroidery, refer to an earlier publication (Goveia da Rocha et al. 2019). In this paper, we are specifically looking at the complexity of the process of making samples above the specific outcome of the project.

2.2 The design process of the Embroidered Inflatables

The starting point of the explorative design process of the Embroidered Inflatables

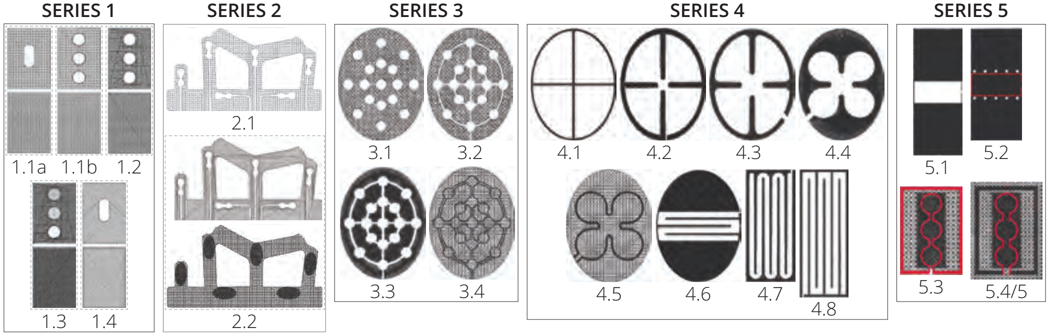

Figure 1. Overview of the design process of the Embroidered Inflatables. The samples were divided into five series based on the different challenges they addressed.

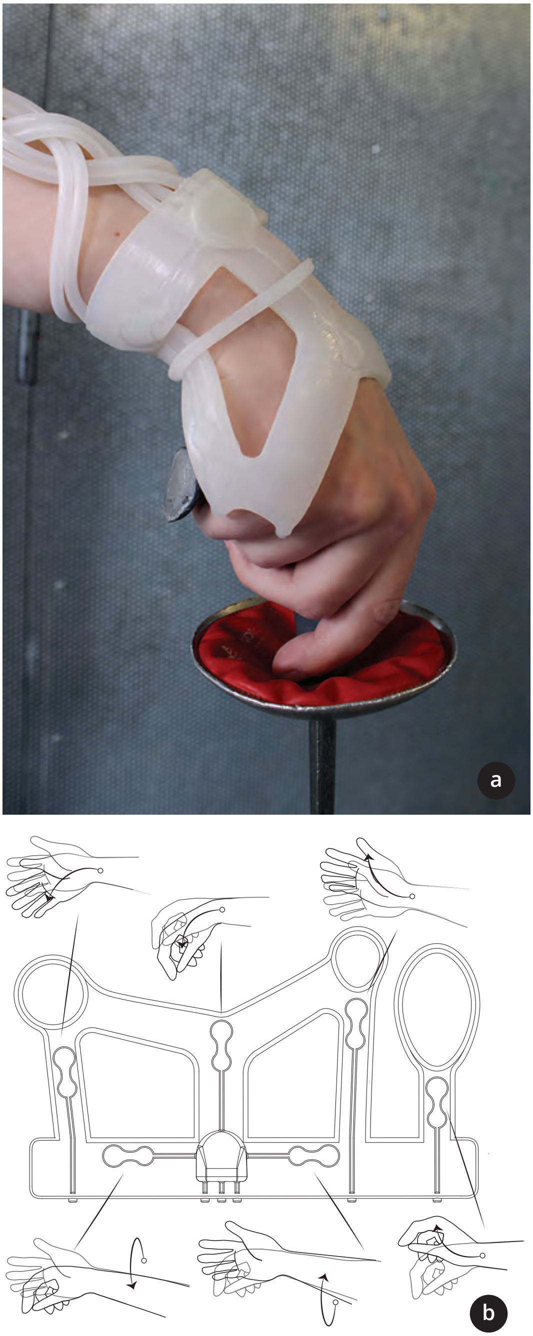

Figure 2. (a) Flow was a wearable designed to support the learning process of physical activities through directional cues. (b) The wearables integrated six inflatable actuators corresponding to the fundamental joint movements of the wrist and forearm.

(Figure 1) was the Flow project (Goveia da Rocha and Tomico 2019). Flow (Figure 2a) was a wearable designed to support the learning process of physical activities. Fabricated as a single piece, cast in silicone, Flow integrated six inflatable actuators into a wrist-worn artifact designed to create pressure points for embodied guidance (Figure 2b). Our interests in the project were both the overall concept of using pressure to communicate with the body and, most importantly, the use of materials as extension of the pumps needed to actuate the inflatables. As such, our original intention with our exploration of embroidery-based inflatables was to transpose the fabrication method used to create Flow to textile (compatible) techniques that would allow implementing the concept of crafting soft wearables with integrated actuators to larger parts of the body.

Flow was made by casting silicone (ecoflex-030) in a 3D printed mold made of PLA filament, using a 3D printed PVA insert to create the cavities that operated as inflatable chambers. In the embroidery-based samples, we used the freedom of routing of the embroidery technique to flip the complexity of the design to the embroidery, which gave us more freedom to create the shapes of inflatables and facilitated the stacking of layers to achieve the single sided behavior. Instead of the 3D printed PVA inserts, the same PVA stabilizer film used to embroider the free-standing embroidery (Gunold Ultra Solvy 80) was used to create the chambers. The embroidery machine served multiple purposes, including creating a strong integration of silicone with textiles through its open structure, creating free-standing substrates, cutting out the film in the desired shapes, cutting out textiles through cutwork needles to integrate the substrates into ready-made fabrics and to assemble layers. The molds were simple,

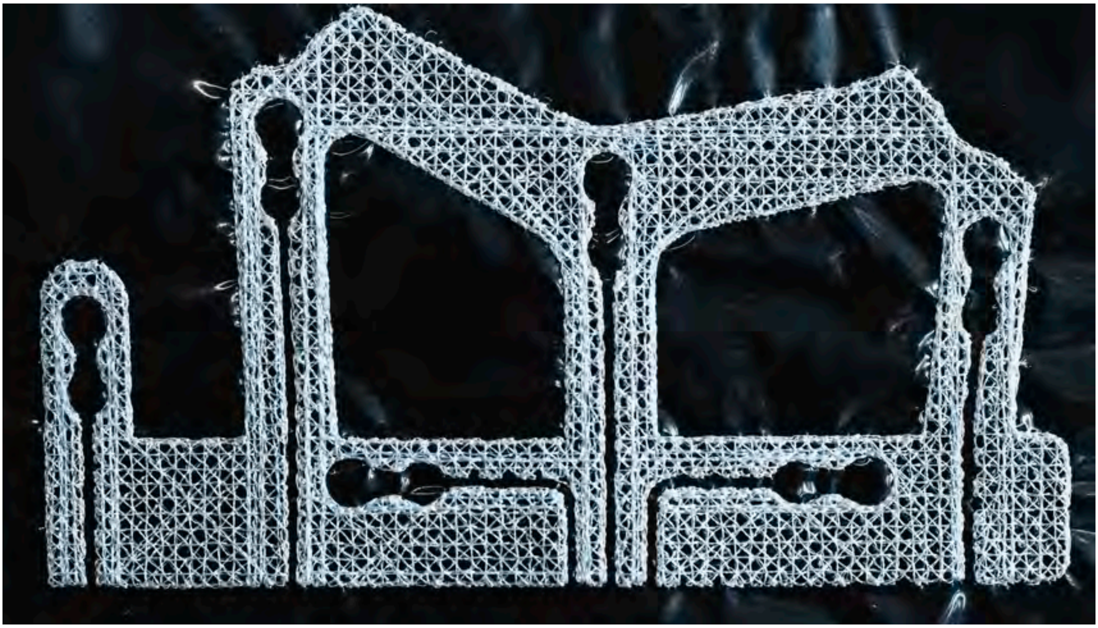

Figure 3. In the samples of series 2, we recreated the design of Flow. The wearable shape with integrated inflatable air paths and pockets was complex, resulting in a repetition of stitches. This motivated us to explore layering and the sewing attributes of the embroidery.

needing to only demarcate the outside shape of the casting area while the shape of the inflatable area could be easily customized through the embroidery.

Interestingly, it was in series 2 (Figure 3), when we recreated the design of Flow, that we started to shift our design approach towards intentionally drifting. On the one hand, we continued to pursue the goal of exploring how to create the asymmetrical inflation through a textile-based technique. On the other, we deliberately drifted to explore the possibilities of designing inflatables through the embroidery technique.

In series 2, our aim was to recreate Flow through a similar approach to the one presented by the Smart Sock project (Goveia da Rocha et al. 2020), in which the chemical embroidery technique is used to create the free-standing embroidery already shaped as the wearable (parts). Different from the Smart Sock, this design had a complex outline to integrate the paths of inflation and inflatable pockets into the shape of the wearable. To create the free-standing embroidery in the shape of Flow, the machine had to travel all around and back several times, resulting in excessive stitch repetition. Although it is possible to edit each stitch manually, the overlap of multiple stitches in the same spot made it impractical to edit the automatically generated net fill stitch pattern we used. Instead, to reduce the repetition of stitches, we recreated the net fill stitch pattern through four layers of low-density fill stitch, each in a different direction. To further investigate how to overcome the challenge of creating complex shapes, we moved onto exploring different structures and stitch types through other samples that we later identified as Series 3 (Figure 4).

As we proceeded in engaging with materials and techniques, we shifted our focus from a goal-oriented journey to also embrace

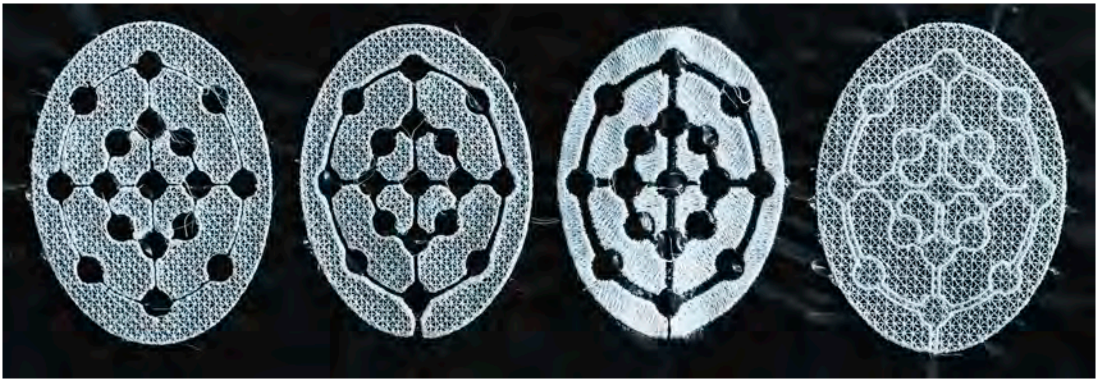

Figure 4. Series 3 explored complex shapes and varying sewing attributes.

questions and opportunities that emerged from the experience of making. The process of moving from one sample to the next happened organically. For the most part, we can see the process of moving through these questions as a process of itineration (Ingold 2010), in which every step is a development of the previous one and a preparation for the next. Because the questions we let lead our way were not incremental, our process could also be characterized as an expansive way of drifting (Krogh, Markussen, and Bang 2015), that aimed to explore the possibilities of creating inflatables through digital machine embroidery and, particularly, chemical embroidery technique.

In this process, we created twenty-four designs that addressed different emergent challenges and questions. Each sample was thoroughly documented. The documentation incorporated technical attributes of the embroidery designs, materials, methods of fabrication and reflections on the design journey (goal, behavior of the inflatable and insights). By revisiting the documentation and reflecting on our process, we identified how we addressed five main topics: 1) sewing attributes to create properties of inflatables; 2) fit & support; 3) improving integration & resolution of complex shapes; 4) enlarging area of actuation; and 5) textile integration. These topics were used to divide our process into five series of samples. Based on our experience and documentation, we reflected on the design implications of fabricating inflatables through machine embroidery.

Our reflection also allowed us to identify three actuation behaviors (Figure 5). We created three new samples, one per behavior, which we refer to as Interaction Modes 1, 2 and 3 (Figure 6). The modes are defined by the deformation of the actuators resulting from their construction and the substrate structure.

In the original account of our project (Goveia da Rocha et al. 2019), presenting the Interaction Modes as a final outcome seemed like the logical endpoint for the process. However, other emerging opportunities showed us otherwise. As an example, we improved the casting process reported in our previous publication through different mold methods for casting locally to avoid bleeding through the fabric. One method involved 3D printing the mold onto the embroidery (Goveia da Rocha, van der Kolk, and Andersen, forthcoming) and the other, using magnetic laser cut acrylic molds. These versions of the molds allowed us to keep the samples in the embroidery hoop so that they could return to the embroidery machine for possible post-production such as embedding

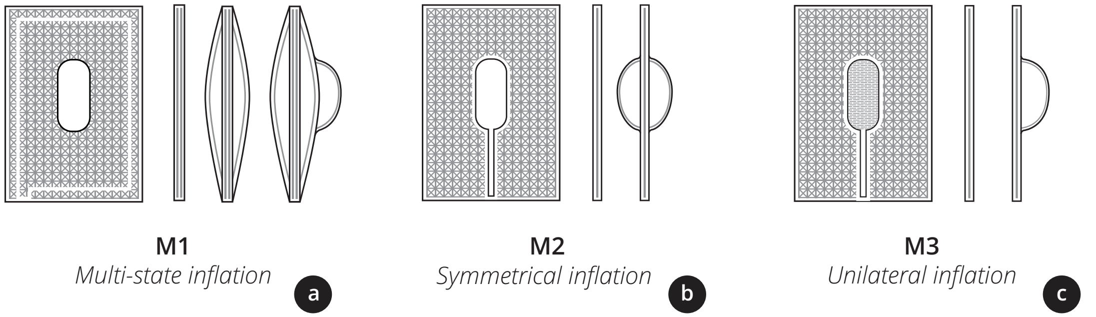

Figure 5. Front views of Interaction Modes 1, 2 and 3, accompanied by their side views in neutral and actuated states. M1 is a multi-state inflatable, M2 inflates symmetrically and M3 inflates unilaterally.

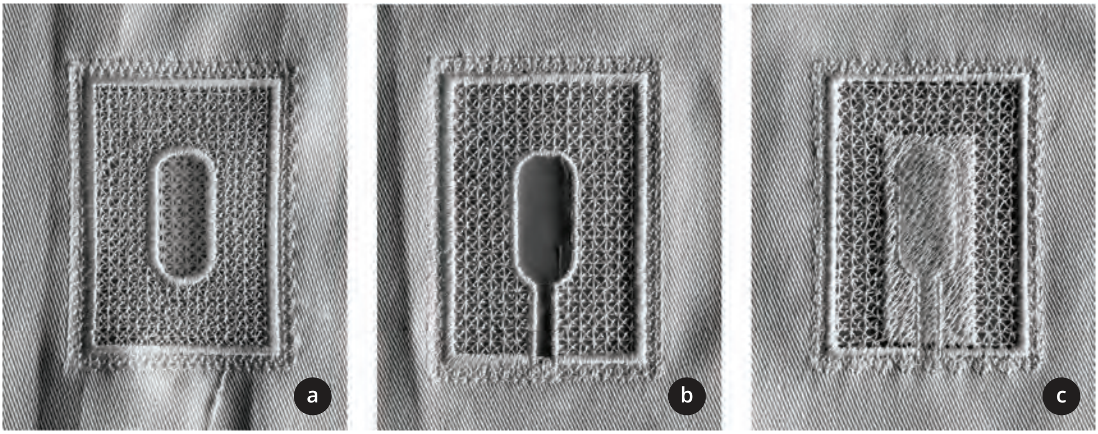

Figure 6. Embroidered substrates of Interaction modes 1, 2 and 3 integrated into woven tex- tile. (a) Mode 1 is made from two separate embroidered parts. (b) Mode 2 consists of a single embroidery part. (c) Mode 3 is a single substrate sewn as layers that integrate a sheet of water-soluble film over the substrate and support pad.

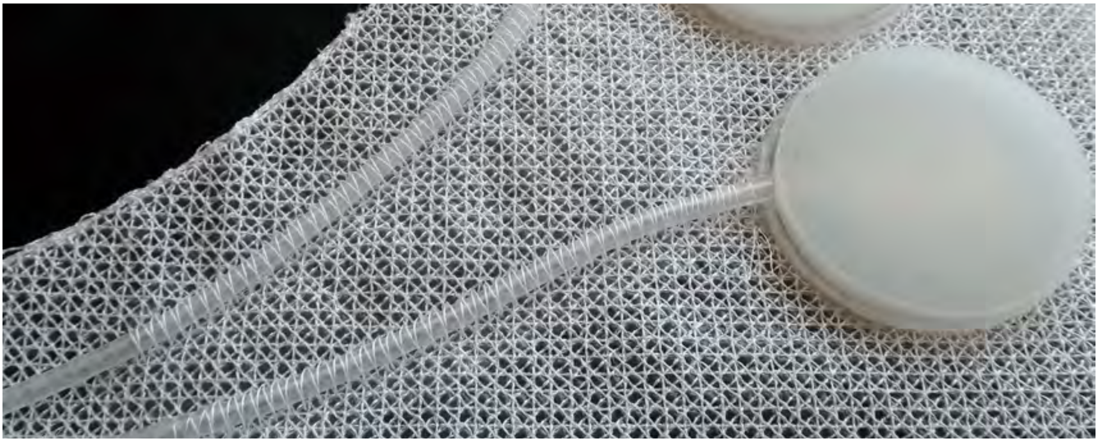

Figure 7. Embroidered sample with integrated tubing. To achieve this, production is carried out in three stages. First the substrate and inflatable area are embroidered, then the silicone is cast. Lastly, the tubing can be connected and integrated into the embroidered substrate using a couching stitch.

tubing, as seen in Figure 7.

While the Interaction Modes were considered an endpoint for the process, there were other possible outcomes to our process as well as interesting loose ends worth revisiting and pursuing in other design journeys. These relationships across projects likely happen in design practice, particularly for designers working closely with a specific craft. We would like to propose that samples can be approached as living things, prone to be revisited and re-signified by new questions which allow us to more explicitly forward concepts, insights, materials and techniques across projects and design researchers. Our process indicated that the formats of presentation and documentation are key to support a shift of approach and to enable a deeper understanding of the samples and artifacts we make.

3 SAMPLE MAKING AND THE SEARCH FOR OTHER PLACES

Unpacking design processes is challenging. For many years, our community has been engaging with questions over the nature of our work and how to expand our understanding over what is the knowledge we can generate by carrying out design actions (Wensveen and Matthews 2015). Therefore, the discussion on the role of prototypes and prototyping remains central in design research.

Peter Krogh et al (Krogh, Markussen, and Bang 2015), acknowledge that designers drift in design processes to continuously learn and adjust themselves to opportunities or challenges that emerge. There are multiple ways we drift in design research to gain depth, acknowledge complexity, systematize knowledge, broaden knowledge and to exploit opportunities that emerge along the way.

The notion of infrastructuring (Ehn 2008), also points at design objects as being more than simply accomplished dead ends. The things we design are also relational and open to being appropriated and appreciated in other contexts beyond the one in which they were created. Designing 'for design after design' involves considering the relationships between people, methods, facilities, tools, materials, machines. This relational view also supported the culture of prototyping developed within the Smart Textile Services project (STS), part of CRISP (Tomico and Wensveen 2014). The STS testbed is a platform in which prototypes are the drivers of design processes through a bottom-up approach, and the act of prototyping is seen as a craft that enables shared ownership and community building through dissemination of the work (exhibitions, facility sharing and designers in residence).

William Gaver (Gaver 2012) echoes the idea that designs objects should remain open for appropriation and appreciation by arguing that "an endless string of design examples is precisely at the core of how design research should operate, and that the role of theory should be to annotate those examples rather than replace them."

Seamful design presents yet another perspective that values the complexity of design processes that argues for making the connections and gaps between physical, digital and social spaces explicit (Rudström, Höök, and Svensson 2005). About design practice and collaborative work, Anne Galloway questions the political and ethical implications of "seams and scars" in design processes (Galloway 2007). More specifically, she argues that the "seams and scars" are markers of past actions or interventions - like things that are cut apart and put back together in a new way. Making them explicit supports us in questioning the conditions in which they occurred, meaning how processes unfolded and what was the role of the players involved. This can encourage a

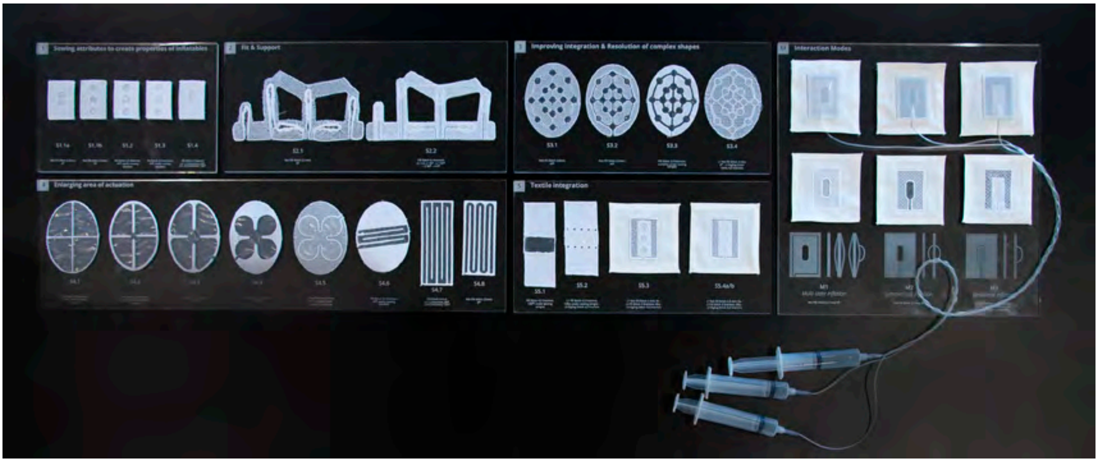

Figure 8. Display setup for the INTERSECTIONS Collaborations in Textile Design Research Exhibition. All samples of the Embroidered Inflatables project were recreated and mounted on six acrylic displays. Visitors were encouraged to interact with the Interaction Modes samples by actuating them with syringes.

search for “places where interventions can be made, or where potential can be found and acted upon” (Galloway 2007).

While each of these design philosophies or research traditions articulates our relationships around practical work differently, all of these approaches look beyond user-centered design to acknowledge and embrace the social, technical and material complexities involved in design practice and, consequently, in Research through Design. In our work, we explore this understanding of the relational characteristic of design practice by questioning which strategies can assist us in opening our experiments up to new relations and opportunities.

We focus on samples because, in HCI and in design research, this is a broad term that has been used to refer to the outcomes of materially driven approaches, meaning that the value and interactive possibilities offered by these prototypes is intrinsically related to their fabrication methods and materials. Similarly to how research products are characterized (Odom et al. 2016), samples can be seen as prototypes that are evaluated by what they really are and what they can do. When engaging with such samples, we may discover that more than the (interactive) qualities we planned on materializing are present. These qualities and behaviors of samples are composed by the negotiations between our intentions with those of the entire socio-technical system of production: material, the machine and the circumstances. When judged based solely on our intentions, a sample may be a failure or a success within our journey towards a specific goal. Yet, that does not eliminate the other opportunities its qualities may offer to another process.

We build on these ideas together with the notion that this way of working is akin to traveling (Goveia da Rocha and Andersen 2020). The designer allows new ideas to emerge through a mindset that invests time in creating things in collaboration with people, ideas, tools and materials. The making process is curiosity driven, but the designer is systematic about documenting experiments so that they stay open for appropriation in other journeys.

3.1 Revisiting samples

We presented the Embroidered

Inflatables project at the "INTERSECTIONS: Collaborations in Textile Design Research Exhibition" (Morgan et al. 2019). The exhibition gave us the opportunity of seeing all the samples as a collection, with the same type of finish and level of importance.

In preparation for the exhibition, we recreated all samples and mounted them in acrylic displays (Figure 8). The sample series 1 to 5 were not cast in silicone to highlight the embroidery. The Interaction Modes, on the other hand, were cast in silicone and connected to syringes so that visitors could actuate them. While in design research we are most used to creating new things or improving them, experiencing the process of "reproducing" samples brought us different insights about the situatedness of sample making. We place "reproduce" here between quotation marks because, as Ingold points out, no two steps are the same (Ingold 2010). The final outcomes were highly reproducible because the embroidery files were the same, but everything else was slightly changed. Unlike in the original set, we embroidered all new samples in the same color for uniformity. The machine sometimes worked better, sometimes worse than before. There were different people in the lab asking us questions about digital machine embroidery, what were we doing or how long it would take before they could use the machine. Receiving questions about embroidery while making them was particularly interesting as it supported us in looking at our samples from new perspectives to use them as answers. This way, recreating the samples allowed us to deepen our appreciation of the technical attributes of the embroidery and, more importantly, our understanding of sample making.

Such samples do not only present a high level of fidelity of look and feel in relation to interaction capabilities. Samples are open ended products with specific properties and behaviors. They are instantiations of the socio-technical systems of production. While their properties are concrete, their meaning is open for change through negotiations with and within a given context (Bergström et al. 2010). To us, this understanding of samples as becoming materials does also relate to how we should allow our work to be revisited. As designers who learn through making, the insights we gain from experiments are also situated in the level of experience we have with the production systems we interact with and the motivation that drives our process at a given time. As such, we propose separating the objects of design, the samples, from our design journey to allow ourselves to come back to them for new negotiations.

To further explore this possibility, we invited a fashion design researcher, specialized in wearable technology for a creative analysis session. In the session, we used the embroidered inflatable samples to discuss possibilities of designing interactive garments that included our actuators. A vest with three integrated embroidered inflatables (Interaction Mode 3 design), one on each shoulder and one on the lower back, was also used in the session as a starting point. Both sets of samples were present but the original set was used most because the samples could be easily taken out of the binder in which they were stored to be manipulated. This meant that the original ordering of items in a series became irrelevant during the session. Instead, they were all seen as a wide collection and samples were analyzed based on emerging questions.

The session included two parts. The first part was an embroidery workshop to explain the techniques used to create the samples. The second part was a discussion of possible applications and the possibilities of designing garments from the samples (bottom-up approach).

Figure 9. Samples used to discuss actuation and expressiveness. The three samples demonstrate three different active behaviors (9a) Multi-state inflation, (9b) symmetrical inflation, (9c) Unilateral inflation.

To allow unexpected topics to arise, we let her take the lead in the discussion to ask things she felt that she needed to know in order to ideate with and from the samples.

Her questions related to four main topics: actuation and expressiveness, color, layering of materials over the inflatables and transitions between materials (from embroidered substrates to other textiles). We detail the new opportunities that emerged through discussions in each of these topics below.

3.1.1 Actuation and expressiveness
Most discussion points about actuation and expressiveness related to understanding the possibilities of designing the inflatables through digital machine embroidery. Questions on this topic included what the size and shape limitations of the inflatables were and how the airways could be integrated. These questions could be easily answered through our samples (Figure 9) because this topic was directly related to challenges addressed during the process of making them. An interesting point that emerged from this session was what other possible functions the actuators could serve in wearables other than pushing against the body: "Is it an option to create active behaviors on the garments through this technique?" To create push against the body, the fit of a garment should be tight. Looking at creating active behaviors on the garment instead, opened up a different view on possible silhouettes that could integrate the actuators. Consequently, a new perspective on the drapability of the samples emerged as a direction to explore. Some features like the shape, the density of embroidery, the direction of the embroidery and the thickness of the silicone could contribute to a higher malleability of the resulting inflatables.

3.2.1 Color
We were not concerned with color during the creation of the original samples. We only made active decisions on color for the exhibition, opting for white for the sake of uniformity and to highlight the embroidery attributes. From the perspective of the fashion designer, however, knowing "What is the impact of the silicone and the embroidery in color? Are there restrictions?" was essential to guide a bottom-up process of designing a garment from the samples. A few of the samples in the original set were embroidered in different colors. Therefore, we could analyze the effect of the silicone over the thread color by comparing the bright yellow and white samples with darker pink ones. While the bright colors seemed unchanged under the silicone, darker shades changed significantly, as seen in a sample from series 2 (Figure 10).

Figure 10. Sample 2.2 recreated Flow. The color changed significantly after casting, particularly on the denser areas.

The density of the embroidery and the thickness of the silicone also had an impact on color: the denser the embroidery or the thicker the silicone layer, the more it darkened the color. This could be used as a feature by exploring how to blend colors through embroidery gradations as well as through varying silicone thickness.

3.1.3 Layering of materials over the inflatables
In our work, we overlayed embroidered designs and materials to create specific properties and actuation behaviors, such as the behaviors seen in Interaction Modes 1 and 3 (Figure 11). Although layering techniques were fundamental to design our samples, in our process we had not considered how layering could be used to change the surface of the inflatables. For the fashion designer, knowing whether it was possible to cover the silicone could open up opportunities for making decisions on concepts for application and look & feel of the inflatables: "Is it possible to cover the silicone? Say, add a liner for comfort or an outside material in case I do not wish the silicone to be visible?". Although we knew that layering could be used in multiple ways, including embedding or appliquéing extra materials, this helped us realize that the technique could be used to add lining, texture or other effects to the samples.

3.1.4 Transitions between materials
The question about the transition between materials pertains to fit. We explored fit in sample series 2 (Figure 10), in which the full form factor of Flow was recreated. From those samples, we knew that one interesting direction to explore was to manipulate locally the fabric character of the substrate and so create properties like stretch in parts of the wearable for improving fit. During the session, an alternative approach emerged. Looking at the vest as an example, she suggested that "for a more forgiving fit, the side panels of the vest could be stretchable." The samples created in series 5 demonstrated that we could achieve a robust integration between embroidered substrates and other textiles, both woven and knitted. However, these transitions only included straight lines. To explore a more organic and subtle transition, we created an extra sample together (Fig 12). In this sample, we already began to move towards a new direction to explore the delicate qualities of lace and transitions between lace and other textiles as seen in garments such as lingerie.

Through this session, we could demonstrate how samples can potentially be appropriated to open up new opportunities. As potential new directions, we identified opportunities of appropriating our samples, including: searching for qualities of drape; creating blends of color through the combination of silicone and thread; applying our layering for other ends such as lining to garments; and further exploring the delicate quality of our substrates.

3.2 Strategies

In design research processes we tend to treat our understanding of experiments as permanent and conclusive. In this view, an experiment is a failure when it does not offer us a direct way of progress towards

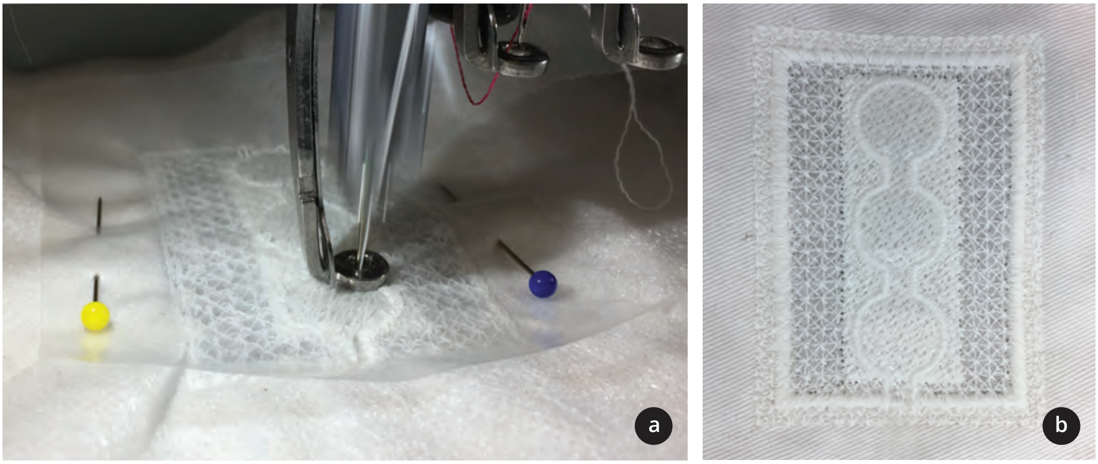

Figure 11. We used layering in many of our samples. (11a) To create Interaction Mode 3, we layered materials by adding two sheets of water-soluble stabilizer: the first as a base for integrating the embroidered substrate and the woven fabric, the second sheet is used to stitch the shape of the inflatable so it stays on the sample for casting. (11b) This sample was made by layering embroidery under the inflatable area to direct the inflation and appliquéing the water-soluble film to determine the inflatable shape.

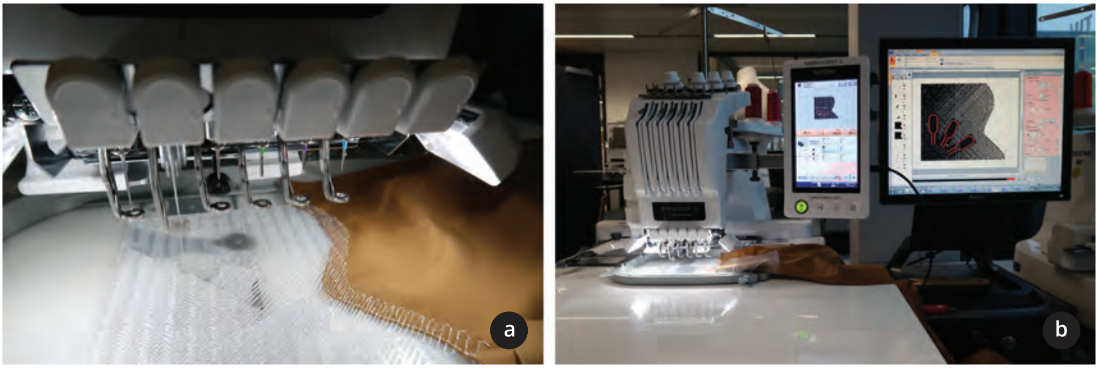

Figure. 12 Inspired by lace and lingerie, a new opportunity of combining the embroidered substrate and other materials emerged from samples of series 5 and Interaction Modes.

our goal and it can therefore be discarded. In such an approach, new findings come from making other things towards new goals. Embracing ambiguity as a resource (Gaver, Beaver, and Benford 2003), the traveler approach sees that "the finding of new things also means looking at old things with new perspectives" (Goveia da Rocha and Andersen 2020). This means that instead of discarding samples that deviate from a given goal, they can be left as open opportunities for drifting (Krogh and Koskinen 2020) towards future journeys. To enable this, we need to explore strategies that support us in preserving encountered opportunities. Through our experience with the Embroidered Inflatables, we found that considering how we document and present our samples is key to ensuring they can be seen as open opportunities.

3.2.1 Documenting samples

The process of sample making through digital fabrication tools presents a challenge of decentralization of data over all the socio-technical systems of production. The knowledge created from making a sample is divided between the experience of making, the digital file, the hardware we use, the post-production and our interactions with the samples. To appropriate a sample in a new journey, we need all of this data to be accessible. Therefore, we see the integration of data as a key factor of allowing samples to outlive the processes that create them.

As previously stated, emergent questions lead our process of making the Embroidered Inflatables. Considering that we did not know which samples would turn out to be the most interesting or when we would return to them, the likelihood that we would have forgotten the details of how a sample was made was high. To support this, we kept a spreadsheet with very detailed documentation of the samples. The format we used recorded data from a) the design journey, b) the software and hardware technical specifications, and c) our experience with the sample. During the process of making, we mostly used this documentation to reflect on our design journey, registering what happened with each sample and what could be done next. Later, the documentation also helped in identifying correlations between sewing attributes and material properties or active behaviors of the samples.

Integrating the data about each sample helped us develop a sensitivity about the relationships between materials, digital assets, and the machine that is necessary to appreciate what each sample is or can do. It allowed us to see the motivations and interpretations that carried us through our design journey, while preserving the details of how they are made and what they can do (properties and behaviors) in a way that allows for appropriation and new interpretations.

Documenting the design process can be time-consuming (Dalsgaard and Halskov 2012). Further investigation on the ways of documenting samples should be conducted to allow for as much data to be collected and centralized without overburdening designers.

3.2.2 Presenting samples

The way we present or store our samples carries an impact in their actionability. Our sample series were presented in two formats: a binder used to store all the samples with their corresponding documentation and annotations; and six acrylic displays that showcased the five-sample series and the Interaction Modes series. On its own, the binder emphasizes the apparent linearity of the process, supporting the telling of a story of how we succeeded in achieving our goal. The exhibition displays, on the other hand, put all samples at the same level of importance, supporting an overview of the design process.

Throughout our new analysis of our work, we began to explore these formats as ways of supporting revisiting samples. We found that it is important to create ways to reach the samples (the material and the documentation) both individually and within collections. Collections help us in identifying similarities and differences between samples but also gaps of opportunity regarding topics that we have not yet contemplated. Engaging with samples individually supports us to reinvestigate them, leading us towards engaging with other aspects of the socio-techno system of production they embody.

In our process, we dealt with samples as a collection, sub-collections (each sample series) and as individuals. We imagine that collections should expand beyond a single project to embrace an entire body of work, open to being revisited. For that to work, we should be able to easily access material samples and their documentation.

4 CONCLUSIONS

Inspired by the streams of thought in design research that aim to create a broader context for design research processes, we have presented a perspective on samples in Research through Design. This perspective builds on ideas presented by the travelers' approach, which proposes that not only the experiments that fit coherent stories should be valued. Seeing each sample as instantiations of socio-technical systems of production, valued for what it is and does, supports us in keeping samples open to potentially kick off new processes.

We developed this through a description of the sample making process of the Embroidered Inflatables and with our reflections on the strategies that enable the revisiting of samples to answer new questions. Suggested strategies included integrating the data about a sample into a single form of documentation and dealing with samples individually as well as in collections.

In our session with a fashion designer, examining samples for what they were and could do supported us in identifying opportunities for other design journeys. While the limitations and implications of taking this approach to samples still need to be explored further, we believe this approach offers the possibility of fostering different relationships with samples within and across projects. Further work in this direction should seek to further specify the characteristics of such samples and investigate documentation formats.

Lastly, we recognize the need for deepening our understanding of the moments when this approach may work. Our samples did lend themselves to the possibility of being revisited, and arguably, this happened because they are material samples, which makes it easier to disconnect them from their original contexts. In addition to this, with the exception of series 2, our samples did not have form factors that connected them to a particular use. This may have facilitated us in playing with them to find interesting qualities to be explored elsewhere. Can other types of prototypes, constructed for specific application contexts, also be easily treated this way? In the future development of this approach, it would be valuable to explore whether research products (Odom et al. 2016), prototypes of high level of fidelity and finish, can be treated in the same way as our samples.

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4.2 In the Thick of Digital Craftsmanship: A Dialogue Between Weaving and Embroidery

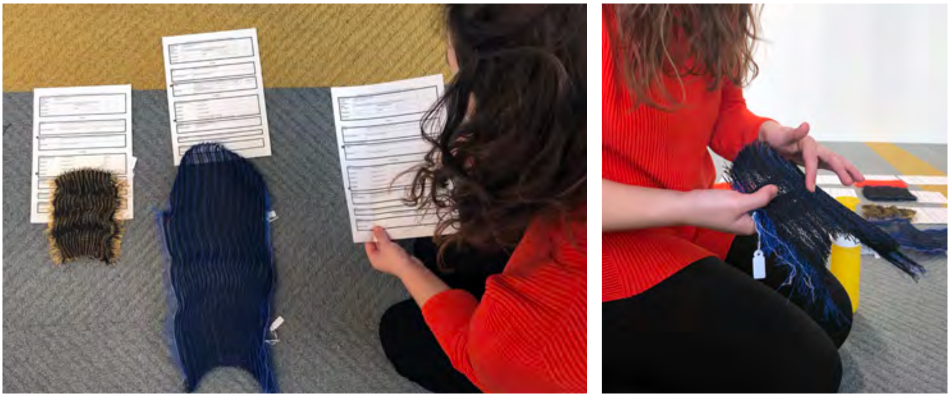

Figure I. Photo from session 1. During the co-analysis of the sample making process, the designer narrated her process and explained the main insights that drove the process. Samples were arranged in chronological order to narrate the process, then rearranged based on emerging themes that motivated the development of new lines of inquiry.

The possibilities and limitations of digital fabrication machines, such as work envelope, are often discussed in material-driven research as ways to describe the kind of things that can be made through a given fabrication method, or the interactive possibilities these machines offer. Our making practices and the ways that such machines or techniques configure them, on the other hand, are less explored and described. Seeing this gap as an opportunity to unpack the relationality of digital craftsmanship, this study aimed to explore the relationship between making practices and the fabrication systems we make with. To do this, I put my practice in dialogue with the practice of Milou Voorwinden, a textile designer specialized in digital weaving, through a year-long study in which she adopted a documentation form created from my practice of digital machine embroidery into hers as a weaver[1]. We discussed her experiences and the sample work she documented in three sessions (Figure I).

Originally, this study also included Suzanne Oude Hengel, a textile designer specialized in knitting with a focus on footwear. The two designers were collaborating in a project and were exploring spacer fabrics in parallel processes. However, Suzanne chose to drop out of the study during the Covid 19 lockdown period, which had impacted her access to machinery. She participated in the first session in which we discussed her experience documenting 20 samples. This interview contributed to development of the concept of loose ends, described in chapter 6. Like Milou, Suzanne had in her collection a sample she called a "happy accident", a sample that had although did not perform as expected, had interesting behavior worth looking into in the future. In her documentation, she used a lot of visual and tangible elements like schematics of the knitting structure and pieces of the yarns used. At the end of this session, she suggested the inclusion of a field for finishing & post-production where information about dimensions before and after steaming would be included. Milou made a similar suggestion.

The dialogue between practices proposed in this study could be seen as a form of *diffractive reading*, meaning questioning one practice through the other. Inspired by Karen Barad's understanding of *diffraction* [4], *diffractive reading* has been used in design as a way of creating shared ownership between designers over the concerns located in subjective and lived experiences, without looking for a shared truth [13]. "Diffractions, such as the complex wave forms created when light is beamed through slits, are 'attuned to difference' and, specifically, the way that those differences, expressed as regions of light and dark, are produced under specific conditions of analysis" [14]. As such, using this notion of *diffraction* to analyze design or design practice is about reading "the way that multiple 'different' objects and memories can intermix to reveal new approaches, ideas, and understandings" [14]. In this study, the dialogue between practices was facilitated through a documentation form. The study did not aim to design an ideal form for documenting sample making processes, nor propose universal 'best practices' for *digital craftsmanship*. Rather, it contributes with accounts of how different fabrication machines configure the personal making practices of two designers differently, supporting an understanding of *digital craftsmanship* based on a relational view. Furthermore, intermixing experiences of weaving and embroidering technical/interactive materials supported revealing conditions for engaging with emergent opportunities in material driven-processes that can support explorative material-driven approaches.

In the following sections, I detail how this form supported our dialogue and her process of appropriating the documentation system. I also reflect on how our practices are configured differently by the fabrication systems we interact with.

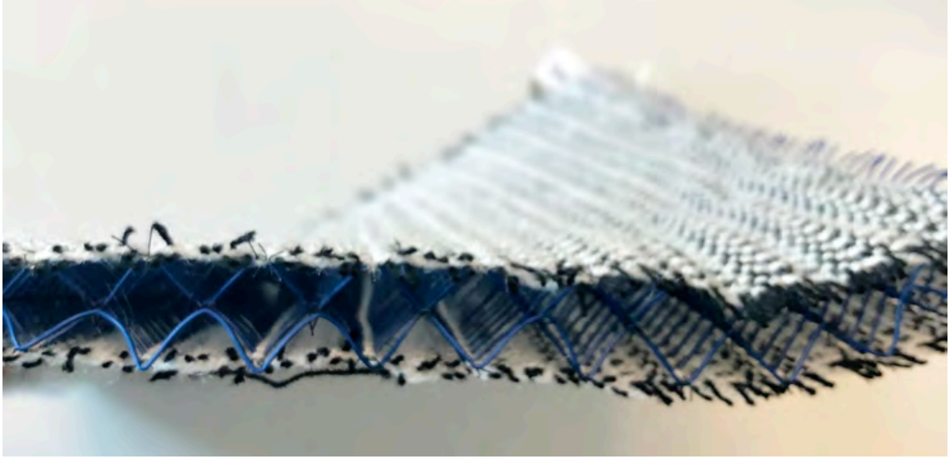

Figure J. Profile of sample LW_3_22 created by Milou. In this development she explored weaving spacer fabrics. These samples were constructed by weaving multilayered structures. The points in which these layers are interlaced are called bindings. Her goal was to create a spacer with dense weave in the top and bottom sides.

Documentation form as a tool of dialogue

The dialogue between practices occurred through a longitudinal study that lasted about a year. The documentation form used to enable our dialogue was developed based on my practice of digital machine embroidery and research interests. The form included different reporting styles from industrial and textile designers with the aim of making the data that is usually distributed between digital file, machine, and project reports explicit and attached to specific samples. This with the intent of supporting designers in reflecting in action about their designs both within the design processes in which they are created and as stand-alone objects. The documentation form template was given to the textile designer to be used in her own projects as means to challenge the way she works and prompt reflection on her design process. For that, she had full freedom to incorporate the documentation into her workflow. She used them to document the development of woven spacer fabrics (Figure J). The access to the weaving machines she used in the project was limited, thus the project was developed through intense weeks of sample making at a time, varying in frequency. Sometimes developments weeks took place months apart from each other. Through her adoption and adaptation of the form to fit her own way of working, we created a shared ownership of the documentation system over time and progressively changed roles from participant/researcher to collaborators. In the next section I detail the structure of the study.

Interview and co-analysis sessions

We discussed her practice and experiences of using the form through three sessions. Each of the first two sessions lasted about 1,5 hours and included three parts (Figure K). The first part was a discussion about her documentation experience through an open-structured interview. In the second part, we co-analyzed her design journey through the samples. This was done by first laying down physical samples in chronological order. Then,

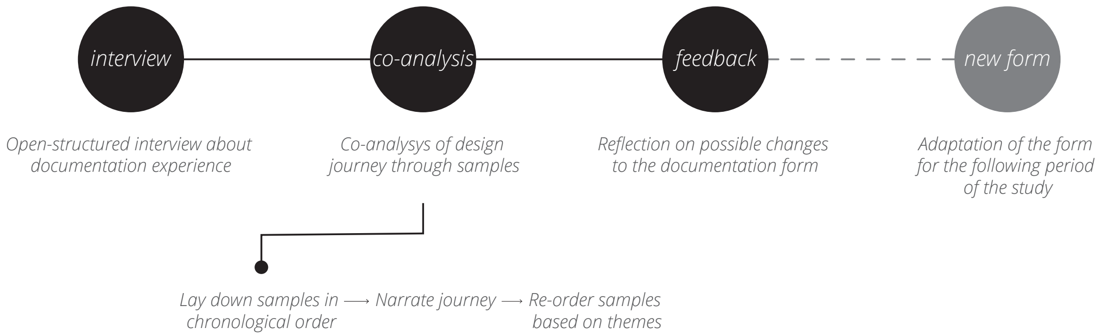

Figure K. Sessions 1 and 2 structure. Each session was divided in three phases (interview, co-analysis, and reflection), followed by a revision of the documentation form.

Figure L. Co-analysis of samples in session 2. This collection included 38 samples, divided in 7 columns. The 5 columns in the middle were themes that emerged in her process.

she narrated her process, explaining the motivation for each sample, or group of samples, and the insights she gained from them. As she mentioned interesting material qualities that she perceived in a sample that triggered new directions for exploration, we moved the sample into a theme column. Other samples associated with this emerging theme were placed in the same column (Figure L). At the end of each session, we co-reflected on potential changes to the template to support her practice. Based on this reflection, an adapted version of the documentation form was created for the following period of the study. Session 3 was a wrap up session based on the open-structure interview and a reflection on the overall experience.

Building a documentation practice

The changes to the form suggested between sessions were relatively small and consisted mostly in swapping the order of certain sections or changing division of content (Figure M). In our sessions, she reported that the On the Floor section was the most difficult for her to fill in due to time. Her access to the machines used in the processes documented in the study was limited, so she had to spend as much time as possible focused on making. Nonetheless, when asked if it should be removed from the form, she said no because it could be useful in the future. In our final section, she reaffirmed this section could be useful in the future, explaining it could be part of the process of revisiting a sample in new projects.

> *"I can imagine that if I want to start a new process, a new project, I will try to take a few samples that I made before and get their forms. Maybe, I would fill that in at that time, just to review the sample. I think that's why I left it in."*

After the second session, she shared a new version of the form she with adaptations she implemented in between sessions. According to her, the order of sections was modified to match the order she filled them in, bringing information that needs to be documented while making, like the machine setup, before information which can be filled in afterwards without as significant loss of details, such as the design journey. This helped mitigate the difficulty in balancing the need to document and the limited time allocated for making. Additionally, she made the form more visual by enlarging the field 'photo' and including color coded tags to track changes between designs, making it easier to recognize the form.

Over time, she also changed how she used the form, which supported her in creating her own system of documentation. At the beginning of the study, she began incorporating the documentation form into her practice by using the hardcopy version of the template filled in by hand. Each sample was tagged with an identification code to connect it to its respective form. By our second session, she had transitioned to filling the forms digitally, which supported

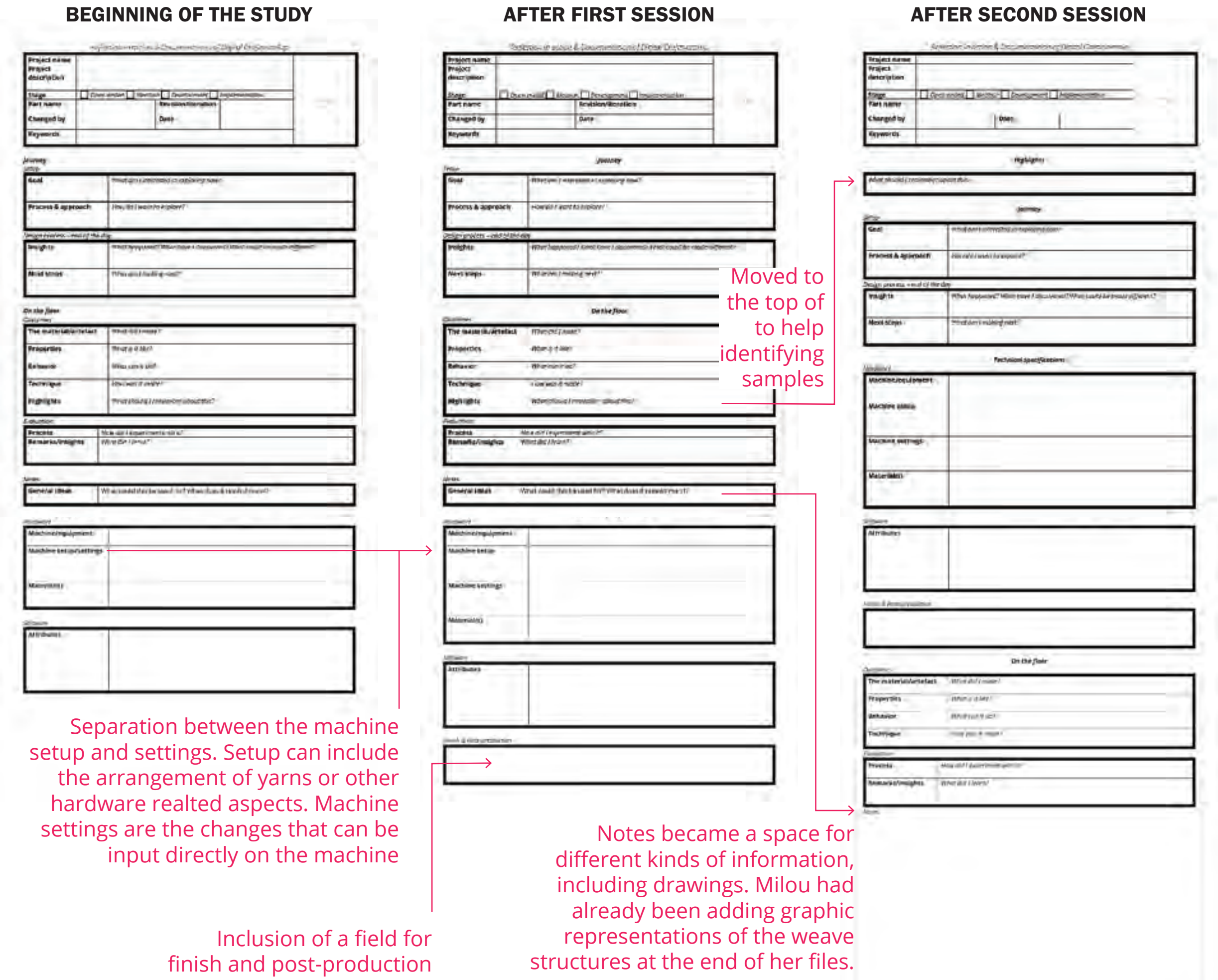

Figure M. Comparison between forms. On the left, is the form given at the beginning of the experiment. The two on the left are the adapted versions based on the reflection during the first and second session.

her in filling them in faster by copying and pasting parts of content that were the same in multiple samples.

> *"I filled them in on my laptop and I think that was working quite well because in one day I had all the documents open on my computer and I was just going through it while weaving and steaming the samples and I could just close them after the day was done."*

She also started to employ versioning as a strategy to update forms when changes to the design were considered optimization only.

> *"That's a thing I find a little bit difficult sometimes to decide 'when do I change the form or when do I keep the form. For example, at (name of company), if I make a change I would name it x number, then stripe A or B*

> *or C or D. I used to make a new page for every one of them but that's too much if it's a really small change in the design. Now I try to put them all in one form."*

Additionally, she started to integrate her notation system for the weave binding patterns she created with the documentation of individual samples. The structure of each binding was documented separately and received a code. The documentation form of new samples based on one of her bindings would refer to it through its code. At the end of the study, she had rebuilt our form into a digital system based on Notion, a note-taking software, which facilitated searchability of the content in all forms through tags and search filters. She also developed the visual identity of her studio, which was applied to the documentation system.

> *"I have a logo and a lot of identity things so there's also a label. This is the label that I use for my samples. Just to write the document number and stuff. And there's also a template. The information stayed the same [as the template we had been using]. I use this part a lot [Journey] but I hardly ever fill in this [on the floor]. The biggest difference has been that I started working with Notion. It's basically like a big Excel sheet with all the information: the file number, the name, the reference if there's a design I used before, date of when I created it, instructions, how many picks – that's the density of the weft yarns –, how many yarns I used, then a lot more. I also use tags and I added pictures so it's really easy to recognize what kind of design I used."*

Through this process of appropriation of the form into her practice, she found her own way of using documentation to see samples both within their design process and as stand-alone designs. The system she created for her practice allows appreciating samples for their individual qualities.

An important insight from reflecting on her reported experience is choosing the moment to document different kinds of data. Time is a known challenge in design documentation. According to Löwgren and Stolterman [53], although the importance of good documentation is widely known, "when a deadline approaches, documentation is not a priority compared to the production of working code." Through the long-term engagement with the documentation form, Milou revealed different strategies to achieve a more consistent documentation practice, such mapping the timing of documentation certain kinds of data with its level of detail. She documented kinds of detailed information that could be forgotten otherwise, such as material specifications or machine setup, before making. Data as goals, has a lower level of detail and could be retrieved from memory, so she reported filling these in while the machine was running. As previously mentioned, the reflections from the 'on the floor' section were mostly left blank with the expectation of being filled in future revisiting. Timing should be considered and further explored designing future documentation systems and to building individual practices of documentation-while-we-make.

Different machines, different practices

The discussions about the form and the strategies Milou used to document her work helped reveal specific ways the weaving loom shapes her making practice. In turn, this supported me in reflecting on my own.

Although both of our practices are informed by turn-taking with our samples and the fabrication systems we make with, – as well as both of us using layering as a key concept in our designs –, the weaving loom configures her practice in a fundamentally different way than the embroidery machine configures mine. While my way of working has largely been configured by the possibilities and limitations of freedom of routing and the stability provided by the embroidery frame, her practice as a weaver is largely configured by the warp. The warp (yarns on the length of the fabric [25]) is an important variable in the structure of woven textiles that can be changed both in density and material. In our first session, Milou pointed out that changing the warp is always a cumbersome task. For this reason, she most often uses the warp entirely before setting up a new one. In the process she documented, this either made it so she had to wait before being able to act on certain insights until she could change the warp, or she had to seek work-around methods.

> *"that's the thing with weaving, you are stuck with your warp so that's something for me to look at for the next [development] week. Then we will add a few yarns and see what type of bindings we can make on top of this."*

As an example of work-around, she mentioned an instance in which she had found a structure she was interested in further exploring, but to do so would require a denser warp. To remedy it, she explored different strategies of making the binding denser using two weft yarns. This allowed her to pursue her insights further until the following development week, when the warp would be changed.

> *"What I did in this sample is that here there are two weft yarns and instead of using them in the same warp opening, I changed that. So that it could be a bit denser."*

More than limiting creative possibilities, the amount of work needed for changing or retying the warp after cutting away samples has implications to her itinerative processes and reflective practice. The warp is tensioned on a roller in the loom, which gives stability to the process. The intra-action between the tension on the warp, the structure of the weave and kind of yarns used determine the material behavior and qualities of the samples. This entanglement can only be assessed once the samples are removed from the loom and the sample has been through any finishing processes needed, such as steaming. This kind of finishing process can significantly change the sample dimensions and impact the sample qualities due to shrinkage of the yarns.

> *"Especially with weaving, there's a lot I cannot really say unless it's off the machine. And then I'm already working on a different sample. It is a bit like, changing something then making a few variations"*

To reduce the workload of redoing the warp and to optimize time, Milou reported that weaving a batch of samples that can be taken out of the loom at the same time to be a common practice in her material explorations. This means that the moment for reflecting on her woven samples is postponed from the immediacy of making to sometime later, when dealing with the warp is considered worthwhile. At the same time, Milou explained that creating samples in batches pushes her to intercalate processes and to pursue several lines of investigation in parallel, such as shown in Figure L. While one batch of samples is on the loom, the previous one can be evaluated, and its insights can be forwarded to new designs. This way of making can be considered a form of revisiting, concept explored in section 4.1.

> *"I also made this one [LW_3_36] that becomes round [meaning tubular] with using different materials in both sides. That also goes back to samples I made before, in the previous development weeks, I also made this kind of round samples so I also wanted to try if it would work with the extra warp yarn."*

Like in weaving, the behavior of embroidered samples can only be assessed once they have been removed from the embroidery frame and the stabilizer has been washed away. However, depending on the size of samples, it is possible to embroider and reflect on samples either as a batch or a single sample at a time. This enables me to choose the mode of exploration I am interested in and to act on emergence quickly.

The point of specifying how the fabrication systems we make with configure our practices is to open opportunities to reconfigure them. In my case, unpacking the practice of another designer provided a rich example of how goal-oriented, although not the conventional understanding of goal, and emergent approaches can co-exist in a material-driven practice through parallel lines of inquiry.

Findings

The long-term engagement in this study revealed aspects about the relationship of fabrication systems and making practices that supported me to further understand digital craftsmanship from a distributed and relational point of view. Documentation was explored here both as a tool to support building a reflective making practice and as a tool to unpack how a practice is configured by the fabrication system the designer *makes with*. Our experiences of digital craftsmanship were shaped differently by the specific machine or techniques we each engage in. With this, we revealed that technique and material choices do not only impact the interactive qualities and properties of a sample, but they also have an impact in our ability to reflect on our making processes and individual material outcomes.

Our discussions during the three sessions and the analysis of the process Milou went through of building her practice of documentation enabled identifying three other points for reflection: *the last meter*; *content, detail, and timing*; and *positionality in ways of documenting*. While the latter two focus on the design of documentation systems, the first point is an opportunity for explorative making.

The last meter

Furthermore, as the result of diffractively reading of one practice through the other, the study also enabled me to identify opportunities to nurture explorative making in digital craftsmanship. By focusing on difference rather than convergence between practices, this study revealed different opportunities of engaging with emergence and explorative making. As one of such opportunities, we can highlight the 'last-meter' of the warp in the loom as a potential mode of exploration through parallel lines of inquiry. This can be an alternative or complementary understanding to the notion of detours that had been introduced in chapter 3. In weaving, having to work with the warp that is already setup to finish that 'last meter' is an implication of the technique that could be taken as an opportunity to experiment with structures or other materials freely, without the expectation of specific outcomes. Extrapolating this for other techniques in digital craftsmanship, the last meter of warp in the loom could be seen as a metaphor to recognize and take advantage of the conditions for emergence. The machine is already turned on and setup, the materials are on the table, and other makers are around, so we can take 'the road less travelled'. What are we going to make?

> *"For the samples that were very different, it was a matter of having the time and the material together with the warp being already there. I think also that I always have lists of ideas of things that I want to follow but you have to make priorities. These experiments may have been lower in the priority list but because we had some warp and material we could try it."*

Content, detail, and timing

In digital craftsmanship, the number of produced samples, the diversity of information involved in making with systems that are both physical and digital, and other kinds of restraint make it difficult to create comprehensive documentation. Like previous literature, time to document was also brought up in this study as a significant constraint. Defining what to document and the level of detail in documentation, a problem also identified in previous work on reflective documentation tools, were challenges I faced while formulating the original form. These concerns continued to be a point for debate throughout the process. This study did not aim to validate the right way to define content and level of detail, but it enabled reflecting on these. Based on the changes between sessions, it is possible to say we did not have considerable differences regarding content, but the importance of certain kinds of data and how we filled those in varied but due to the needs of the technique we each engage in. In her version of the form, for example, a bigger field for 'software' in the technical specifications enabled her to include visual elements of weaving notation systems. As such, matters of content and level of detail depend on the configuration of the fabrication system and the intentions of the designer. What could be recommended is trying to document as much as possible, while exploring means to make information retrievable in the future. Photos, for example, can capture rich data that could be easily forgotten or not evident at the time of making. Such data can include technical aspects like labels of yarns, machine setup, and machine settings but also contextual data, which we might want to retrieve in the future. Time is often mentioned as a challenge in design documentation, but an important insight from this study was timing. It was possible to identify an interesting relationship between timing and level of detail of data in how Milou incorporated the documentation form into her practice. Further work in the direction of developing approaches for documenting-while-we-make and other documentation systems could consider timing as a solution for the lack of time.

Documentation as reflection of the designer

As a final point for reflection, this study enabled considering the importance of reflecting on the documentation formats we propose and our positionality. According to Laura Devendorf and Kimiko Ryokai [16], "the way a fabrication system is designed configures relationships between humans, machines, materials, and digital models, and reflects the ideology of the designers: ideas of who or what should have agency or control in the making process". Like the design of fabrication systems, the ways of documenting can reflect the ideology of designers: the kind of information we prioritize and how we choose to notate it say something about how we design, with what we design and what we expect of our designs. The documentation form used in this study originally reflected my set of values and design philosophy. My aim with the form was making explicit kinds of information distributed throughout the socio-technical system of production to support explorative approaches. Other formats, such as workbooks [30, 78], could be used to document rich and multifaceted of material-driven processes. However, my aim was also to enable the notion of revisiting which I judged easier to do with individual pages because they enable the creation and reconfiguration of collections, as well as reordering and isolation of samples. The section "*On the floor*" aimed to emphasize this potential by enabling the appreciation of samples outside of the process of their creation, extending them agency to open new directions of investigation. The prompts added to each field reflect my own background as an interaction designer. Over time, Milou adapted the form to reflect her own set of values and interests. In an approach of documenting-while-making, documentation means not only recording data about the process and individual samples, but it can also configure our practice. As such, it is important to be critical and explicit about the assumptions and values about making and knowledge that a given format embodies.

Conclusion

Unpacking making processes and personal practices is a difficult task. This study approached this challenge by employing the notion of diffractive reading to create a dialogue between practices. A documentation form created from my experience of making with digital embroidery machine was used as tool to facilitate this dialogue. Through a long-term engagement with this form, Milou could build her own practice of documentation further. Three sessions allowed us to discuss her experience and slowly unpack the specificity of her practice, which also helped me unpack my own. As a result, the dialogue between our practices enabled evaluating the ways the fabrication systems we make with configure our practices. This study makes a methodological contribution to unpack individual practices of digital craftsmanship. Furthermore, the reflections on this process contribute with insights regarding documentation systems that support explorative making.

4.3 Making Matters: Samples and Documentation in Digital Craftsmanship

Published as

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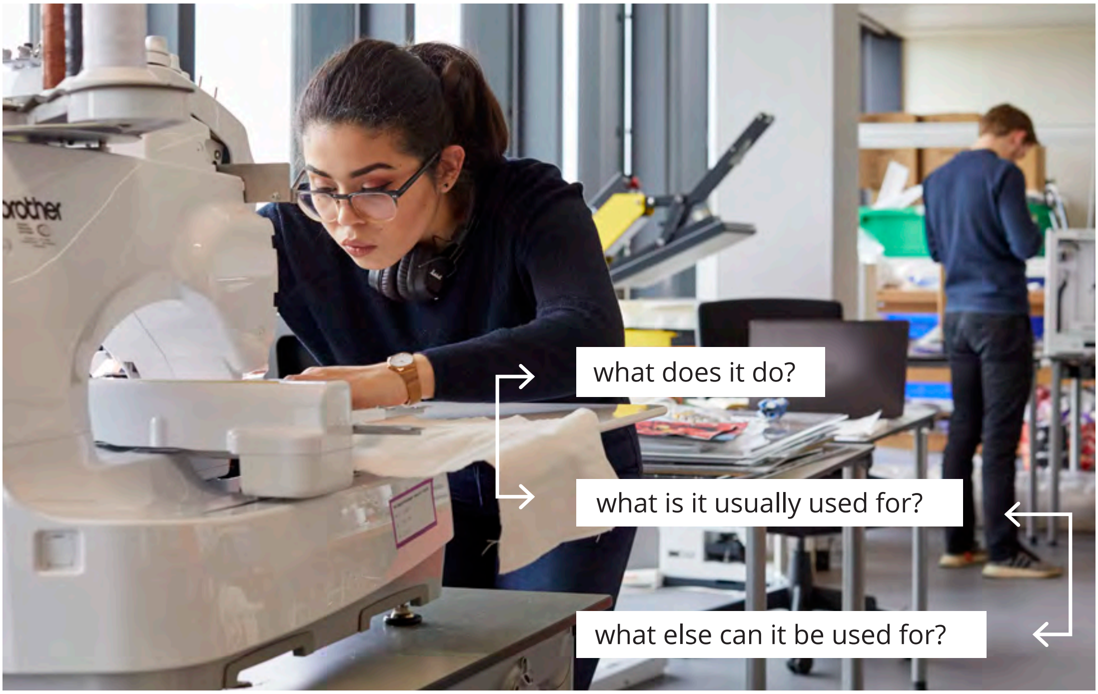
ABSTRACT

Digital fabrication machines enable the creation of a wide range of artifacts and materials. In the process of exploring the possibilities within these digital modes of creation, many samples are made. To encourage cross-pollination between different practices and strive for a community that shares more information, this research investigates the state of the art of sample making and documentation practices in the context of Digital Craftsmanship. Through in-depth interviews with designers with a focus on digital craftsmanship, in this paper we unpack some of the practices and challenges in material driven processes related to how to design, evaluate, document and archive material samples. We reflect on making practices, what forms of knowledge are produced through making and how the use of samples in different design processes can be supported through documentation.

KEYWORDS

Digital Craftsmanship; Fabrication; Design practice.



*Both authors contributed equally to this work

INTRODUCTION

The production of tangible things is largely driven by making. In recent years, we have seen the work of designing tangible and interactive things expand the making of satisfying and working prototypes towards the making and experimenting process inherent in the design itself. As we involve increasingly complex systems of technology for both the function and the production of our designs, the balance between human craftsmanship and digital production is renegotiated again and again. We consider this re-negotiation the core method concern of digital craftsmanship as it evolves in the meeting between design and fabrication.

Digital fabrication machines enable the creation of a wide range of artifacts and materials. This way of working has created a new perspective on making where the digital meets the hand in ever evolving ways. We consider this a kind of digital craftsmanship, which leans equally on the capabilities of the digital machinery and the skill and craft of human hands at the intersection of the digital and non-digital [1]. In this way, digital systems are creating new possibilities for the practice of craftsmanship that then may unlock the potential of existing expressive media and encourage the creation of others [8]. Within digital craftsmanship, as in other kinds of crafts, the physical execution of an idea is not considered the final step of the process, but the starting point. In this hands-on approach of working, material exploration, physical craftsmanship and digital ways of making take center stage [2]. As designers learn by doing, they go through loops of trial and error. Here, making is a way of thinking with the hands and then letting the resulting things support imagining and talking about ideas that are difficult to fully understand or articulate solely in language [2]. Within design research, making is taking on an increasingly important role as a way of exploring. As a result, making is gaining popularity as a research method in itself [6].

Samples

In design research, the term "samples" is used to refer to the outcomes of material-driven approaches, meaning that the value and interactive possibilities offered by these prototypes are intrinsically linked to their manufacturing methods and materials [5]. The material-driven processes result in complex encounters between intention and artifact, material and skill, chance, and opportunity [5]. This way of working is complex and multifaceted, and as a result, difficult to document and communicate [3]. The large number of samples created in material-driven processes can make documentation overwhelming, causing designers to focus instead on the communication of the end result [10].

We believe that such selective documentation of sample process is a missed opportunity. The high fidelity of digital fabrication makes them uniquely suited to be revisited in other design journeys [6]. However, in order for new projects to benefit from the tacit knowledge gained through previous sample making, thorough documentation is required. Such documentation may also play an important role in sharing (tacit) knowledge that can facilitate new collaborations.

To arrive at a better understanding of both common, established practices of designers and the differences that may be machine/technique dependent, we wanted to explore sample making and documentation practices in the context of digital craftsmanship. To do this, we conducted a series of in-depth interviews with design researchers and practitioners with a focus on digital craftsmanship through a wide range of techniques.

In this pictorial, we unpack their experiences and highlight some of the practices and challenges in materials-driven processes related to the tasks of making, evaluating, documenting, and archiving material samples.

In this, we do not seek to formalise ways of making or documenting, but rather to begin the work of identifying challenges and opportunities that may be encountered in how designers deal with samples within their design practices. We recognise that practices are diverse and multifaceted, and we focus on reflecting and broadening our understanding on the knowledge created in digital craftsmanship, and how digital fabrication tools support or affect these. We hope that engaging in such matters can encourage our community towards cross-pollination between techniques, practices, and ideas.

INTERVIEWS

To gain more insight in the way designers create, archive, document and use their samples, we interviewed nine design researchers and practitioners engaged with what we would consider digital craftsmanship. The selected participants had expertise in a wide range of practices based on digital fabrication machines like weaving, embroidery, 3D printing, and laser cutting.

The in-depth interviews were conducted in two parts. The first part of the session was set up as an expert interview [11] to gain more insight about their expertise and their sample making and documentation practices. The second part was a co-reflection session [12] in which they picked a sample they had previously made as a starting point for deepening the discussion on their practices of making.

Data Analysis

During the interviews the designers highlighted the importance of having the physical and visual presence of their work around them by hanging samples on the wall. For this reason, we used the same

Designer 1 uses a method of material driven design to explore the limitations and potentials of digitally controlled manufacturing techniques. They combine laser cutting, sublimation printing and 3D-printing with an expertise in textiles.

1

Designer 2 explores the design of digital domestic technologies using speculative deisgn. They focus on how the material can guide the design process. Designer 2 has an expertise in textile processing techniques like laser cutting, 3D-printing and digital weaving.

2

Designer 3 engages with digital manufacturing like laser cutting, 3D printing and digital embroidery. Through a learning-by-doing approach, designer 3 investigates the advantages and disadvantages of a technique or machine to explore new manufacturing possibilities.

3

Designer 4 has expertise in industrial embroidery, particularly technical embroidery. They focus on textiles across technology, fashion and interiors. The design process is conducted through the combination of research on culture, industrial design, technology and craftsmanship.

4

Designer 5 has expertise in knitwear and textile design. They are drawn to unusual textures, intricate structures, and organic shapes. With a particular interest in the intersection of philosophy and knitting, their work explores materiality, contradiction, metaphor, and intuition.

5

Designer 6 is interested in digital manufacturing and the future of making. They explore new ways of making by building and adapting digital fabrication machines with a focus on 3D printing and electronics.

6

Designer 7 is fascinated by products and their relationship with manufacturing processes. They focus on production systems and do research into how certain materials and digital production techniques lead to new ways of working. Their vision is based on using new digital techniques to the manufacturing of textile products.

7

Designer 8 guides other designers in their work with a focus on the emotional expressivity of interactive products with programmable material qualities. They investigate shape-changing materials and how to design for the expressive and aesthetic qualities of interactive products.

8

Designer 9 focuses on material and textile development. They have a specialization in knitted textiles. By using techniques in an unconventional way, deisgner 9 tries to reshape making to show the countless possibilities of textile innovation.

9

Expertise of the designers interviewed

method for the analysis. We transcribed relevant points of the interviews, printed them and clustered their experiences related to the tasks of making, evaluating, documenting, and archiving material samples.

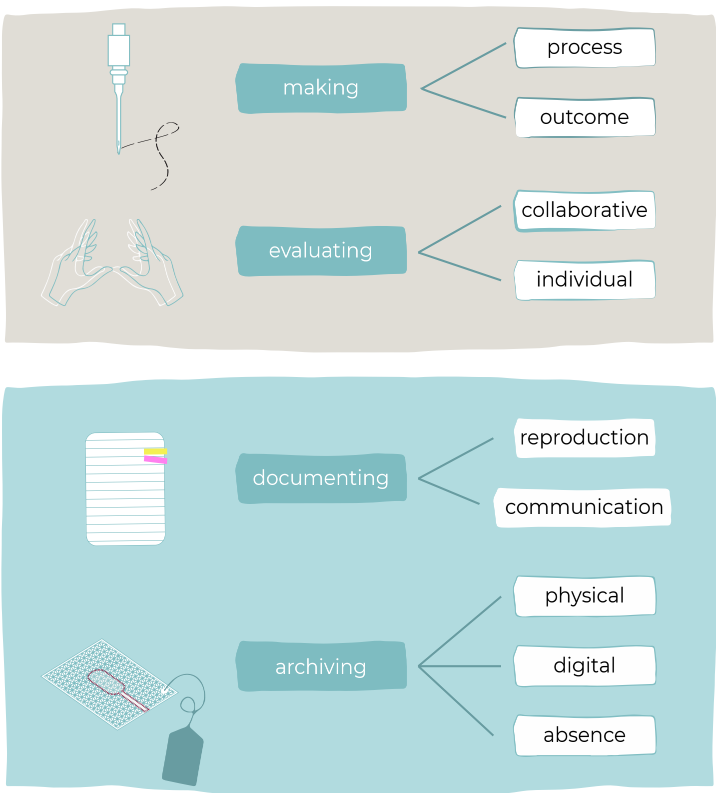
A good deal of the information provided by the designers was in visual form. For that reason, photos provided by the designers as examples of their practices were added next to the clusters of quotes extracted from the transcribed interviews. The resulting collages or image-clouds, as we called them, attempts to preserve the richness of the designs and practices of designers engaged in the interviews. By making the clusters visual, we also leave them open for new interpretations.

FINDINGS

Our findings were clustered in four tasks: making, evaluating, documenting and archiving. We believe this division can support us in articulating challenges and knowledge gained throughout our design processes.In doing this, we aim to support furthering the efforts done by researchers in the field in finding language to discuss the outcomes and the emerging practices in digital craftsmanship [4].

Overall, it was noticeable that designers often associated the task of making samples with evaluating them. Although the documenting was sometimes part of this process of making/evaluating, the documentation itself was often grouped with the archiving of samples.

In the following sections we present our image-clouds and findings related to each of the four tasks.



MAKING

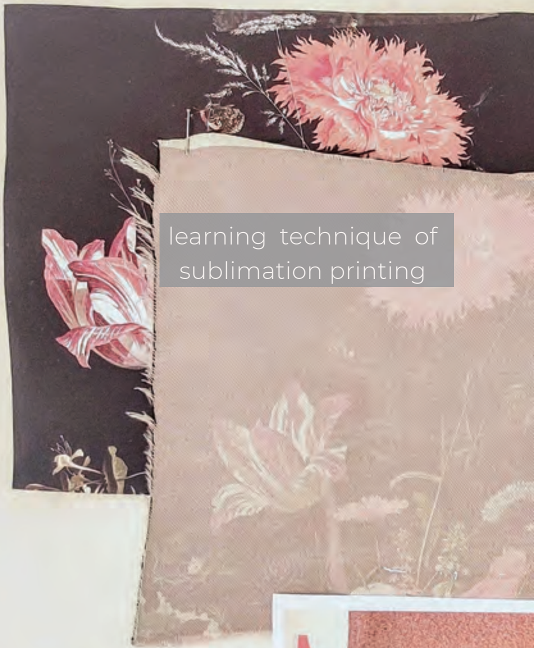
The designers interviewed for this study have a wide variety of practices. From highly intuitive and exploratory methods such as material speculation, where the material drives or shapes the process, to more systematic and structured approaches. All designers are experts in digital craftsmanship: their affinity with digital production is where all their practices converge. While some focus on designing systems and delve deeper into the manufacturing process itself, for others, the creation of the physical sample is the goal.

Process

We observed that for some designers the emphasis is on the making rather than the made thing. Following the ethos of learning by doing, they determine the advantages and disadvantages of different approaches and gain knowledge through the making itself. Often the unpredictable things that occur in the development process of sample making are addressed and used as starting points for new explorations.

Outcome

For other designers interviewed, the physical sample itself plays a big role in their practice. Samples can serve as a way to take the next step. It is a way to make an idea tangible, validate it and put it into practice.



learning technique of sublimation printing

I think samples don't play a big role. It's usually about the process of making the sample. The sample itself, whether it was successful or not, is not that important to me. If it went well, then you know that it worked, so that is a kind of validation of the process that you have set up. If it doesn't work, then you know it doesn't work and you probably know where it goes wrong and what you have to change. But the sample itself, as it is usually not the objective... Once the sample is ready, it is also ready again; then the sample is no longer needed

6

early explorations of interaction possiblities using conductive thread through digital machine embroidery no matter how efficient I want to work, I sometimes need those physical samples in order to take another big step, it's always the physical sample that takes us a step further. For me, the samples are very important. 4

With only the documentation they really only know the ingredients of the recipe but not the recipe itself. Then you will be able to go in all directions. 9

material selection for tactile interface to control light system

machine knitted samples exploring shaping and material behavior

doubleweave exploration to create origami folds

EVALUATING

Depending on the type or stage of the project, samples are evaluated in different ways such as putting the samples in context, pinning them to mannequins and testing them with electronics. Some of the interviewed designers use input from others to evaluate their work. Others are more individually oriented and use their own insights as instruments of evaluation.

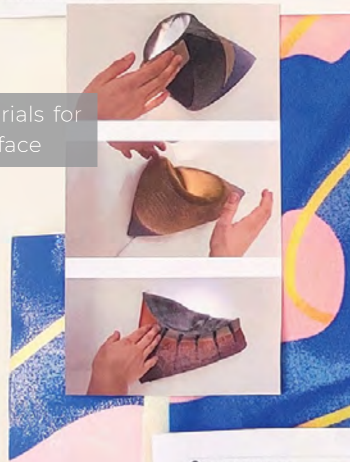
Collaborative

Some of the designers work collaboratively and seek outside perspectives to evaluate their process. Through showing their samples and talking about them with other people, they have a broad range of input into the process.

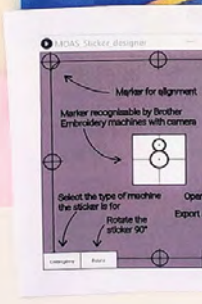
Individual

For others, the creative process is a very involved process with themselves. They motivate their work through their own insights.

comparing performance of conductive materials



exploring materials for tactile interface



You also talk to people and then they contribute ideas and then you come to something. So you never did it all by yourself.

6

We work in teams a lot in projects, which I really like because then you always have more people to bounce ideas off of, a bit of a back-and-forth

2

I often work on my own so **you are a walking library yourself** 7

Everyone has their own way of writing code, the same with the setting of a 3D printer, **there is a lot of feeling involved. Just a little thing needs to change and everything is lost.** 8

Documentation mainly happens in my head, that is more of a **mental note and I make some notes but it is mainly a very involved process with yourself** 3

overview footwear woven samples

drawing schematics

annotating screenshots

DOCUMENTING

What the designers interviewed agreed on was that documentation should happen immediately after a sample is created. This can be contradictory. If you are in the right workflow, many iterations are made in a short period of time, making it difficult to keep up with their documentation. To keep documentation up to date, continuity is important. However, this can be easier said than done due to the different forms and formats that samples can take and because of the enthusiasm for the next steps. Next to this lack of structure, a lack of time is also a common challenge within sample documentation. The way designers document varies from notes in text, sketches or mental notes, labels , or tags on the samples themselves (sometimes provided with a distinctive code) and photographs taken of the samples. Since all designers work with digital crafts, there are also the digital files and settings of the machinery, which are often documented within the used software.

Reproduction

Documentation can be used as a tool to enable reproduction. The importance of this varies per project and per designer. Some of the design researchers we spoke with indicated that documenting in a way that allows for future reproduction is of great importance or even value of their work. For other designers, the value of their work is not stored in the documentation. In some cases, they even have to prevent others from copying their designs.

Communication

In collaborative ways of working, documentation can play an important role. When several people are working on a project, samples and their documentation are used as a communicative tool for sharing knowledge.

linking physical samples with their digital files through unique codes

If I make all the samples myself and then the other person doesn't know how to work with them, it won't help, you won't get anywhere.

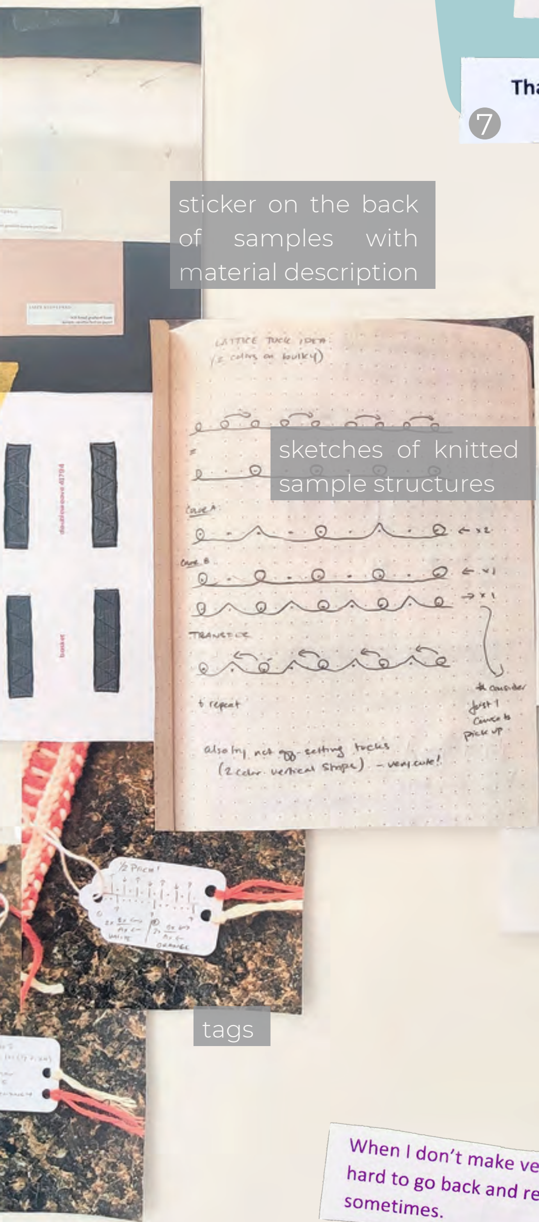
4

The samples and the documentation are really about communication.

9 If you get out of your flow of making, you don't just get into it either. You have to get on the train because otherwise you're just beside it. I've done that sometimes as well, when I was creating, I also did the archiving, and then you're really demolished at the end of the day. You have to process so many stimuli or you need an assistant to help you. Maybe that's just a necessity at some point.

You let people build on what is there but they also have to be able to add their own twist to it and not copy what is already there. They have to think up something new. They have to think up something new. They have to delve into what is possible but also create new space for further development. 8

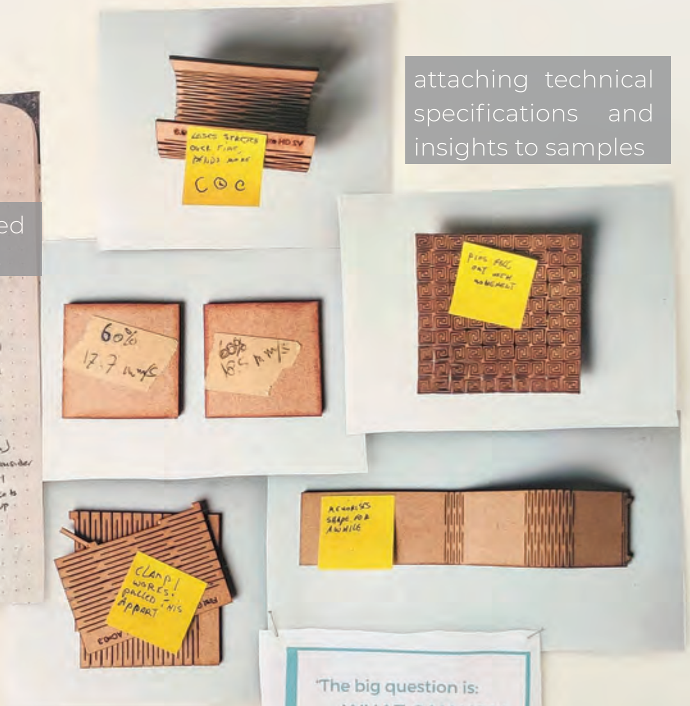
7 That's funny, now that I'm talking to you I realise I'm documenting more than I'm aware of.



sticker on the back of samples with material description

sketches of knitted sample structures

tags



attaching technical specifications and insights to samples

"The big question is:

WHAT CAN YOU DEDUCE FROM YOUR SAMPLES AFTERWARDS?

That is the special thing about digital, a lot is already stored in your process." 7

When I don't make very specific notes, it can be really hard to go back and remake it. Even for myself sometimes. 5

ARCHIVING

The way the samples are archived can play a role in applying the knowledge gained in future work. Among the interviewed designers, a physical and visible way of archiving is preferred, but samples often end up hidden from view or even disappear after the project is finished.

Physical

Designers stressed the importance of the physical presence of samples and the ability to feel, see and experience them. Hanging samples on the wall is one of the methods designers use to facilitate this presence and to visualize the design process. Digital imaging plays a significant role. Through photographs of samples, designers archive in a digital yet visual way. This is done for several reasons: storage along with the digital files is easy, a timestamp is automatically added to a sample, and photos are convenient to share with others.

Absence

While the designers we spoke with agreed on the importance of having samples physically present, they said that when a project is finished, samples often travel from their spot on the wall to boxes, or they disappear entirely. Some designers have a structured approach in labelling their archived samples sorted by project and date of making. For others, this structure has less value.

keep the samples visible

Hanging the samples on the wall is more like you have a lot of puzzle pieces in your head and then you put them down so you can zoom out. 1

8 But a lot of iterations that don't work are not really saved or anything like that. Then you try something with them or you adapt them or you break them and then they disappear.

7 We take an awful lot of photos and videos because you can stream super-fast and store them in a reasonably **organised way**. In research projects with other designers, you then **share a photostream**.

It is much easier to retrieve much more information from a photo.

project box: "I really have a whole stack of black boxes and I have a timestamp on them. Then I have a folder with everything I made around that time all together."

samples, illustrations and planning on the wall of a studio as a way to visualize the design process

5 Sometimes I keep them in **sketchbooks with notes next to them and other,**

older samples get put into Tupperwares.

I try to keep them **organized by the type of structure** it is.

DISCUSSION

For this process, we spoke with both design researchers and practitioners, and we found that they have distinctly different sample making practices. While practitioners are more concerned with the made thing, researchers are more concerned with the lessons they learn during the making of the artifacts or the new opportunities that a technique may open. For design researchers, it is important that they document in a way that enables other researchers to analyse the same data in order to obtain the same results as the original research study, thereby reinforcing the conclusions of the original study. For practitioners, in some cases the concern is the avoidance of reproducibility. Here it is important to mention that most designers role shift between the two identities depending on the phase of a project and their focus.

The type of crafts the designers are involved in also influences their working methods. A flat woven sample is easier to archive than a 3D-printed sample of a large volume. But whereas a 3D-printed sample can be taken straight out of the machine after creation, woven samples are often not made one by one but in batches before being taken out of the loom. This also impacts how and when designers can reflect on their proces and outcomes. With designers who work on commission, it may be that the samples they make are given away to the client, or sold separately as craft objects.

In the context of digital craftsmanship, there is an ongoing conversation about the possibilities of materials and techniques, however the ways in which these tools shape our practice are not as widely scrutinised. By exploring the current making practices, we aim to open up a conversation about practices in the context of digital fabrication and crafts.

This pictorial is an attempt at paying attention to how this process is currently managed by a series of designers active in this field. We propose that the craft technique of sample making is emerging as a key area of design work, and that paying attention to how these samples are made, interpreted, integrated and documented, provides us with suggestions as to how we may continue to incorporate new technologies and materials into our design processes.

CONCLUSION

The possibilities of exploring material properties and creating complex artifacts through digital fabrication has attracted many design researchers and practitioners into digital craftsmanship. For some of the designers we interviewed, the focus is on the making process rather than the made thing. For others, the physical sample retains the core value as an outcome. Depending on the phase and end-goal of a project, designers document more or less methodically. While some of the designers work collaboratively and seek external perspectives to evaluate their process, others motivate their work through their own insights and experiences. As a result, documentation plays different roles in different practices like supporting the reproducibility of the designs, reflecting on the knowledge gained through making or as communication tools for those working in teams. Documentation is done in text, sketches, or mental notes, labels on the samples themselves and pictures of samples. One of the main challenges reported was archiving samples. While the designers agreed on the importance of having samples physically present, they said that often when a project is finished, the samples are packed down or discarded. Other challenges include time, lack of continuity, and an over-enthusiasm for the next steps.

We are not providing guidelines or

practical frameworks to how this should be addressed, nor are we proposing that there is one unique method or strategy that should be incorporated by designers in the field. This pictorial simply aims to draw attention to the processes that are already in use in digital craftsmanship, but rarely discussed or described. As designers we prefer to show that final versions and describe our process in hindsight as if there were little deviation or error. This pictorial is an attempt to pay attention to designerly strategies used inside the process, before the final design and as we are still "in the thick of it".

We believe that it is the cross-pollination between different forms of applied craftsmanship that will show us the broader range of possibilities afforded by the meeting between craft and fabrication. We hope that this short pictorial may inspire and encourage paying closer attention to the material and samples we make while working towards our design goals, in turn allowing a deeper understanding of the tools we use and the ways we might work together.

ACKNOWLEDGMENTS

We thank all the designers who generously shared their working practices with us during the interviews.

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5 Collaborative practices in sample making

> *"If a computer interface is hooked up to a given instrument, is the computer part of the apparatus? Is the printer attached to computer part of the apparatus? Is the paper that is fed into the printer? Is a person who feeds the paper? How about the person who reads the marks on the paper how about the community of scientists who judge the significance of the experiment and indicate support or lack of support for future funding? What precisely constitutes the limits of the apparatus that gives meaning to certain concepts at the exclusion of others?"*
>
> *Karen Barad [3]*

Up until this point, the practice of *designing with* machines has been explored mostly as a relationship between a single designer and a digital fabrication machine. In this chapter, I expand the exploration of *designing with* in *digital craftsmanship* to include multiple machines, as well as more designers, into the sample making process. Two projects were developed in this direction, FabriClick and Exquisite Fabrication, in collaboration with industrial design students. These projects were published in "*FabriClick: Interweaving Pushbuttons into Fabrics using 3D Printing and Digital Embroidery*" and "*Exquisite Fabrication: Exploring Turn-taking between Designers and Digital Fabrication Machines*", respectively. The two publications propose different strategies to add complexity to samples by moving them between machines, and, together, support a reflection on collaborating with our socio-technical systems of production.

FabriClick was a serendipitous collaboration with Maas Goudswaard and Abel Abraham, who were exploring on-body textile interfaces based on 3D printing on stretched fabric. One day, I was walking towards the lab, when I saw bright red and blue cool looking samples on their table and asked them about their project. They explained their experiment and asked me if I had suggestions of possible fabrication techniques that could be used to turn their samples into functional pushbuttons. As mentioned in chapter 3, during the development of the Embroidered Inflatable samples, I identified the stability given by the embroidery frame as an opportunity for moving the work out of the machine to add layers of other materials or perform other processes (Figure N), then bring it back to the machine for new embroidery steps without compromising the alignment of the designs. The problem of how to fabricate the pushbuttons emerged as an opportunity to further explore the possibilities of combining other digital fabrication processes with the embroidery, while the work was still on the embroidery frame. This led us to collaborate in developing a jig system and workflow that unified

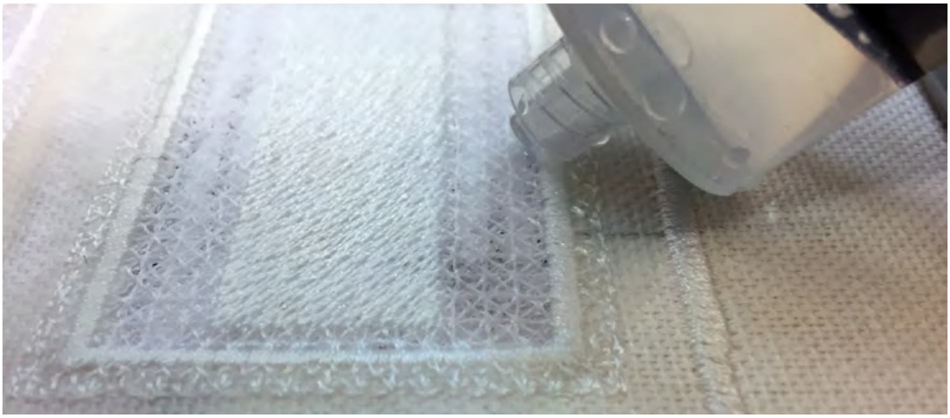

Figure N. The frame gives stability to embroidery, allowing the work to be removed from the machine for different steps. In the Embroidered Inflatables, this was used to locally wash the water-soluble film off from samples for facilitating the silicone casting process as well as to add layers of material for creating more complex structures.

digital machine embroidery and 3D printing to fabricate their FabriClick pushbuttons. The molds I had previously used for casting silicone on the embroidery samples were composed by separate laser cut pieces that could be reconfigured depending on the side of the fabric I was casting on (to make the inflatables airtight, casting was done in both sides). Based on this idea, the jig system was designed to be reconfigured depending on the stage of fabrication.

The pushbuttons were composed by two layers of fabric, each processed separately, then assembled by the embroidery machine to become an interface. Combining fabrication processes through the jig was not only pertinent but necessary for this application: the precise alignment of both layers required them to remain stretched until the end of fabrication. However, if we extrapolate the idea for other cases, the need of custom frames introduces important limitations. First, the design must fit all machines involved in the fabrication process. Secondly, introducing other techniques to the workflow will likely require adaptation or redesign of the hardware of the jig, making it more complex to explore new ideas.

The proposal of *Exquisite Fabrication* was to continue to explore combining digital fabrication processes into a single workflow through an alternative approach that traded-off accuracy for more flexibility to the process. I invited Jori van der Kolk to participate of the project because of his expertise as a maker. He also had previously built a silicone printer for another project which allowed us to address the casting process of Embroidered Inflatables as design case. Until then, the best method for casting silicone to create the inflatables I found was using laser cut molds pressed together with magnets (Figure O). The technique worked well but presented inconsistencies between castings, such as exact amounts poured and leveling, caused by manually pouring the silicone. Therefore, in Exquisite Fabrication, we chose to address both the mold and the casting process, replacing the laser cut mold by a 3D printed dissolvable one. This improved the reproducibility of the silicone casting process and gave us the possibility of changing designs of the molds. Additionally, this included a third digital fabrication machine to the same workflow of sample making. Rather than connecting processes through hardware, like in *FabriClick*, *Exquisite Fabrication* approached interoperability through two software tools designed by Jori, MOAS SD and MOAS TT. The tools supported the alignment of the designs done by each machine through placement stickers and coordinates for resetting the zero point of the printers. The sample created in this process traveled between machines and back and forth between designers to complete four steps of fabrication. In doing this, we recognized the value of leveraging the capabilities of each machine, as well as the expertise of each maker. The process allowed us to reflect on some of the implications of engaging with multi-machine and multi-maker collaborations and to propose strategies for nurturing an attitude for collaboration between designers and machines.

Previously in this research, I had pushed the capabilities of digital machine embroidery to create things that might not usually be associated with the technique, such as defining the form factor and behavior of inflatables, by approaching the machine as a collaborator. FabriClick and Exquisite Fabrication expanded my understanding of collaborative making by taking the next step of including others (human and non-human) into the same process of designing with. In both projects, the proximity between machines and makers in the lab was key to initiate collaborations. This is compatible to findings from prior research in collaborative craft. In exploring collaborative practices and hybrid processes, Nimkulrat et al. [63] found that “meaning is created not only through the maker’s interaction with materials and tools in space but also through interactions with them over time.” In this, they refer to the proximity of the skilled makers with the tools in the lab where they worked

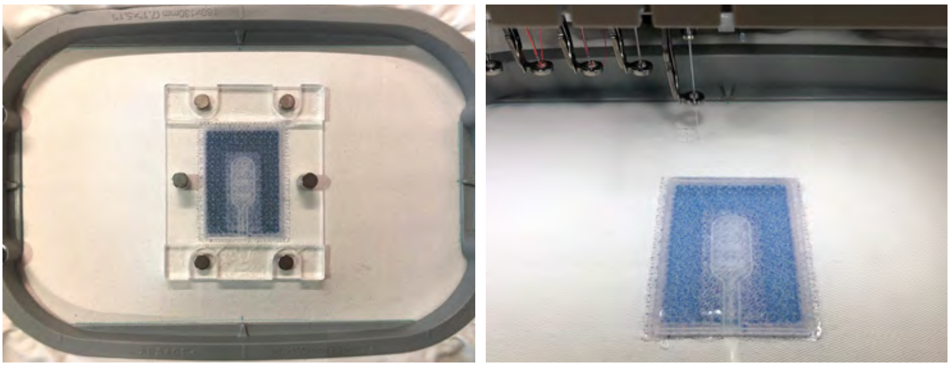

Figure O. A laser cut mold put together with magnets was used to cast silicone onto the embroidery sample without removing it from the frame (left). This allowed bringing the frame back to the digital embroidery machine for a new embroidered design (right).

as well as between each other as important resources to foster crossing-over between (analogue to digital) practices and tools. The experiences of FabriClick and, especially, Exquisite Fabrication enabled reflections on how to extend this idea of co-presence.

Turn taking is the term I use in this dissertation to the feedback loop between collaborators. It is this process that allows machines to have more agency in the designing process and designers to leverage on the knowledge and skills of others. Beyond performing a sequence of actions in the way we intended, what happens when we watch the machine at work is the enactment of new opportunities unfolding. These opportunities are grounded in the edge capabilities of the machine entangled with materials, design choices, skill & practices of a community. To support collaboration in explorative making, the guiding principles for designers according to Becoming Travelers are simple: create time to make things, create a sensibility to appreciate what was done and be systematic (section 3.4). When more designers and machines become collaborators in the same process, these principles are joined by the importance of nurturing an attitude of trust in each other's expertise to allow for shared ownership & risk. Turn taking between designers also means understanding that collaboration is not so much about compromise but co-inhabiting a space and a timeline.

In the context of this dissertation, the forms of collaboration in these projects demonstrate how the entanglements within socio-techno system of the lab are more complex than our initial model of digital craftsmanship described. As previously mentioned, the concept of intra-activity, proposed by Karen Barad as an extension of Bohr's epistemological framework based on the two slit diffraction experiment [3, 4] influenced my view on samples. When reflecting on FabriClick and Exquisite Fabrication, Barad's argumentation about the boundaries of apparatuses that led to them articulating intra-activity also supported me in reflecting on the model of feedback loop in digital craftsmanship presented in chapter 2 (Figure C). This model shows the inside boundary of the apparatus, but not the outside one. Our samples are not observation-independent objects, and they are not created within independent, isolated spaces. Directly or indirectly, the ideas, samples, people, and machines that co-inhabit the lab in a timeline rub off on each other. To engage with the potential of collaborative practices and explorative making, we need not only to 'look backwards and forwards', as it was suggested in chapter 2, but also 'look to the sides', to widen our view of who and what is part of our socio-technical system of production (or apparatus). This requires developing a sensitivity towards what is at hand and the intra-actions that occur in the lab to enable collaborations with this "extended" socio-technical system of production. Secondly, it is important to find ways of acknowledging the part the co-inhabitants of our timelines play into our processes. Chapter 6 proposes one of such ways through accounts of collaborations with other designers working in the Wearable Senses lab and their samples.

5.1 FabriClick: Interweaving Pushbuttons into Fabrics Using 3D Printing and Digital Embroidery

Published as

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ABSTRACT

Mechanical pushbuttons, which provide physical landmarks and clear tactile feedback, are easily accessible and highly reliable in eyes-free use. Potentially, their merits can improve the experiences of on-body or wearable HCI. However, they are not commonly adopted as a user interface of smart textiles because the physical mechanism of conventional pushbutton hardware requires further integration, which should be seamless enough to be comfortably worn. In this pictorial, we present a design exploration of the methodologies for interweaving mechanical pushbuttons into fabrics. The exploration used a frame system, which unifies the workflow of digital embroidery and 3D printing and enables the exploration of the physical design. Throughout the process, we investigated methods of integration and fabrication by making and presented our findings with proof-of-concept implementations. We also discussed the alternative designs and interaction methods as well as their implications to enlighten future research directions and opportunities.

KEYWORDS

Fabrication; Pushbuttons; Embroidery; 3D Printing; Wearables

1 INTRODUCTION

On-body and wearable user interfaces boosted the availability of human-computer interaction [11, 35]. Exploring smart textiles is one of the promising approaches to realizing them [32]. Wearable interfaces augment their users' bodily expression and ease their access to digital information. Furthermore, their closeness to the skin enables the users to exploit their skin sensation and bodily proprioception for eyes-free inputs [18]. Hence, they afford private and subtle interactions that are socially acceptable [30].

Researchers investigated ways to improve the user performance of eyes-free interactions, such as adding physical landmarks and tactile feedback [42]. Nonetheless, tactile pushbuttons, the conventional eyes-free user interface that is ubiquitously deployed surrounding us, are often opted out from their considerations due to their hardware composition. Tactile pushbuttons provide physical landmarks that feedforward [43] the input location and feedback clear and expressive tactile sensation when the user is pushing on it. However, generating such clear and expressive tactile sensation requires a physically constrained spring hardware structure, which is a non-trivial implementation for soft wearables. A straightforward solution is installing or embedding the hardware on or into fabrics. Still, such a loose integration with the rigid components may compromise its wearability and create undesirable user experiences.

In this pictorial, we present the FabriClick,

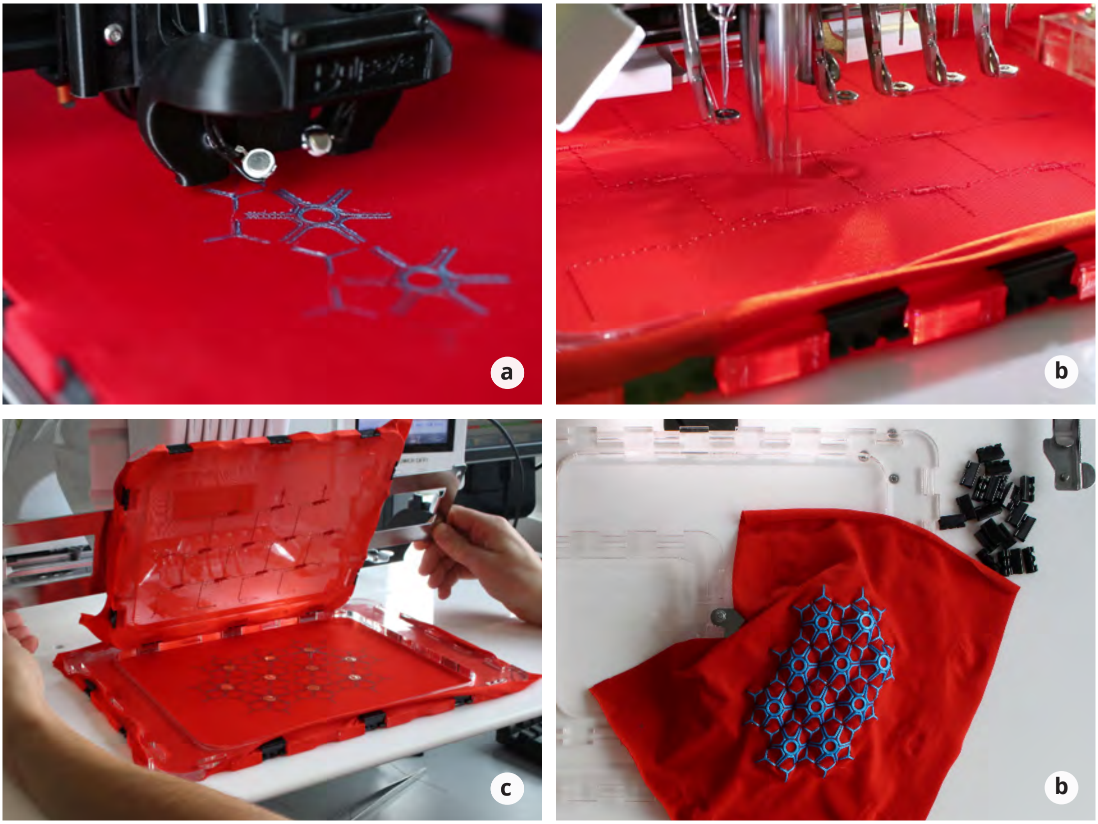


FIGURE 1 *The frame system enabled us to create functional pushbuttons, composed by two layers of textile. (a) Print or embroider patterns on one pre-stretched Lycra sheet as the Button layer; (b) Embroider conductive and insulation traces on another pre-stretched Lycra sheet as the Circuit layer; (c) Align the two layers and stitch them together; (d) Remove them from the frame to form the 3D pushbuttons.*

a design exploration of the fabrication methods and processes of interweaving mechanical pushbuttons into textiles. The goal is threefold: 1) to afford the textile's physical landmarks, 2) to enable clear tactile feedback when the users are pressing them, and 3) to form reliable electrical connections. To achieve the goal, we utilize digital machine embroidery and FDM-based 3D printing techniques. A digital embroidery machine was used for creating the conductive traces and for accurately assembling the layers. An FDM-based 3D printer was used as an assistive method that facilitates our exploration. We use the embroidery machine and the 3D printer to add physical and electromechanical components to each of the fabrics while keeping them soft and comfortable.

We also developed a frame system (Figure 1) that leverages on the stability granted by the embroidery frame to combine different techniques. The frame system functions as an extension of both the 3D printer and the embroidery machine, enabling the machines to print 3D models and embroider on the pre-stretched fabric sheets directly without compromising the alignment between the layers needed to make the final integration possible. Through iterative design, we used the frames to research how to make reliable pushbuttons on textiles in different ways, including isolated and tiled buttons, for on-body interactions. The findings and implications were discussed and presented with proof-of-concept implementations.

The main contributions of this work are two-fold:

- The frame system, which unifies the workflow of digital embroidery and 3D printing and enables exploration, and
- The FabriClick, textile pushbuttons which are the results of the exploration, that tightly integrated the functional elements into soft fabrics.

RELATED WORK

Related work is organized into the following categories: textile sensors, digital fabrication for passive haptics, and fabrication machine augmentation.

Textile Sensors

Textiles have functioned for millennia as wearable materials that afford warmth, modesty, fashion, and protection [34]. To enable interactivity in wearables, HCI researchers developed textile sensors for user inputs such as touch and gestures by capacitive [24, 32, 33], resistive [17, 26], or inductive [7] sensing through incorporating sewing, weaving, braiding, and digital embroidery techniques. Nonetheless, although the textile sensors can provide some inherent haptic feedback for the user inputs through its texture, the feedback is not as clear and coherent to the sensing state as those of tactile pushbuttons, which allows for eyes-free inputs such as blind typing. As a result, the users may need to confirm their inputs with additional visual, audio, or tactile feedback. Otherwise, the users can be very cautious about using the textile touch sensor if they think the sensing algorithm cannot reliably deal with false-positives, as if typing on a touchscreen. The lack of clear haptic feedback and the support of error-free haptic feedforward limits the user experiences of tactile sensors in eyes-free wearable applications.

Digital Fabrication for Passive Haptics

Passive haptic feedback, such as the tick heard when pressing a push-button, can help the users to ascertain their eyes-free inputs. Wearable researchers leverage passive mechanisms such as SensorKnits [25] or utilize the haptics from conventional electronic modules such as MakerWear [14] to provide haptic feedback. Researchers also use 3D printing to make customizable haptic controllers such as springs [12], tines [36], and magnet-embedded mechanisms [46]. Although they can be attached to the fabrics or sandwiched between layers of fabrics, these rigid materials are not like fabrics. Without further miniaturization, these rigid modules may reduce the flexibility, stretchability, and softness of fabrics. Miniaturizing these phidgets, however, may make them more difficult to use. To use them as ta computer user interface, they need to be paired with an additional sensor as they do not include a solution in the mechanism.

Fabrication Machine Augmentation

Jigs or add-ons can augment or extend the capabilities of fabrication machines without requiring extensive hardware modification on them. Various work combined a robotic arm with a 3D printer to increase its degree of freedom of printing to five or six [4, 5, 39, 45]. There are various conventional 3D printers, such as the SnapMaker printer (www.SnapMaker.com) or the Dubot Magician printer (https://www.dobot.cc/), supporting interchangeable modules that can transform a 3D printer into a CNC machine, laser milling machine, robotic arm, or a pen holder. Some modules can be retro-fit to industrial machines, such as the Coloreel unit which enables real-time thread coloring during processing in industrial digital embroidery machines (https://www.coloreel.com/).

Researchers also proposed adding sensors to enable an additional interaction loop between human and machine during 3D printing [44], laser cutting [9], manual milling [47], CNC milling [40], or digital embroidery [10]. Adding an additional effector next to the original one allows functional devices to be made, such as adding a coil winding mechanism for making electromagnetic devices [28].

Passive add-ons can be easily customized, made and maintained. LaserOrigami [23] added a support grid to allow users to laser cut 3D structures through bending rather than a manual assembly of parts. Scotty [22] added an additional material removal mechanism to remove layers of physical objects. Katakura et al. [13] used physical add-ons to repurpose a 3D Printer head as a robotic arm for attaching/detaching printed end-effectors for model assembly. In augmented reality, RoMA [27] added a simple rotating platform for users to communicate with a 3D printer by rotating it.

The frame system that we presented in this work is another passive add-on that not only allows for unifying the workflow of both 3D printing and digital embroidery but also serve as a jig during the manual crafting process.

FABRICATION METHODS

The fabrication methods that we use in this exploration should satisfy three main criteria. First, the buttons should be highly wearable (C1), which means that the product should be soft, flexible, possibly stretchable, and comfortable to wear. This can be achieved with methods that can tightly integrate the functional elements with fabrics so that the introducing functionalities will not override the material characteristics of fabrics. Second, the buttons should be functional (C2), which means that the product should provide clear tactile feedback and reliable signals; furthermore, the product should be durable enough to withstand repeated use and the casual movements from being worn. This can be achieved with methods that produce reliable materials that can withstand the uses in a wearable context. Last but not least, the methods and techniques should be generalizable (C3), which means that the fabrication methods should be versatile yet repeatable, therefore the future designers can adapt the buttons as functional elements in their own applications.

Based on the three design considerations, two digital fabrication methods, digital embroidery, and 3D printing were chosen for this exploration. Both digital embroidery [3, 20] and 3D printing [16, 29, 37] can directly add physical components to the fabrics and keep them soft and comfortable (C1). By leveraging the tensions of fabrics and origami patterns, it is possible to implement spring-like behaviors that can render clear haptic feedback [1, 16, 29, 37, 38] (C2). Electromechanical components can be introduced by using conductive threads [6, 31] or filaments [41], which can carry reliable electrical signals even when the fabrics are pressed or stretched (C2). Embroidery machines allow for making 2D models with variable thickness (a.k.a., 2.5D patterns) by manipulating the stitching methods [15], whereas 3D printing provides the freedoms to make 3D models. Both methods provide versatile and precise controls that are both reliable and repeatable (C3).

THE FRAME SYSTEM

To facilitate the exploration, we developed a novel frame (Figure 2) system to unify the 3D printing and embroidery process. The frames system consists of four layers: 1) Baseplate, 2) 3D print frame, 3)

Embroidery frame, and 4) Inner support plate. The Baseplate is installed onto the print bed to force the alignment of all frames placed on the print bed of the 3D printer (Figure 3a). The 3D print frame and Embroidery frame (Figure 3c) are made for aligning the 3D printing and embroidery patterns, respectively. The Inner support plate provides physical support when it is needed to 3D print the back of the fabrics with embroidery. Both the 3D print and Embroidery frames provided guidance for placing binder clips, which are used for affixing the stretched Lycra fabrics and keep the fabric under tension while changing machines. Each frame can be used separately with a pre-stretched fabric mounted, and put together as a whole when alignment between two layers is needed.

Figure 3b shows the process to calibrate the mounted base plate on the 3D print bed. We first embroider a cross in the center of the machine, and then mount it on the frames and place it on the print bed with the base plate. Then, we 3D print the same cross pattern on the embroidery one to know the offset, and translate the base plate to the center of print bed accordingly.

FABRICATING THE FABRICLICK

With the frame system, we began with embroidering onto pre-stretched fabrics. To transform the fabric into a 3D structure when the fabric is de-stretched, we experimented with a layering technique to locally manipulate the fabric character of the Lycra through sewing layers of various sewing attributes on top of each other, which allows the buttons to rise evenly. The Lycra fabric that we used has a blend of 80% nylon and a stretch ratio of 500%, which provides a wide range of stretchability for us to adjust the tension needed.

Star-like patterns, which consist of a central point and several legs, were chosen in the exploration. The topology of a star unit provides one degree of freedom, and the numbers of legs can control the tension. A

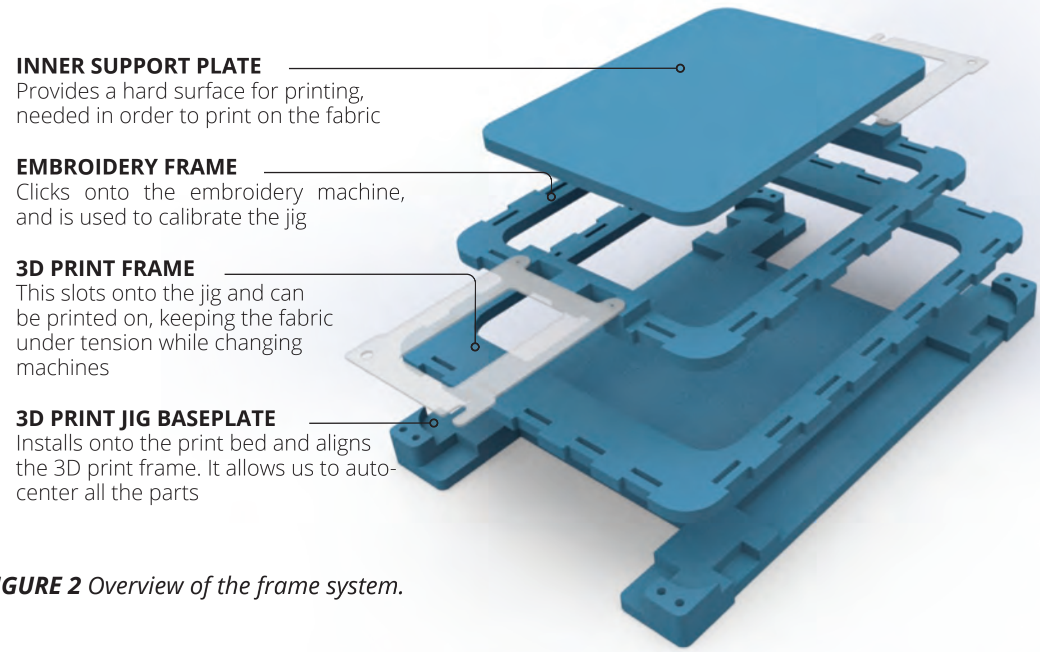


***FIGURE 2** Overview of the frame system.*

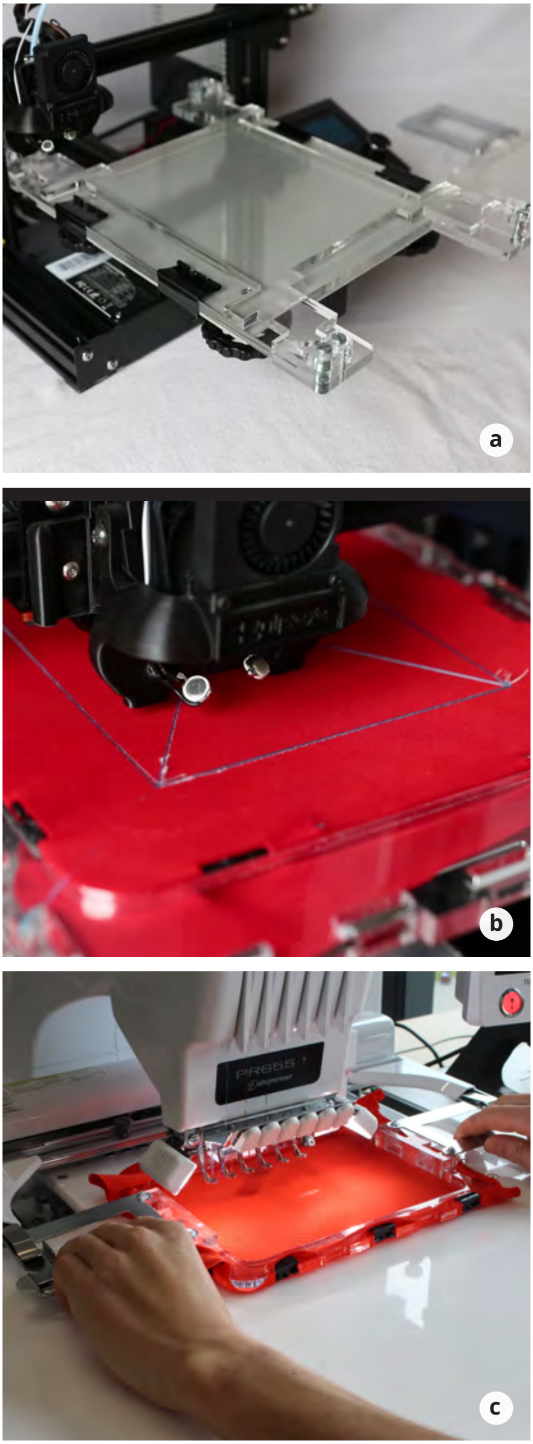


FIGURE 3 (a) Base-plate installed on a 3D printer; (b) Calibration; (c) embroidery frame mounted on an embroidery machine.

star unit with at least four legs provides a desirable balance. Nonetheless, with more than eight legs, the button also does not provide the required flexibility with our current button size. Since units with 3, 4, 6 legs are tileable, we make tesselation patterns with the star units of 4 to 6 legs.

On a pre-stretched fabric layer, embroidering a star-like topology will result in a button-like 3D geometry when the fabric is de-stretched. We experimented various parameters of the star-like patterns, such as numbers of legs, width and thickness of the stitches, and different ways of stitching. A Brother 655 digital embroidery machine and the Brother PE-Design 10 software were used in the exploration. As a result, we found that using a stem stitch in opposed directions over a dense zigzag stitch significantly increases the sturdiness of legs with the layer thickness increased. We also increased the thickness of embroidery using a 3D puff embroidery technique, which creates volume by placing a foam material on the embroidery frame before sewing a design and then using a dense satin stitch that will both cut the outline of the foam and cover it in the desired shape. Still, we found that when the complexity of the pattern increases, the friction between the stitches stiffened the pattern, making the button's behavior less predictable, as shown in Figure 4; also, due to the frictions, we noticed subtle differences between samples. Since the factors potentially burdened our exploration, we sought for an alternative solution.

3D printing, therefore, was used as an approximation of ideal threads in which the internal frictions are negligible. We used a conventional FDM-based 3D printer (Creality Ender 3) to print the star-like structures onto pre-stretched fabrics. We choose the Tronxy Flexible TPU Filament for printing over the common PLA ones because it provides both structural

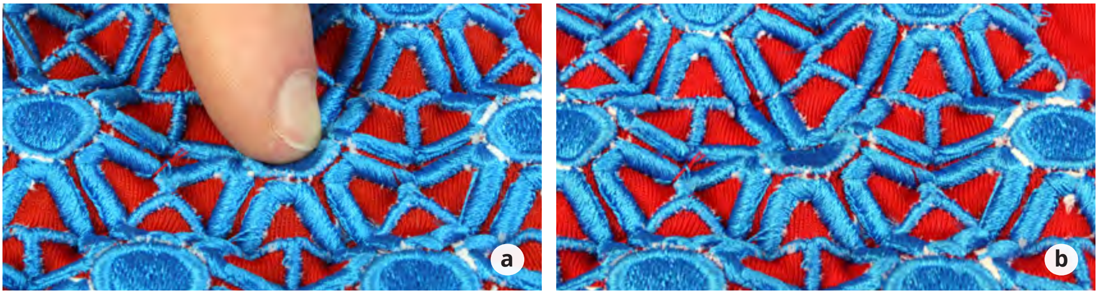


FIGURE 4 Buttons made by an embroidery machine. (a) Pressed a button. (b) Released a button.

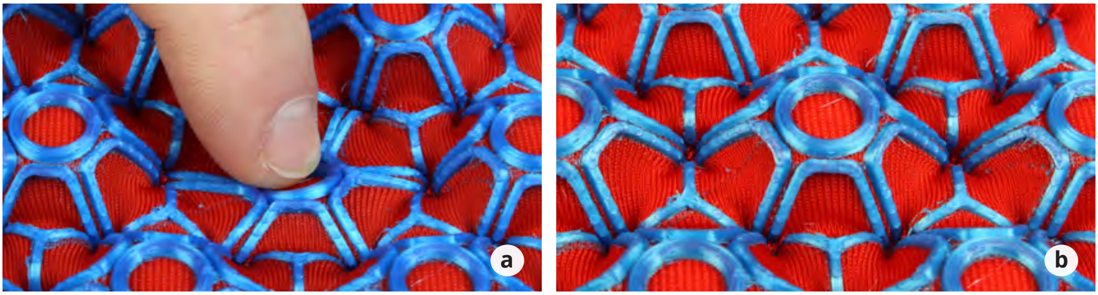


FIGURE 5 Buttons made by a 3D printer. (a) Pressed a button. (b) Released a button.

FIGURE 6 Isolated buttons: (a) star-like pattern; (b) a touch point added on the top; (c) 1x3 matrix of isolated buttons.

integrity and flexibility. We printed the model at 230 degrees celsius, so the print did not melt the Lycra fabric. The width and thickness of edges were controlled by G-codes using Cura 4.3.0. As a result, the 3D-printed button provides more consistent properties among different samples of the same design, and the behavior of buttons is more predictable (Figure 5). The distinction between the haptic sensation in different designs (i.e., thickness, width) is also clearer. Taking to our design considerations into account, we choose this 3D printing method to facilitate our further exploration.

Making Button Layer

Making Isolated Buttons

Star-shaped buttons (Figure 6a) acted bi-stably yet differed in terms of consistency. We found that hexagonal structures with double-barred legs worked best to form reliable button-like structures. Nonetheless, the force distribution around the legs was still unstable. We stabilized them by adding a round touchpoint, which constrains the bounce-back movement and makes the button more comfortable to press (Figure 6b).

We adjusted the structure tension by modifying the thickness of prints. A more rigid form with thicker prints rendered clear tactile sensation through its shape change, and sunk in deeper once clicked. To compensate for the additional tension, we added double-barred legs within the hexagonal shape by connecting neighboring leg pairs to increase the stability. With this design, we are able to create a matrix of isolated buttons, as shown in Figure 6c.

Making Tiled Buttons
We further arrange the buttons into a matrix of tiled buttons, so the buttons can be used as a collective as an interactive surface. Then, we noticed the button state interfered with the surrounding ones. We also noticed a distinct variation in the tension between the buttons located in the center of arrangements as opposed to those on the edges. Therefore, we further manipulated the tension distribution along with the button structure by using a 2.5D taper structure (Figure 7a), which gradually increased the thickness throughout the length of the structure legs. This technique further softened the surrounding of each button and consequently, reduced the crosstalks between the buttons in the matrix, as the comparison shown in (Figure 7b and 7c. Consequently, the buttons can be reliably used when tiled as a hexagonal (Figure 7d) or a rectangular grid (Figure 7e). Lastly, we further improve the stability of buttons by minimizing the distances between each leg so the functioned as hinges that limited the movement of buttons to one degree of freedom. The circular touchpoints were enlarged to 1cm to better fit the human finger and offer slightly less key travel. The detail of the final design of the button layer is shown in Figure 8.

Making Circuit Layer
To make the Circuit layer, we first used 2 ply Adafruit stainless steel conductive threads (https://www.adafruit.com/product/640) for prototyping. We began with a simple analog resistive circuit by embroidering

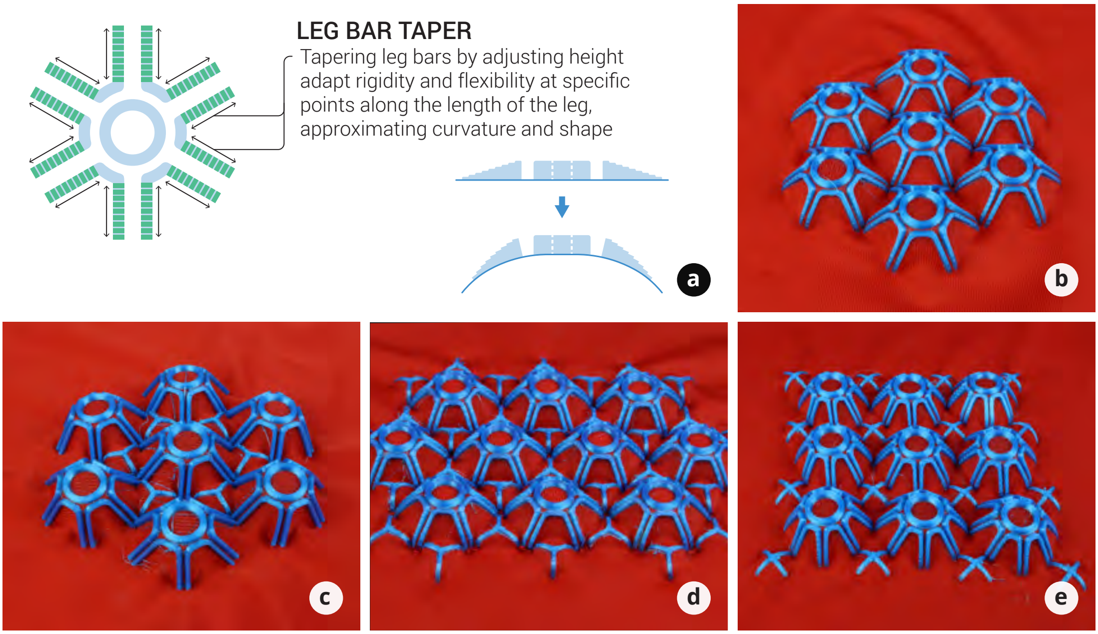


FIGURE 7 Tiled buttons: (a) design and results in a 2.5D taper structure; (b) buttons with the taper design; (c) Buttons without the taper design; (d) ten buttons in a hexagonal tile; (e) nine buttons in a 3x3 tile grid.

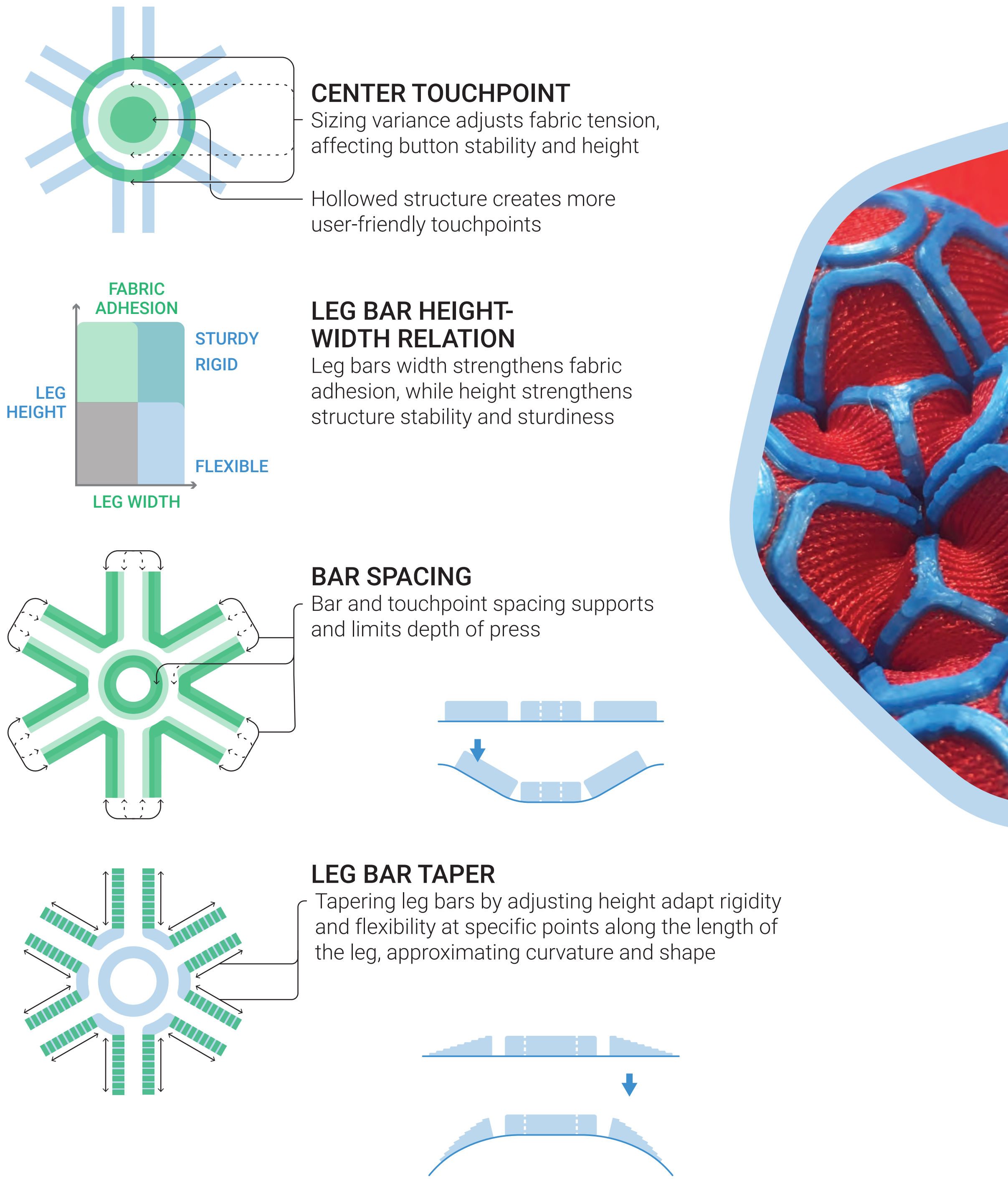
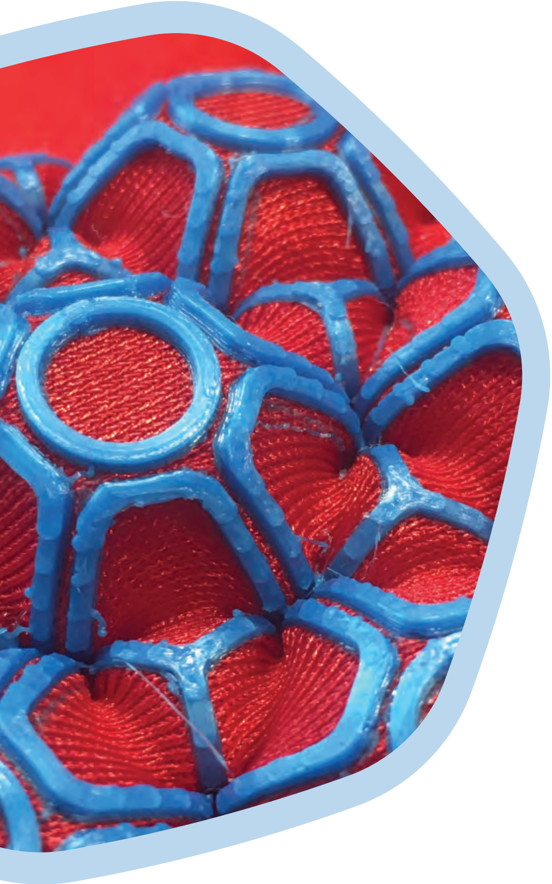


FIGURE 8 The Design of Button Layer.

MATRIX TILING PATTERN

Hexagonal button design provides ease of tiling and adaptable arrangement possibilities to position consecutive buttons and other matrix patterns

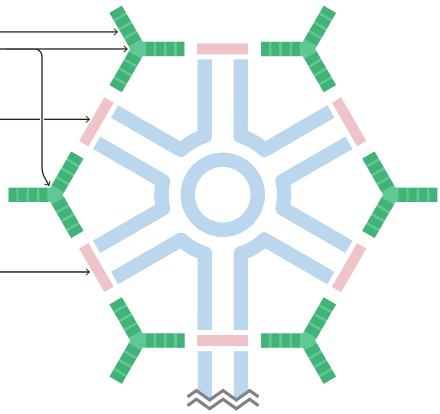


TRIANGULAR SPACERS

Miniature button-like spacers distribute buttons evenly, improving usability by isolating buttons to draw individual focus and prevent accidental button presses

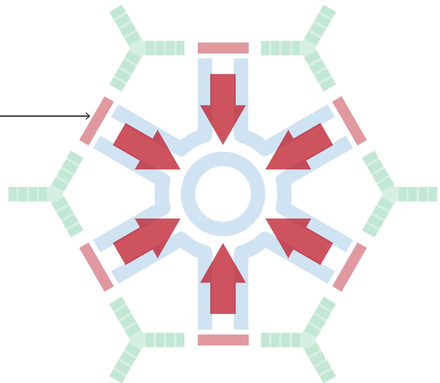
Spacers retain tension in the empty, tension dead-zones created by button distribution, reducing overall instability

Spacer legs are tapered to accurately adjust tension in dead-zones and surrounding areas



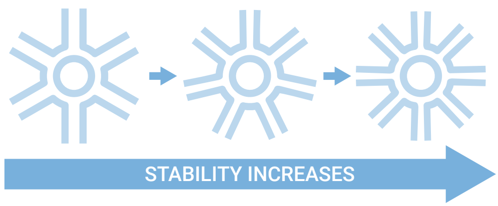
CONNECTOR POINTS

Connector points are located between adjacent button legs at the hinge, sharing diagonal force from the underlayer



LEG COUNT

Higher leg counts stabilize the button better, and equal length leg bars give best results by diffusing fabric tension evenly



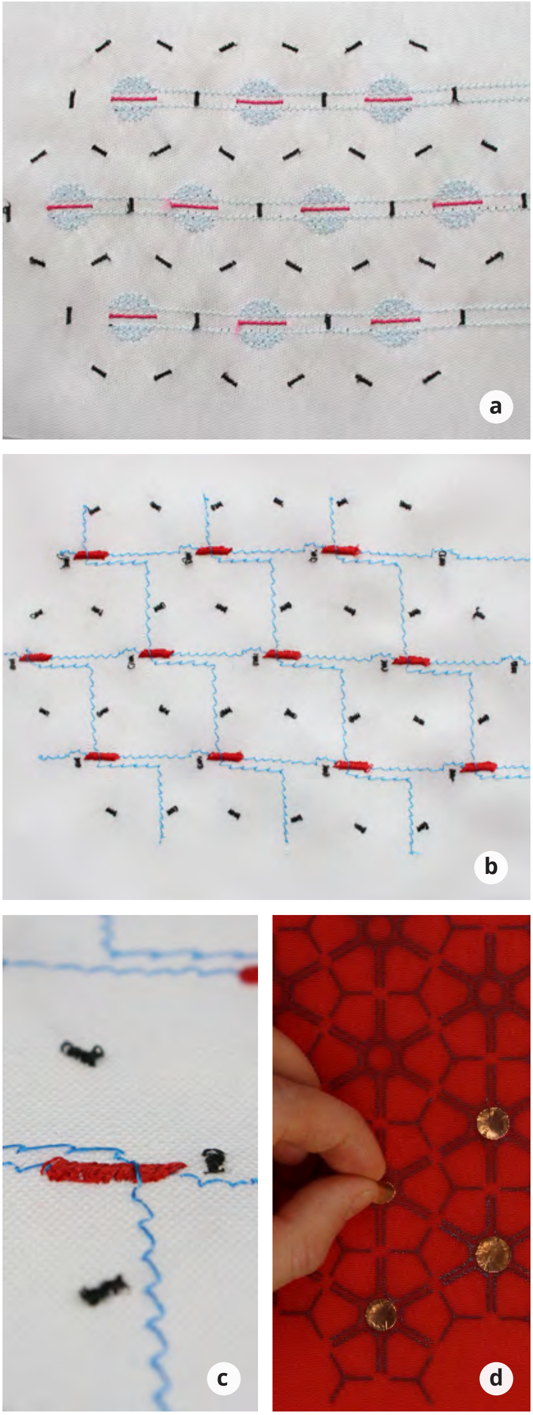


FIGURE 9 Circuit layer: (a) resistive circuit design; (b) button matrix circuit design; (c) the intersection; (d) conductive pad under each button.

a zig-zag stitch pattern along each row of buttons (Figure 9a). By manipulating the length of trace like a potentiometer, we can use the resistance measurement to infer the location of the button pressed. Although it is easy to fabricate, we found the resistive values are changed by stretching the fabrics as the same circuit acted as a stretch sensor as well. Also, the resistance of each sample differs so reliable sensing requires calibrations, which is a crucial burden for scalable deployment.

Towards a more scalable design, we adopted a button matrix circuit, which has rows and columns (Figure 9b). This digital circuitry is more reliable when the fabric is stretched and bent, but also more complicated to fabricate because of the crossed wires. We resolved this problem by incorporating non-conductive threads for the insulation layer and adjusting the circuitry (Figure 9c) to prevent short-circuit failures.

To make the button press events detectable, we manually attached an additional conductive pad (Figure 10d), which is made from vinyl-cut thin copper tapes to the bottom of each button. This manual assembly effort can be replaced by incorporating conductive threads with the embroidery button layers in the future iteration. Pressing a button shorts the corresponding circuit crossing and enables the event to be detected. Like conventional button matrices, multi-press events can be detected through time-multiplex sampling, which scans the states of one row of buttons at a time. The schematic circuit diagram of a 10-button matrix is shown in Figure 10.

In our final design, we replaced the stainless steel yarn into the HC 40 highly conductive thread (https://www.madeira.com/) to make the textiles more resilient in dealing with a higher range of resistivity. The circuitry was then adapted to be embroidered onto a pre-stretched Lycra fabric. Eventually, we were able to build flexible circuitry that can reliably detect button presses.

Integrating Two Layers and Forming the Pushbuttons

After the two layers are fabricated, we integrate the two layers through machine embroidery by fitting the frames together. The frames force the alignment between two layers so they can be simply stitched together in one more pass of stitching. After the two layers are stitched together, the frames can be removed and the tension forms the buttons into a 3D structure (Figure 11).

To evaluate the tactile sensation, we test three implementations of different design, which is of different leg length with or without the tapering technique, using an Imada digital force gauge. We plot the results as the reaction force-displacement graph as shown in (Figure 12a). The results show that, in every sample, the reaction force clearly reduced after the displacement, which is correlated to the

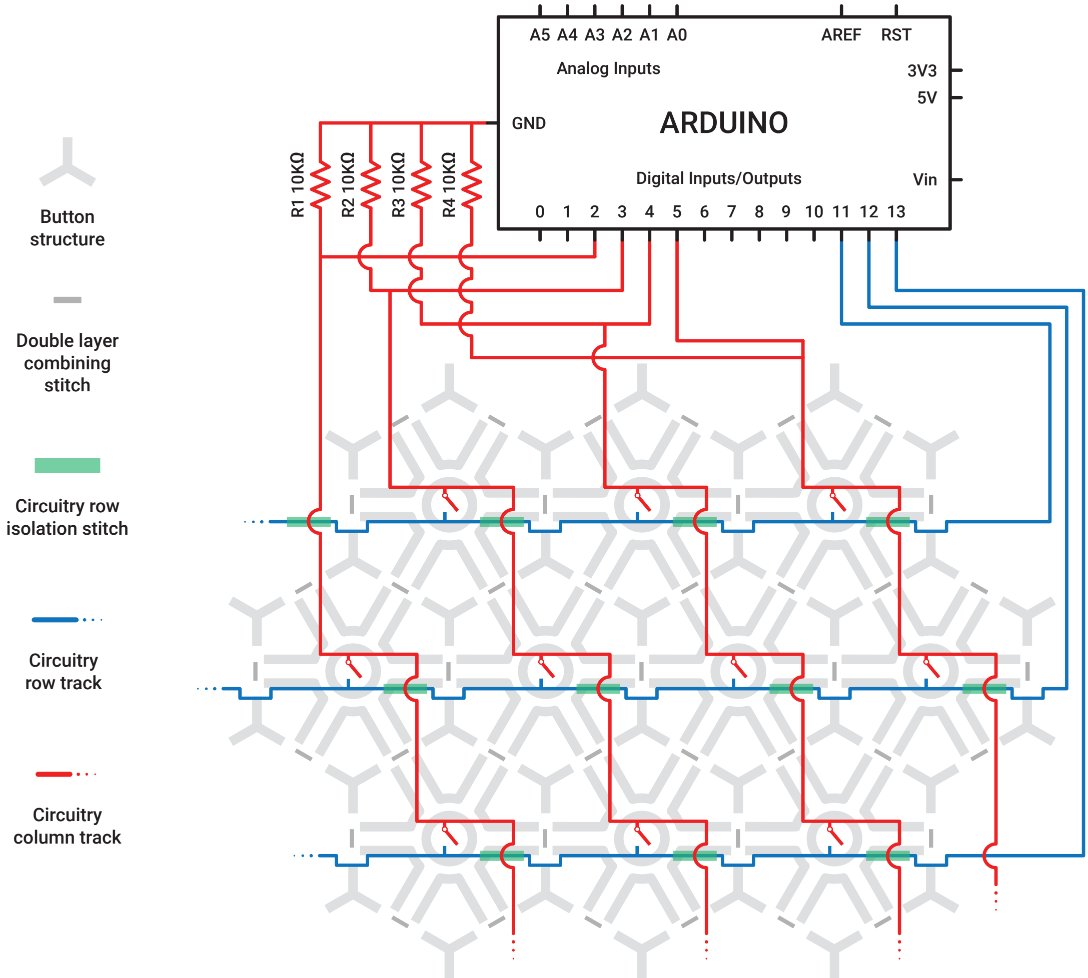


FIGURE 10 The schematic circuit diagram of a 10 button grid.

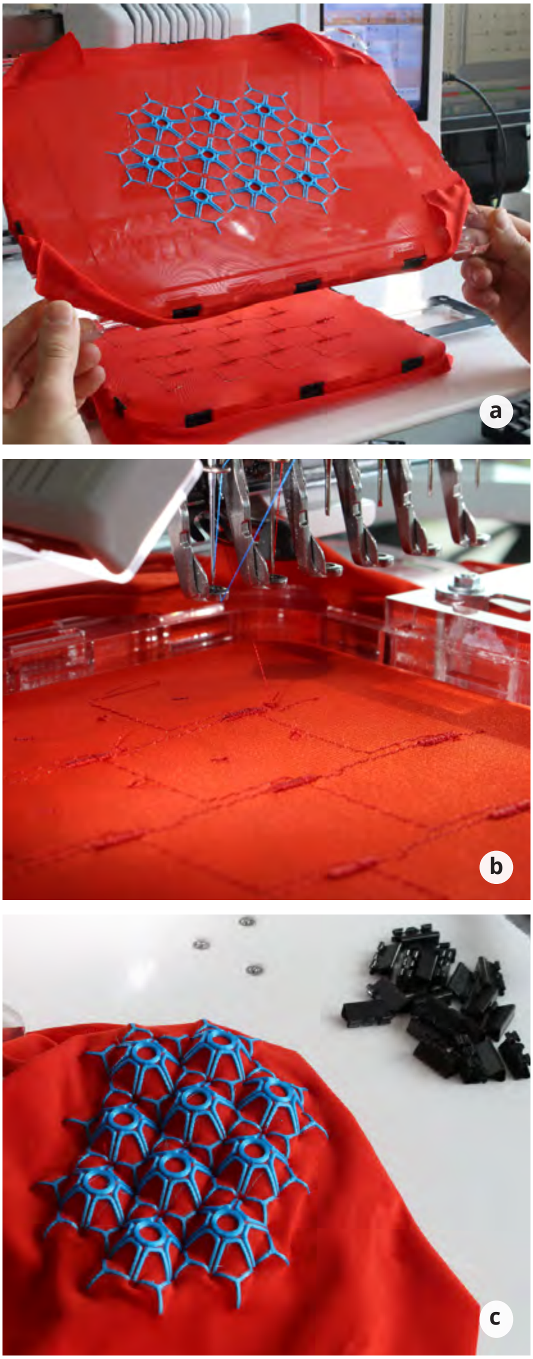


FIGURE 11 Layer integration: (a) button layer and circuit layer in the same design; (b) two layers of pre-stretched fabrics are aligned by the frames and placed on the embroidery machine; (c) result of 3D buttons after the fabrics were removed from the frames.

exerted force, surpassed a threshold. This shows clear evidence of the haptic feedback. The two tapered buttons are both easier to press down than the non-tapered ones.

The durability of fabrications was tested by pressing a button 4000 times using the same apparatus and measuring the force-displacement relationships again. The results show that, although the FabriClick becomes softer, the force feedback still exists (Figure 12b). Also, the resistance of the circuitry only slightly increased from 49 ohms to 52 ohms after the button was pressed 4000 times, which also suggested promising reliability.

Using the Pushbuttons as a Computer User Interface

To use the FabriClick as a computer user interface, we connect the conductive yarn to a signal processor through a circuit board (Figure 13). 10K ohm pull-down resistors were added into the circuitry. As the yarn cannot be soldered, we attached the conductive thread to a thin isolated copper wire with a small crimp, so we can form a reliable permanent connection between the thread and signal processor, which is Arduino in our implementation. The computer can, therefore, detect the button events through serial data communication.

Summary

With our frame system, a 3D printer and an embroidery machine, we describe the walkthrough of fabricating a functional pushbutton on textiles as a user interface as the following six steps (Figure 14):

1. Print the Button layer: Stretch and fix a Lycra fabric on 3D Print Frame, apply it on the base plate of a 3D printer and print the button layer.
2. Post-process the Button layer: Attach connecting pads at the bottom of each

button after the print is finished.

3. Embroider the Circuit layer: Stretch and fix another Lycra fabric onto the Embroidery Frame, install it on the embroidery machine and embroider the circuitry in an order of rows, isolation, and columns.
4. Integrate the two layers: Add 3D Print Frame with the buttons layers with the connecting pads facing the circuitry.
5. Form the FabriClick pushbuttons: Remove 3D Print Frame and Embroidery Frame from the embroidery machine and detach the fabric from both frames.
6. Connect to computer: Build the physical connection and data communication between the pushbuttons and

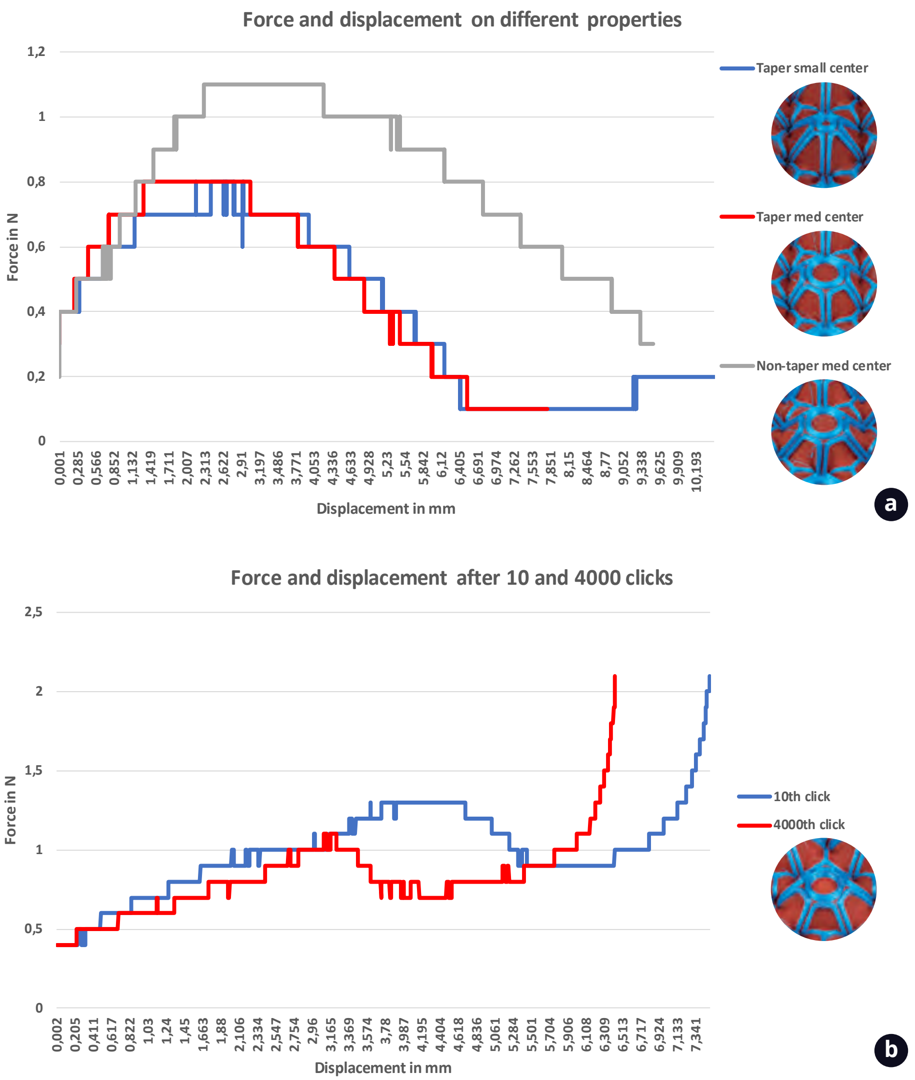


FIGURE 12 Haptic feedback measurement: (a) Reaction force-displacement plot on different designs: (blue) tapered long legs, (red) tapered short legs, (gray) non-tapered short legs; (b) Reaction force-displacement plot after 10 (blue) and 4000 (red) on a sample design.

computers.

Although the current system still requires human intervention in step 2 and 6 as well as moving the frames and/or buttons between each step, the proposed frame system does unify the workflow of both 3D printing and digital embroidery and make a straightforward integration possible.

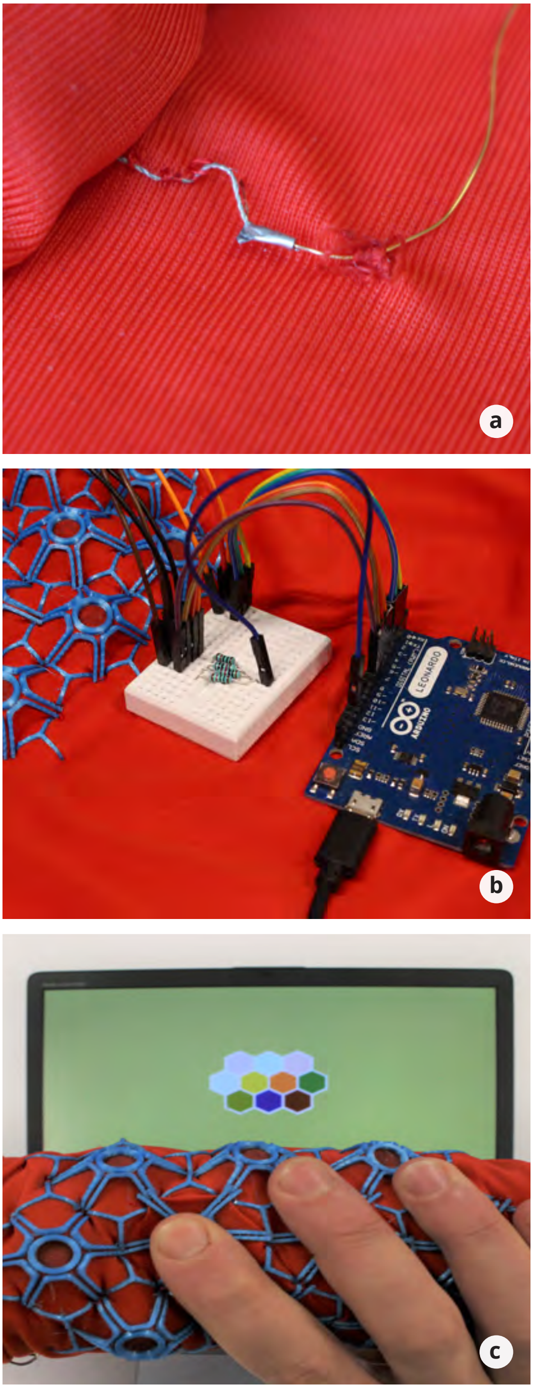


FIGURE 13 Connecting the FabriClick to a computer. (a) Connecting the embroidered circuitry to an Arduino using crimps; (b) Circuitry on the breadboard. (c) Results as an on-screen visualization of real-time signal processing.

User Experiences of On-Body Deployment

To explore the possible interaction design, we made several samples of sleeves based on our hexagonal button structure design in a different scale (Figure 15a). We tested them in an informal embodied ideation session with five subjects to acquire early user experiences. Overall, the participants recognize and appreciate the haptic feedback of the textile pushbuttons, and think the samples are soft and comfortable to wear. We further summarize the findings as follows.

A matrix of isolated buttons, if the density is low, can easily be laid flat (Figure 15c). Therefore, it is flexible enough to be deployed on most of the body locations. However, the appropriateness of button locations is highly dependable on the cultural and social appropriateness as well as the meaningfulness of the intended semantic mappings.

In contrast, a large tiled panel consists of a high density of buttons, which tends to curl into themselves due to the amount of tension that the buttons apply to the textiles. Therefore, it wraps well around smaller limbs like an arm, but it is less suitable for a large flat surface, such as the trunk or larger limbs of the body.

Compared with isolated buttons, a larger array of button structures looked and felt like a collective, so the experience of using it is more like pressing on the larger felt pad, which is flexible and stretchable.

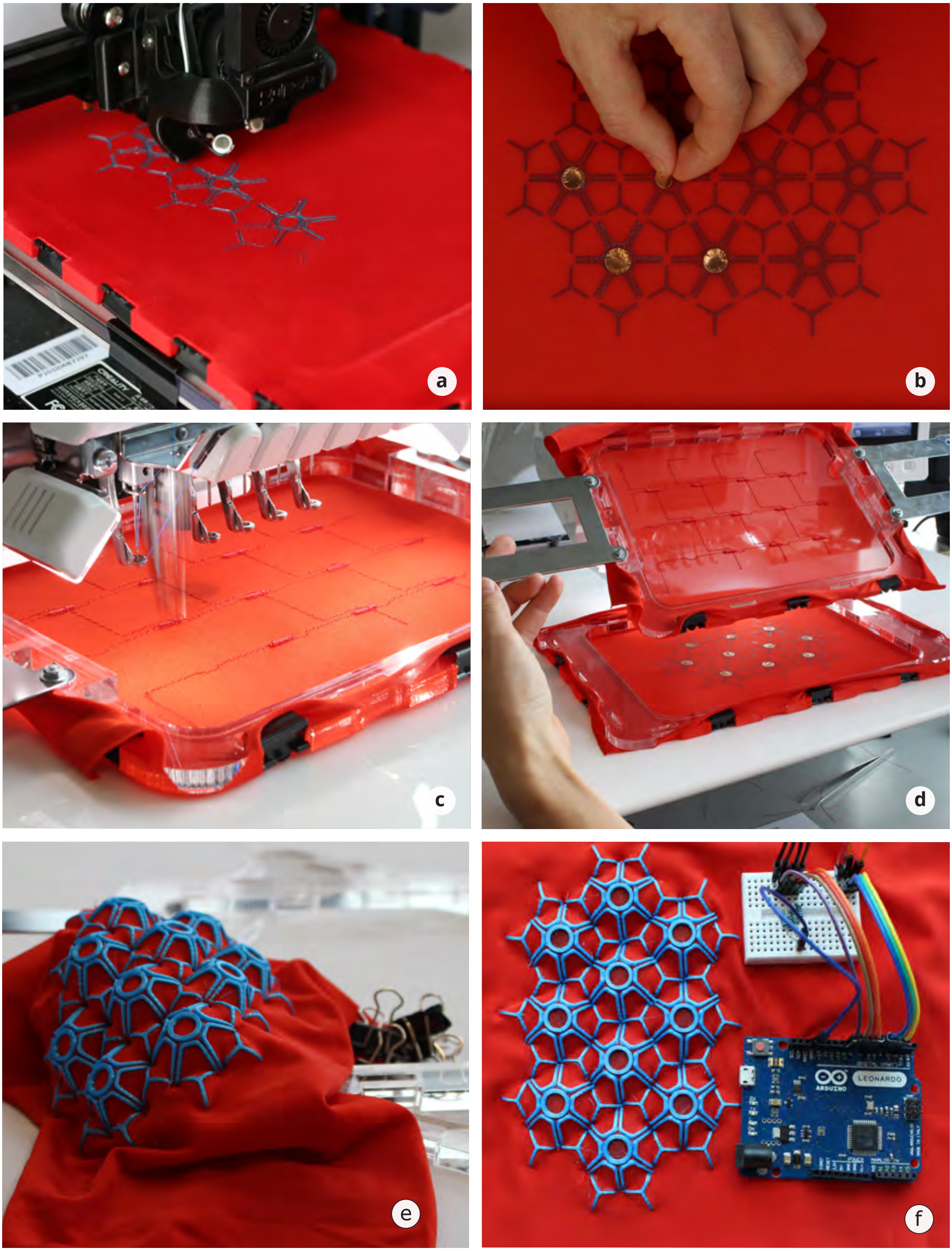


FIGURE 14 The workflow of making the FabriClick through the frame system. (a) Print the button layer; (b) Post-process the button layer; (c) Embroider the circuit layer; (d) Integrate the two layers; (e) Form the pushbuttons; (f) Connect to Computer.

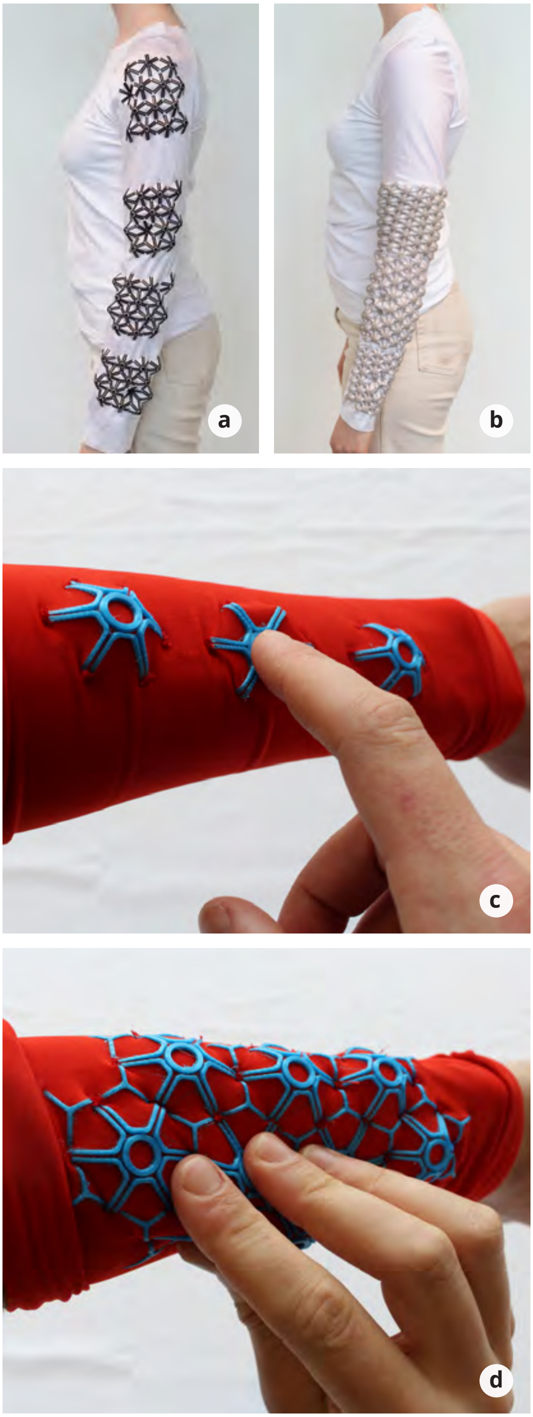


FIGURE 15 On-body deployment of the FabriClick: (a) sample sleeves with buttons; (b) pressing one of the isolated buttons; (c) squeezing the tiled buttons.

Therefore, it not only affords touching and swiping but also rich interactivity, such as squeezing and rubbing (Figure 15c).

We also found that button arrays placed on the location of soft parts (e.g., upper arm) or moving parts (e.g., elbow joints), were not completely reliable. During the body movement, some pressed buttons recovered to the released state and became 'clickable' again, while others reached another state of the bi-stability, which is in a negative height that required the users to reset them by pulling on the other side of the sleeve, lifting or shaking their arm, or pushing the button back up from the underside. The stability problem could be mitigated if the sleeve fits users' body tightly; otherwise, the instability still can be hedonic features that invite its wearer to interact with the buttons playfully.

These findings helped us proceed with a better focus on the final implementation by developing a better understanding of the interaction dynamics of the interface.

Applications in Example Scenarios

The FabriClick interface is generic enough to be implemented in a broad range of contexts. The always-available, textilebased buttons could assist patients to alert medical staff when in need or be used as a life-logging or self-reporting interface that is easy to access (Figure 16a). In whole-body or VR gaming (Figure 16b), the buttons can be rich-haptic controllers that provide haptic feedback without asking the users to hold a remote controller or to wear a bulky controller that may impede their movements. In social contexts, the buttons from the wearer could be either extruding, exaggerated to attract others attention and curiosity of others, so that could become an icebreaker that facilitating social conversation (Figure 16c). Or it can be hidden or made implicit as a private object that can soothe the wearer when pressing on them through the haptic sensation.

DISCUSSION

Alternative Designs

Tactile Switch

In addition to push buttons, a switch can be made by exploiting the bistability of buttons. The rectangular button (Figure 17a) reached another stable state after it was pressed (Figure 17b). Squeezing the button can recover its state (Figure 17c). However, the challenge of this design is to retain a reliable electrical connection between the upper and lower layers, which are both flexible. Adding magnets to the corresponding location of each layer could achieve the desired reliability, but the strength of magnets should be carefully chosen to ensure the state recovery.

Pressure Sensing

Pressure sensing can be realized by incorporating digital embroidery using resistive yarn [26] or with a resistive sheet [2].

2.5D Landscape

The height of a raised structure can be manipulated through 3D printing or embroidery [21] topology. Therefore, future work can consider leveraging computational design to realize a continuous, 2.5D landscape, such as Geodesy [8].

Scale

Beyond further optimizing the FabriClick push-buttons for finger and hand inputs, which is the main objective of this work, future work can further perpetuate more scalable techniques and methods that can embed functional tactile elements into a different scale of objects. For instance, making body-scale buttons as part of furniture can facilitate embodied interactions, or making imperceptible, micro-scale buttons into the fabrics as lightweight impact absorbers. The sensing circuitry embedded in these buttons could empower new data-driven services.

Richer Tactile Sensation

For a higher-level embodiment in the eyes-free applications, one can also consider deploying various embroidered textures on the top of buttons to provide an additional layer of information that can ease the users to target the button in need. Adding an embroidered actuator to the button can further deliver digital information through a more expressive tactile communication, but also increase the deployment and maintenance cost accordingly.

Reducing the Manual Assembly

One of the prerequisites of this technique is the pre-stretched fabrics, which should be applied to the frames with an uniformly-distributed tension before printing and embroidery. In other words, low tension

FIGURE 16 Possible application scenarios of wearing the FabriClick pushbuttons: (a) A self-reporting interface for a patient; (b) Tactile input devices for VR gaming; (c) Ice-breaker for social interaction.

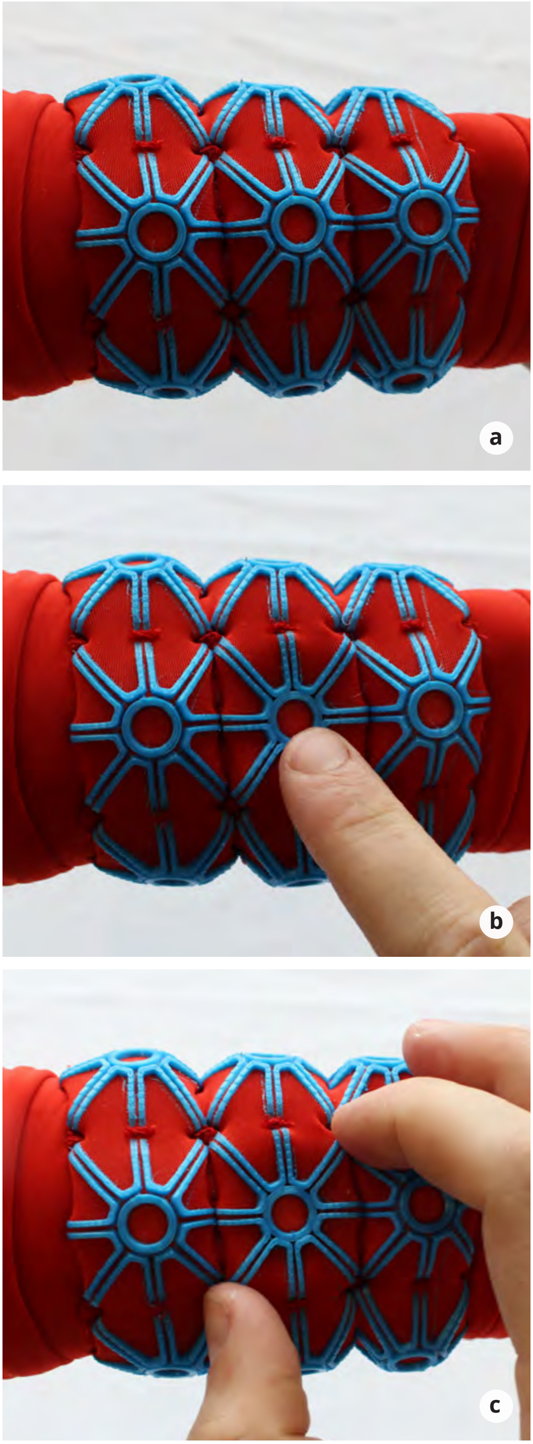


FIGURE 17 A 3x3 grid of tactile Switch: (a) No switch is pressed; (b) One switch is Pressed; (c) Squeeze the pressed switch to recover it.

and wrinkles cued by wrongful stretching may fail the later procedures. This is currently done manually with experienced makers, but it can be achieved and automated through robotic machinery. A repeatable and consistent way to apply pre-stretched fabrics on the frames will make the technique more scalable.

Instead of adding crimps to each thread manually, aggregating the embroidery circuitry to a printed circuit board (PCB) mounted on a standard connector (e.g., Dupont) can make the interfacing efforts easier. A reliable electrical connection between the threads and the PCB can be established using previous techniques [19]. With an interactive system such as a Sketch&Stitch [9], the placement of PCB can be decided after the circuitry is fabricated so further customization is possible.

The placement of a conductive pad can be automated by embroidering a pad using conductive thread before printing the button layer. Using conductive 3D printing to print the conductive pad at the backside of the button is also possible, if the printing of both layers are strictly aligned.

The loose ends of the threads after the embroidery usually needs to be trimmed. The post-processing efforts of the additional techniques, such as the 3D puff embroidery method that we explored for increasing the layered thickness, also need to be considered. Future work should also investigate the reduction of these post-processing work to decrease the amount of the human labor required.

After the adaptation of the above techniques is achieved, a straightforward approach toward full automation could be to use a robotic arm system and jigs to move and install the frames on the machines in different stages of manufacturing. Like the highly-automated PCB manufacturing processing, testing and quality assurance can also be achieved during the process while the fabrics are still in its stretch states. This can maximize the scalability of the fabrication towards a larger quantity, therefore the users can better focus on designing their applications rather than making and testing the functional buttons.

Customization and Creativity Supports
As both 3D printing and digital embroidery machines are versatile devices, additional customization can be added during the process of making. For instance, additional features such as labels of buttons can be added by either machine in different stages of fabrication, depending on the desired effects. Software tools for 3D printing and embroidery design can consider such creativity supports, so these features can be seamlessly integrated into the final product as well as the workflow.

CONCLUSION
In this pictorial, we have presented the FabriClick and its fabrication method using a new passive add-on to interface two existing machines without the need for retooling. This augmentation allows us to directly fabricate the mechanical structure and electrical circuitry on each pre-stretched Lycra fabric layer, using digital embroidery and FDM-based 3D printing, and integrate these two layers together as textile-based push-buttons. The result is a highly stretchable, flexible, and comfortable material, which is useful for wearable and on-body interactions. In addition to this, our project suggests that the making of such low technological additions to machines of fabrication opens new possibilities for design innovation in smart textile applications. As a result, we feel that this area warrants further investigation and explorations into the possibilities on the edges of digital fabrication. By limiting the technological sophistication of these devices we imagine that this can be done in explorative and experimental ways, preserving the flexibility and designerly approach to the fabrication.

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5.2 Exquisite Fabrication: Exploring Turn-taking between Designers and Digital Fabrication Machines

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Figure 1. Detail of sample created in the project through a process of Exquisite Fabrication. The fabrication of this embroidery- based infatable sample took four steps, done in three diferent machines: digital machine embroidery, a flament 3D printer and a custom Liquid Deposition Modeling (LDM) 3D printer. The steps were a) embroidering the substrate, b) 3D printing a mold on the embroidery, c) 3D printing the silicone and d) integrating the tubing through a couching stitch.

ABSTRACT

Digital fabrication and craftsmanship is entering into a new phase with increasing levels of complexity and a renewed desire for composites and cross-material experimentation. However, allowing work to travel from machine to machine remains a challenge in terms of workflow, communication, orientation and material. Based on an exploration to combine embroidery and 3D printing in the pursuit of inflatable solutions, we propose the metaphor of the drawing game Exquisite Corpse to outline the three emerging concerns: turn taking, orientation and trade-offs. We propose a set of guidelines that suggest ways in which we may allow different digital fabrication machines to be used in sequence, as a method for adding complexity to the things we make and the ways our machines may talk to one another.

KEYWORDS

Fabrication, Digital Craftsmanship, Turn-taking, Prototyping

1 INTRODUCTION

The way we design and fabricate things is changing due to the growing adoption of digital fabrication technologies like 3D printing, laser cutting, and digital embroidery. The levels of reproducibility, accuracy and fidelity of finish of such

*Both authors contributed equally to this work

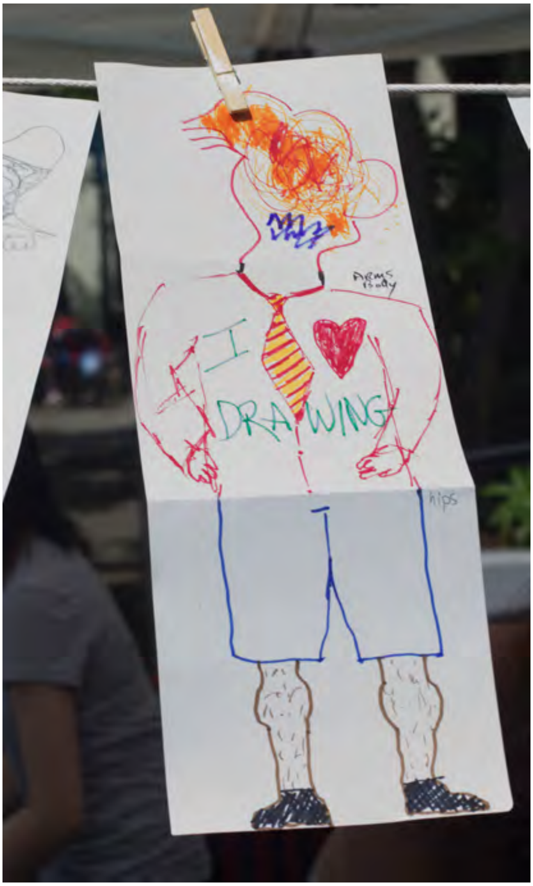

Figure 2. Example of a Exquisite Corpse drawing. Photo by Alan Levine, 2012, CC BY 2.0 via Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Exquisite_ Corpse_Art_(7356894034).jpg)

technologies allow for new possibilities that were not available with more traditional design processes, in which concept development preceded the inclusion of fabrication methods and material considerations into the process [18]. More specifically, these technologies enable designers in exploring real implications of production systems, supporting bottom-up approaches to design based on the capabilities and opportunities offered by the machines and materials [11]. We see this shift reflected both in research and industry by the growing interest in different methods of fabrication from companies such as Adidas, New Balance and others implementing 3D printing for mass manufacturing of shoe soles [21].

The close collaboration between designers and machines brings the experience of using digital manufacturing closer to that of traditional craftsmanship, where a constant dialog exists between the craftsman and the material [20]. To enhance this experience, researchers have been exploring the interaction between human- machine [7], digital craftsmanship [4, 6, 8], Interactive Fabrication [16, 24], digital manufacturing practices [23] and production systems for personalisation [17].

Although examples of designs based on digital fabrication techniques and systems abound [13], there is little cross-pollination between techniques. Some efforts in this direction combine several technologies into one machine, such as Popfab [19] and Jubilee [22]. Here, multiple technologies are combined into one, but in order to achieve this, compromises are needed to allow multiple technologies to work within the same machine. This limits each technology and narrows down the potential combinations to techniques that are similar. Combining a 3D printer and a CNC milling machine, for example, is much more feasible than bringing together a 3D printer with a digital embroidery machine. In 3D printers and the CNC milling machines, the bed position is fixed and the nozzle or bit moves in the 3 axis. In the digital embroidery machine, the stitch is formed by interlocking top and bottom threads. As moving top and bottom would be unstable, the embroidery frame moves instead.

In this paper, we introduce an approach that encourages exploration, cross-pollination and improvisation in the fabrication process, which we refer to as Exquisite Fabrication. In this, we refer to the classic surrealist art game, Exquisite Corpse [5], where different people collaborate on a drawing in stages, knowing only the transition points of body parts such as the neck or legs (see example in figure 2). We propose that our contribution is the notion of the exquisite corpse as a cultural metaphor to facilitate a practical approach to working between multiple machine systems for fabrication. In this approach, each machine can remain itself, and instead the samples travel between various machines to get the advantages of combining multiple fabrication technologies. To take turns in the making process, only the transition or the starting point for the new process needs to be known. To make this work, we focus on supporting the alignment of the sample across different machines. In this way, the system of production available to the designer is flexible enough to include, exclude or replace machines. If a new digital machine comes on the market with new functionality, this machine can be incorporated into the workflow, without having to be fully compatible with the other machines.

In order to facilitate this approach, we designed a machine operation alignment system (referred to as MOAS), a system created to support the alignment between different digital fabrication tools. In this paper, we provide a description of an example design process, that focuses on maintaining the designerly and collaborative qualities of the work, while providing a simple system that facilitates interoperability of two existing fabrication systems. This example is the detailed process of implementing MOAS to develop an inflatable actuation sample (see figure 1), fabricated by combining digital machine embroidery and 3D printing techniques, as a design test case. While the design focus of the process is the creation of an embroidered inflatable, this paper is entered on the broader possibilities for exploring turn-taking between disparate systems and distant collaborators. We propose the metaphor of the Exquisite Corpse to outline the ways in which we may allow different machines for fabrications to be used in sequence, as a method for adding complexity to the things we make and in turn new ways for our machines to talk to each other.

2 RESEARCH CONTEXT

The project was started with the explicit aim to explore the possibilities and implications of transporting samples across the machines in a lab. Inspired by the challenges found in previous work in the area of actuation in soft wearables [12], we used the Embroidered Inflatables as a design case of combining 3D printing, digital embroidery and silicone casting to create textile-integrated inflatable actuators. The Embroidered Inflatables already combined the processes of digital machine embroidery and manual silicone casting. We expected that by automatizing the casting process and creating a system for transporting the sample across machines, we would not only solve a technical issue (interoperability) but also develop an approach and a working metaphor (Exquisite Fabrication) to support different crossovers between skill sets and distinct machines.

As silicone adheres only to itself, combining it with other materials requires an open structure or a porous surface it can sink into. In our test case, we aimed to create self-supporting substrates by using digital embroidery as an open structure to facilitate integration of the silicone with textiles (see figure 3). The material qualities of the substrates and, consequently, the interactive possibilities of the final inflatables can be changed depending on the sewing attributes or layering of the embroidered designs. While

Figure 3. Sample created in our process of Exquisite Fabrication being actuated

the advantage of this fabrication method is shifting the complexity of fabrication from the casting mold towards the embroidery, which is more reproducible, the casting is still crucial. Manually placing the mold and manual pouring of the silicone hinders the reproducibility and control of the actuators. Even slight tilts of the mold or small differences between the amount of silicone in each pour can cause the inflatable actuators to behave differently from each other.

For the purpose of this exploration, we decided to approach the casting process through two kinds of 3D printing, one for creating the molds and the other for pouring the silicone, and create a system to facilitate the transition between the machines. As previous work has shown [10, 11] it is possible to use an embroidery frame as a fixed device that travels between machines. However, we wanted to overcome the limitations of the maximum operation areas of the machines involved as well as to remove the need of retrofitting machines with compatible hardware. In the following, we detail the design process of the system and report on the implementation and outcomes.

3 INTRODUCING THE MACHINE OPERATION ALIGNMENT SYSTEM

In order to support the creation of multiple-machine samples, we designed a Machine Operation Alignment System (MOAS). The system was developed recognizing the value of leveraging the capabilities of each machine, as well as the expertise of each maker. As such, instead of creating a multi-purpose machine, our goal was to allow separate digital fabrication machines to interact as a system without changing how they normally operate.

We realized that the game Exquisite Corpse could be used as an effective metaphor for how each process builds on the other, making turn taking between machines the core concept of MOAS. Rather than designing and envisioning all steps upfront, the work practice we propose leans towards exploration and improvisation. Each new machine does not need to know all that happened before. Rather, it only needs to know where to start the new process. As such, the design of MOAS took into account the following factors: 1) The operations done by a machine should align with the operations done by the other machines; 2) The system should support decisions to be made on the fly; and 3) MOAS should intervene as little as possible on the regular use of each fabrication machine, allowing easy and rapid implementation of a machine into the system.

The result is an open system that consists of the digital fabrication machines and software tools designed to facilitate turn-

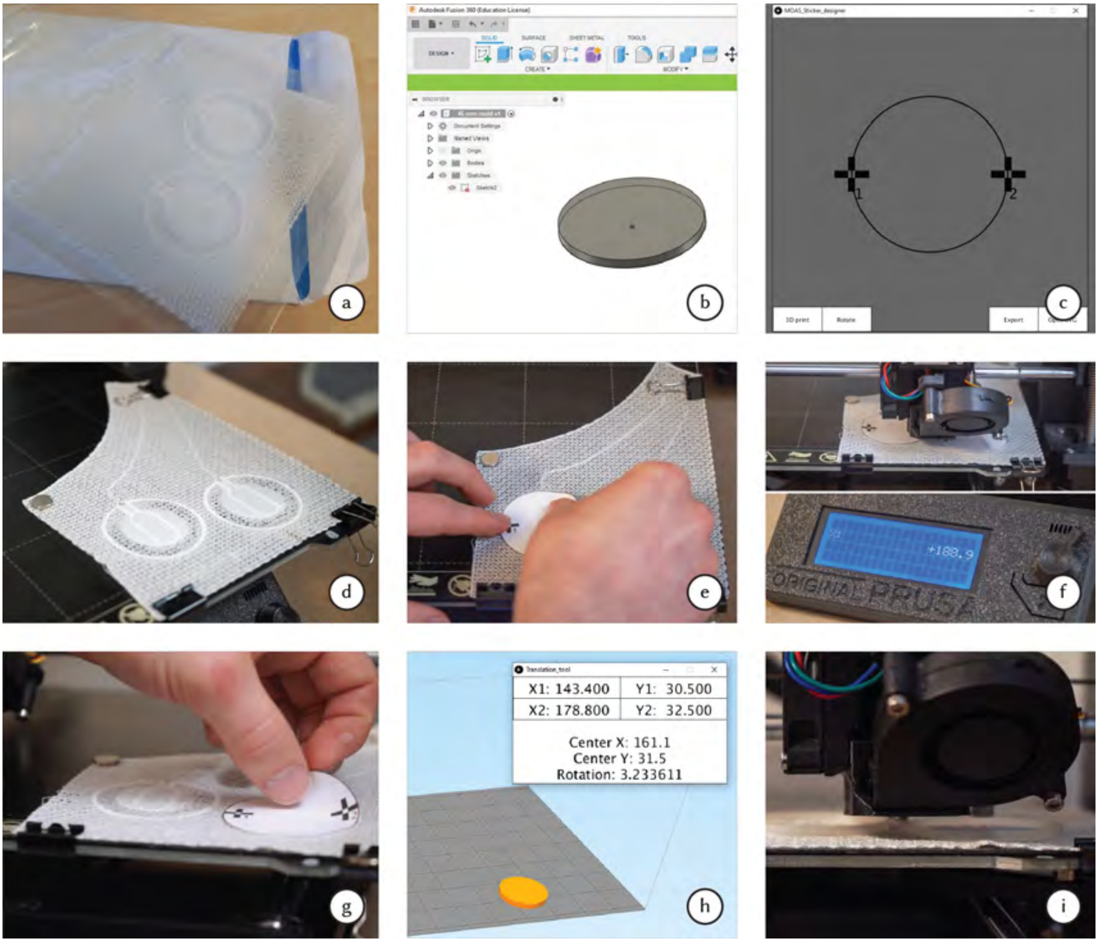

Figure 4. Workfow of 3D printing a thin mold on top of the embroidered sample: (a) received embroidered samples; (b) preparing 3D model. (c) making sticker in MOAS SD based on an SVG from the 3D model; (d) Placing sample in the 3D printer; (e) placing stickers. (f) recording marker coordinates; (g) removing sticker; (h) positioning fle with MOAS TT; (i) 3D printing mold.

taking between them. These software tools aim to create a common language between machines that may function very differently from one another, enabling design researchers to combine techniques by adding, removing or replacing machines from the subsystem used in a given project. This language is mediated by a main software tool, the MOAS sticker designer (MOAS SD), which generates markers to help position a sample into a new machine. While some machines allow positioning the file in the working area through an interface, others need this process to be done via software. For such cases, we designed a second software tool, which we called MOAS Translation Tool (MOAS TT), to give the needed X and Y positions of the operation as well as rotation.

As a design case, we combined digital machine embroidery and two kinds of 3D printing through MOAS. Through the design process of creating an embroidered inflatable sample, we experienced through a first-person perspective the challenges of combining techniques and of turn taking, not only between machines but

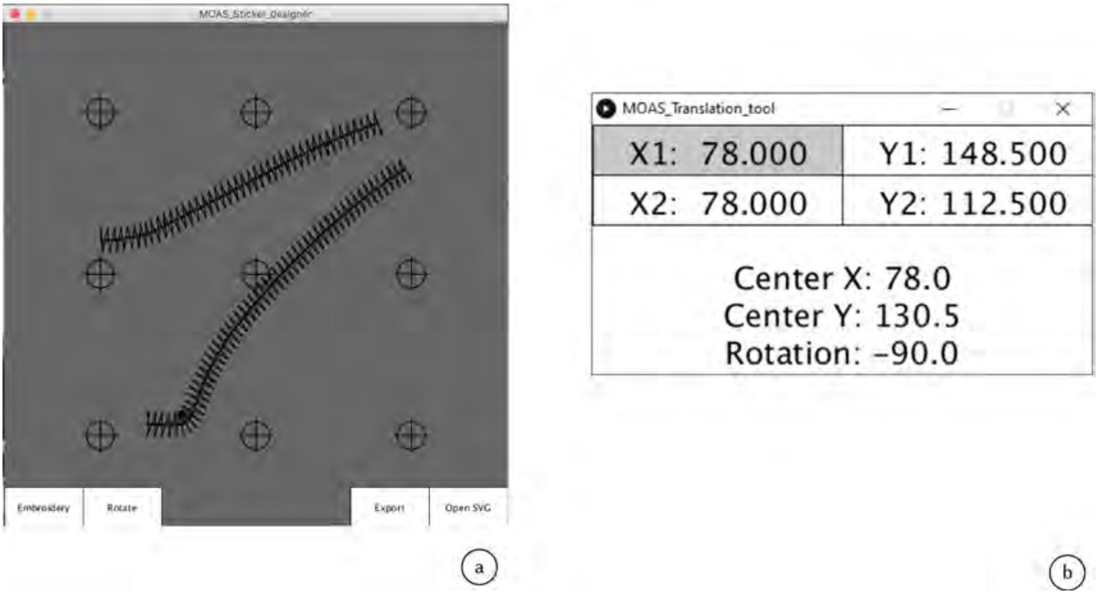

Figure 5. Screenshots of MOAS applications. (a) MOAS SD creates the stickers with markers that support the alignment of the sample in diferent machines. (b) For machines that do not have an interface that allows changing the alignment, like in 3D printers, MOAS TT takes the coordinates of the markers to give the center point and rotation for input in the proprietary software of the machine.

also between designers. Based on this experience, in the following we articulate our findings about multi-machine collaborations. We introduce a new method for design researchers to work with digital manufacturing, not as isolated technologies but as a larger system.

Every digital fabrication machine carries with it its own coordinate system, i.e. it knows its own zero position. Every operation needs to be aligned based on this reference frame. MOAS uses this principle as a basis for alignment. By finding points in the reference frame of the machine, the location and rotation of an operation can be calculated with simple trigonometry. To place an operation in the machine, a sticker is made with the MOAS SD software. Each sticker contains a number of markers. The amount and shape of the markers may differ per machine. The machine is aligned to the marker in a way that works with the standard operation of the machine (see figure 4).

Different kinds of machines as well as different models of machines have features that pose different implications when using them with MOAS for alignment. These differences may include access to the working area of the machine, work envelope and interfaces. Some machines, like digital embroidery machines, allow for positioning an operation through the interface of the machine itself. In such cases, the markers on the MOAS sticker are used to find the offset and rotation within the machine.

Machines like 3D printers, on the other hand, do not offer the ability to change the location of an operation once it is prepared for printing. For such machines a second piece of software is needed to calculate the position of the operation so it can be placed in the right position before slicing. In this case, the stickers feature two markers. The X and Y locations of these makers are used by the translation tool to calculate the position of the sticker within the machine. This piece of software gives the coordinates of the operation and its rotation. These values are then used to position the model or file in the software of the machine. To participate in Exquisite Fabrication, each following operation needs a starting point. Through the stickers, MOAS provides this starting point to the machine. Independently of the machine, MOAS is used for alignment of each new operation that is done. New machines can be added to the process seamlessly due to the starting point provided by MOAS.

When making multiple versions of the samples, machines can be replaced when another machine can be used to achieve a similar outcome, or machines can be removed when their operation is no longer needed or easily substituted. As a result, Exquisite Fabrication turns all machines and people in a design or research lab into collaborators. Where previously each machine was used individually, they can now work together to create a shared outcome. Different designers can each apply their expertise and combine techniques to create new artifacts that would not exist without the cross-pollination between technologies and makers.

4.1 Stickers and translations

Two pieces of software were created to support Exquisite Fabrication: the MOAS sticker designer (MOAS SD) and the MOAS Translation Tool (MOAS TT) (figure 5). Both tools were created using Processing [2] and can be run as standalone applications.

The sticker designer is the backbone of MOAS. It creates the stickers that are used for alignment. The stickers serve as placeholders for operations within a machine and feature a set of markers that the machine can align to. The number of markers and their shape depends on the machine. All types of machines work slightly differently and, for that reason, the markers are tailored to work best with a specific machine.

Using the MOAS SD works as follows. The outline of the operation is exported as an .SVG file. This can be derived from the file used for embroidery or an export of the bottom of a 3D model. The machine the sticker is designed for is selected, and based on the width and height of the file, the software determines the placement of the markers. A new .SVG can be exported that includes both the outline as well as the markers.

In some cases, a machine cannot be aligned to the sticker directly e.g. a 3D printer. The MOAS TT was created for this. MOAS TT is auxiliary software that takes the coordinates of two markers on a sticker and provides the center point and orientation of the sticker i.e. operation, within the machine. This information can be used to position the operation in the software of the machine.

4.2 What the machine knew already

Digital fabrication machines usually come with proprietary software. This software is used to prepare digital files compatible with the machine. For 3D printers, this software is the slicer, which converts three-dimensional models into code for the machine. For embroidery machines, embroidery digitizing software is used to program the sewing order and sewing attributes of embroidery patterns. Final adjustments, including size, position and rotation can be added on the machine via its screen interface. Other software, such as CAD (e.g. Solidworks) or a vector graphic editor (e.g. Adobe Illustrator) can be used in the design phase. MOAS works alongside the existing software for a machine rather than replacing it. This way, MOAS has a minimal impact on the operation of a machine. The digital file of the new part of the sample is created as the design researcher normally would, using the appropriate proprietary software. From the design file, an alignment sticker is created by the MOAS SD. This sticker is used for alignment, either directly through the interface of the machine or with the use of the MOAS TT. MOAS TT works in conjunction with the machine's own software by providing the coordinates and orientation of the model.

5 FABRICATING EMBROIDERED INFLATABLES THROUGH MOAS

Based on the Embroidered Inflatables [12] as a design case, MOAS was developed to combine digital embroidery with 3D printing. The differences between the two techniques supported us in designing a software tool that is flexible to adapt to how each machine operates. 3D printing and digital machine embroidery have been combined on several occasions. The paper Combining Strings & Fibers details the use of digital embroidery to embed wires into 3D printed objects [3]. With this approach, the yarn embedded in the 3D printed parts adds functionality that cannot be achieved otherwise. FabriClick combines the 3D printing of soft materials with embroidery on stretched fabrics to create textile pushbuttons [10]. The FabriClick jigs build on the embroidery frame to allow the fabric to remain under tension when changing machines and keep the alignment between machines. From these implementations it became apparent that a system can be created to let samples travel between machines where each machine can add something to the final outcome. In the case of FabriClick, the jigs only work with machines that are modified to work with the jigs. A solution that does not rely on these kinds of modifications would make the process of transporting samples between machines much easier to implement and not limited to certain technologies or work envelopes of machines. The Embroidered Inflatables [12] demonstrated that one possible fabrication process for soft actuators is a hybrid of digital machine embroidery and silicone casting. Laser cut acrylic molds can be used for the casting, but performing the casting manually can result in errors and low repeatability as both the placement of the mold and the quantities of silicone in each pour are hard to control. In using MOAS, the goal was to improve such casting by 3D printing the mold onto the embroidery and using a custom 3D printer to deposit silicone when and where needed. For this action to be successful, the 3D printers need to be able to print in the right location. Due to the isolation measures against the spread of COVID-19, the 3D printers and embroidery machines were located in different cities. This physical separation meant that each type of machine was operated by a different researcher. Therefore, the material samples travelled through mail back and forth between the two designers involved in the fabrication process. MOAS facilitated this collaboration by allowing each design researcher to draw from their own expertise, using the machine in question to fulfill the next step in the fabrication process.

6 THE DESIGN AND FABRICATION PROCESS OF THE SAMPLE

The design process of the new Embroidered Inflatable sample was done in four fabrication steps (figure 6): embroidering the substrate, 3D printing a mold on the embroidery, 3D printing the silicone and couch stitching the tubing via digital machine embroidery.

The main aim of each step was predetermined. The research team agreed on which fabrication processes would be combined and what would be done in each step (substrate, mold, casting, tubing integration). However, we allowed opportunities to emerge when deciding on how to proceed with each process,

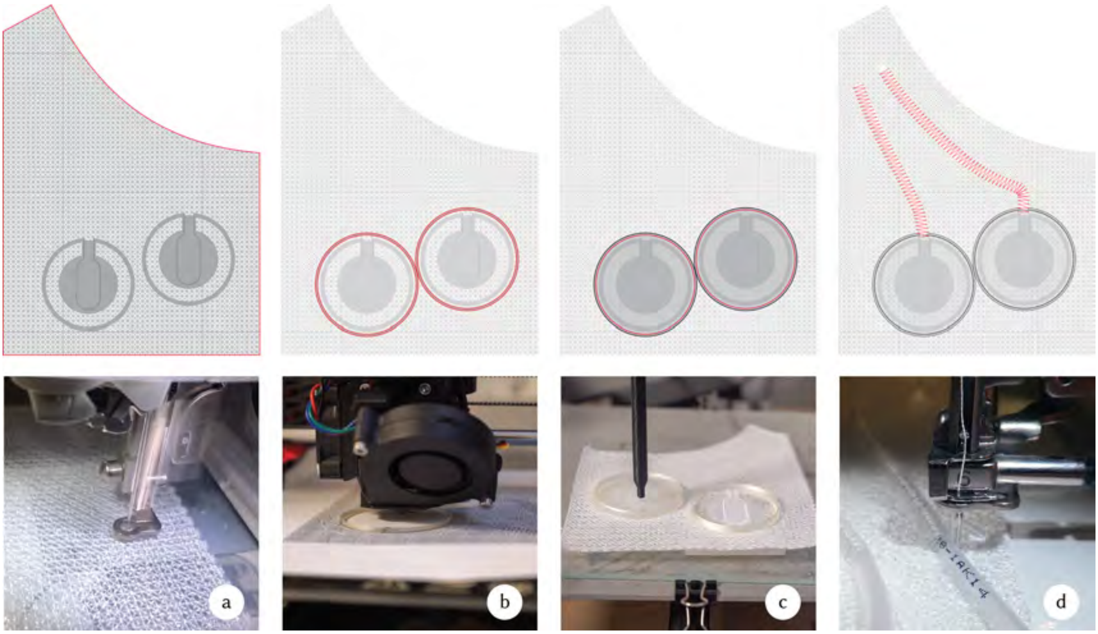

Figure 6. The sample was transported between three machines to perform four fabrication steps: (a) embroidering the substrate, (b) 3D printing a mold on the embroidery, (c) 3D printing the silicone, and (d) couch stitching the tubing via digital machine embroidery.

including which technical specifications would be used in the design of each part. The embroidery steps were carried out by one design researcher and the 3D printing steps by another. This meant that turn-taking happened not only between machines, but also between collaborators and techniques.

The first fabrication step was straightforward. A free-standing substrate was embroidered including the outline of the inflatable, a support pad and appliquéing [1] an extra layer of the water-soluble stabilizer that will create the pocket to create a unilateral inflation (similar to the design of Interaction Mode 3, described by Goveia et. al [12]). The sample was removed from the embroidery frame and sent by mail to the other design researcher. MOAS SD was used to create an alignment sticker for the 3D printers. Since the 3D printing of the mold and the silicone had the same general shape and would happen in the same area of the sample, this sticker could be used for both 3D printing fabrication steps. The sample was attached to the bed of the 3D printer and the sticker was placed over the outline of the inflatable. Using the MOAS TT and the 3D printer's software, the digital file was aligned to the position of the sticker. The digital model is raised slightly from the bed of the printer to account for the thickness of the sample. The sample with the mold was then transferred to the silicone printer and the same steps of placing the sticker, aligning and printing were executed.

To support us understanding the implications of different machine features to alignment through MOAS, we also used two different digital embroidery machines to compare experiences. For that, we carried out one last embroidery step, couch stitching the tubing, on both a domestic embroidery machine (Brother Innov-is 750e) and a professional one (Brother PR1050X). The latter has a built-in camera that supports precise

Figure 7. To engage in this kind of making, we had to accept the shared risks and ownership of the process. The last step was high risk because it was the most experimental. This step consisted of integrating tubing through couch stitching. The tube had to be manually arranged as the machine stitched.

alignment of designs. The camera is also already meant to support alignment by scanning a specific sticker design, which we incorporated into the MOAS SD. The domestic machine we used, on the other hand, had no LED pointer or any other indicator of the precise position of the needle on the frame. To check whether the position is correct, the needle had to be lowered into the fabric. Typically, the process of precisely positioning the design onto the frame can be done in two methods that can be combined. The first method of precisely positioning the design is making sure the material onto which the design will be embroidered is aligned with the center of the embroidery frame while setting the fabric (or stabilizer) in the embroidery frame. The second method is to adjust the position and rotation of the design on the display of the machine. For this machine, we used nine markers on the MOAS sticker to skip the first method.

7 WHAT DID WE LEARN

Our design case allowed us to experience through first person perspective some of the implications of engaging with multi-machine and multi-maker collaborations. In this process, we experienced the making like a game of Exquisite Corpse, each action was followed by the next until we arrived at a result that was more than the sum of its parts. This had implications in different aspects: turn taking, improvisation and trade-offs.

7.1 Turn taking

While an obvious aspect of a system designed to move work from one machine to another, turn taking emerged as a much more complex and personal aspect of the work. As makers we found ourselves not just aligning our samples and materials, but also our dedication to the process and our individual making ethos. We were forced to share our craft and machines in closer ways than we had expected.

In the process of making, designers gain intimate knowledge of the materials, techniques and tools they use. We learn how the machine works so that we can encode and decode potential errors or interesting effects based on our understanding of the process. The turn taking between design researchers brought interesting dynamics to our collaboration and our relationship with the process of making. In our process, whenever one maker gave the sample away for the other one to continue, this next maker had to play a game of Exquisite Corpse in order to be able to build on what was already done. In turn, each maker became attached to the sample and, as such, the sample encoded a piece of each maker and how they each approached their craft.

Our experience was that this turn taking between makers was a close and instinctive exchange and that it was quite different to more traditional co-creating. When co-creating, all parties involved stay in control of the creative process and can negotiate the compromises to be made. Sharing a sample with someone else to let them take a turn in making meant sharing a part of ourselves through the sample and letting go of the control over the outcome. We had to trust that the other person would treat the sample with the same level of care and dedication we did.

Besides building trust in each other, we learned that to enter this type of collaboration, we had to accept the shared risks and ownership of the process (Figure 7). Every time the sample changed hands (and machines), the risk of something going wrong increased. Likewise, the lucky chance of one of us receiving the sample with a positive unexpected result was also part of turn taking. Accepting these risks required a strong feeling of shared ownership and shared responsibility.

Although the turn taking between people facilitates the letting go of control over the design to allow opportunities to emerge, we believe that Exquisite Fabrication can also be carried out by the same maker engaging with machines. In our experience, the turn taking between machines may also be an interesting dynamic as the order of operations and nature of each machine/technique effects the opportunities for future steps. To make our inflatable, for example, the first step in the process is to embroider the free-standing embroidery that served as the base of the sample. As the embroidery is relatively fat, it enabled the 3D printer to add the walls of the mold without problems. Inverting the order of processes would not have allowed us to execute the same sample. Different opportunities would have to be explored. This shows that the order of operations may open up different kinds of opportunities for next steps of Exquisite Fabrication. In future work in this direction, exploring the other paths inverting operation orders or types of machines would be an interesting way of further exploring what it means to design bottom-up, from the sample one has at hand.

7.2 Improvising & understanding machines

While the system we devised was designed to make a complex process easy and less prone to error, we found that even with these new guidelines a certain level of improvisation was required in order to micro adjust each turn. There are a number of aspects to this, one is the inherent tolerance in each machine and how they may amplify each other, another is a simple inherent precision of the hand. Micro adjustments and improvisations remained important aspects of the way we worked.

The initial vision for the system was that it would provide a technological solution to the transfer of work-in-progress between machines. In our experience, however, we found that each step required some level of improvisation on how to implement MOAS to transport the sample between machines. This moment of picking up the sample to think “what now?” created anchoring points or seams [9] in the process that pushed us into investigating the possibilities of the machine and the material.

The MOAS application allowed us the simple flexibility to replace the marker designs and the number of markers on stickers to adjust to each machine/ process. To check the alignment of the last step with the marker in the domestic embroidery machine, the position of the needle needed to be lowered into the sample. However, lowering the needle into the silicone would damage the inflatable. To increase the chances of there being two or more markers that could be used for alignment, the stickers for embroidery contained nine markers. Their positions around the outline of the part match points the machine can move to when the starting point key is pressed on the display.

The markers were adapted differently when testing the system using the professional machine with a built-in camera. The central marker was changed to match a design that the machine could automatically recognize through its scanning feature. The machine correctly recognized the marker and aligned the file accordingly. A visual check and some final adjustments were necessary to achieve the best alignment. The rotation was usually of by one or two degrees. As such, we found that to engage in Exquisite Fabrication, improvisation worked together with exploring and understanding how the machines we use work to make the best use of the capabilities of each machine. Rather than pushing towards the technological solution, the tool is used as much as it is needed.

The area or volume in which each machine can operate is different and machines treat their work envelope differently. 3D printers are rather straightforward in this respect, they have a set volume they can work in, always building up in layers from bottom to top. Scaling up the size of a printed object can be achieved through strategies like modularity. Digital embroidery machines present different challenges. While they are limited to a maximum sewing area, it is possible to reposition the material in the embroidery frame to overcome this limitation. When deciding on doing an operation with a machine, you must work within its workable area or seek viable strategies to overcome its limitations. In Exquisite Fabrication, this also means you have to investigate what your material sample is/does to inform what you want to make next.

7.3 Trade-offs

Every engagement with a tool, a machine or a collaborator comes with its own risks and promises. The trade-offs inherent in every system is the one aspect we as designers appear unable to anticipate. The MOAS system generated a number of trade-offs between efficiency and flexibility and precision, and in turn offers suggestions for best practice.

Our proposal of Exquisite Fabrication aims to foster exploration and cross pollination of techniques. This proposal builds on ideas of corresponding with the materials/ tools [14] and intentionally drifting in the design process [15]. We propose using the moments of turn-taking between machines or people to be anchoring points to enable drift. Steps should not be fully planned in advance, but instead, be open to emerging opportunities and improvisation. This way, the concrete possibilities of a step can inform the possibilities for the next.

While working with MOAS, we found the process of being open with the sample and the machine to be a trade-off between precision and flexibility. When aiming for precision, the whole process needs to be thought through. The result might be the most accurate and polished. However, the process is carried out with the expectation of a specific result as a measure of success, leaving little chance for the possibilities that arise along the way to be taken into account. When engaging with Exquisite Fabrication, the results of every step can become the starting point for consideration for new directions. To allow this process to happen, design researchers also trade control over their outcomes for discovery by letting others and machines offer new opportunities and starting points, like in the game Exquisite Corpse. To add something to a sample, the only thing a maker or machine needs to know is where to start. What comes after is not of importance for the current step, decisions can be made on the fly. We found this to still be true in our design case, even though we pre-determined which actions we would perform. In our case, we wanted to be as precise as possible about the alignment of steps to make a functional actuator that would be more reproducible than those poured by hand. The planning ahead of how each step would be carried out was not important. Each maker had the freedom to choose which machine they would use and how they would incorporate MOAS in its use, letting the sample, the software and the machine inform the way.

8 CONCLUSION

With this project, we have attempted to create a common language between machines and makers to practice turn taking, while playing a game of designerly Exquisite Corpse. The resulting process allows each machine and maker to take turns by building on the actions carried out previously. This aims to foster collaborative exploration and cross pollination by deliberately breaking up the process between machines/makers. As we have described here, the collaboration between people and systems are both technical and cultural in nature.

This means that alongside the design and distribution of a system for the technical coordination of work, it is of equal importance to provide a cultural narrative for these collaborations. A distant collaborator does not only need to know what work must be done, but also perceive that the turn taking is explicit, meaning that the potential risk and outcomes are shared and understood. As such, we aim for these systems to allow a shared understanding of "what is at hand". Rather than imagining a full plan of operation and executing it, the breaks of each turn should invite makers to ask the sample material and the machines they are using what kinds of processes can be done next. We experienced and explored this first hand through the making of our soft-inflatable sample as a design case. To complete this Embroidered Inflatable, we moved the sample between three different machines to complete four steps of fabrication. Through this process we showed the possibilities that arise when allowing turn-taking between machines while letting each machine be itself. We discussed the trade-off between precision and exploration as well as the implications of collaborating with multiple machines and makers on the same sample. Entering this kind of process in collaboration with other makers required building trust in the expertise of each other, which supported us in letting go of control over the outcomes during the turn taking process. Based on our experience, we believe that engaging in Exquisite Fabrication can be a fruitful exercise or approach for designing bottom-up processes, allowing decisions to be made based on the real implications of the production systems we have at hand and facilitating the creation flexible systems of production.

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6 Making as a traveler

"If emergence is underrepresented in reports and even in practice, then at best this leads to misrepresentations of practice-based design research, and at worst to a constraint on designers' ability to use their skills. A better appreciation for emergence would benefit both research practitioners with a clearer view of how their work can count as research, and the wider community in engaging with practice-based design research."

Gaver et al. [29]

This chapter presents the last publication of the collection that forms this dissertation, the Portfolio of Loose Ends. Presented in a pictorial format, this publication extends the notion of making as travelers by reflecting on the implication of putting this approach into practice in the WS lab and providing practical strategies for its implementation. The Portfolio of Loose Ends is an exploration of how to communicate material-driven research in a way that supports a traveling approach. It included design memoirs, (technical) documentation, and embedding vector files into the publication itself. The design memoirs unpack the complex inner workings of the lab and how relationships between co-inhabitants might develop in this environment. Who were the people in the room, which machines were running, and which samples were on sight all had an impact in the making of the four samples presented in the pictorial. The format of documentation proposed is a combination of different reporting styles that contextualize the sample within a project (journey) and detail its technical and experiential qualities (technical specifications and on the floor) so that the sample can be appreciated on its own. Together with these practical strategies, this pictorial further explores travelling as a metaphor for explorative making practice by introducing two key concepts to the travelers' approach: loose ends and fellow travelers.

Loose ends are successful samples that are not suitable to the main inquiry of the present design research process, but that under certain circumstances can become starting points for new investigation lines. It is an attempt to highlight the potential of samples being analysed both within and outside their contexts of creation, first identified in chapter 3. The idea particularly evolved from the dialogue between weaving and embroidery, shown in chapter 4. One of the samples continued to re-emerge in my conversations with Milou (Figure P). According to her in one of our sessions,

"This was a mistake, this was not supposed to happen, but it looks really nice. It was like this because the warp yarns are shrinking. So that's what I wrote down. This mistake is actually really nice. It's happening here as well... it took us a while to realize that it was the warp

Figure P. “Mistake” sample that supported thinking of the concept of loose ends

yarns, not weft yarns, that were doing this.”

This sample did not shift the direction of her process, but it was turned into a loose end to be revisited in another journey because of the time she invested in documenting and analysing it. I experienced similar situations in the process of the Embroidered Inflatables and in the process of samples of the Portfolio of Loose Ends, in which certain samples and ideas were pinned for a future revisit.

The figure of the ***fellow traveler*** was first mentioned in “Becoming Travelers” (section 3.4) in the literal sense, as a person in the train who might “occasionally reach over and examine our degree of craftsmanship, turn the cloth over, and approve or sigh” of the embroidery work we would take with us in our commute to and from work. The recognition that a continuous process of experimentation could be informed and enriched by attuning ourselves with the space in which we work and the people around us (even if just in passing) led to simple rules of engagement for making as travelers in digital craftsmanship: make time to make things, collaborate with materials/people/ideas and be systematic about documentation. These rules are simple but allow us crafting things in collaboration with the whole lab, provided we nurture strategies and practices to revisit samples as starting points for new journeys. In this chapter, the figure of fellow traveler is presented as metaphor for a potential collaborator. Fellow travelers are the human and non-human collaborators that co-inhabit our working timelines. They may join us in (part of) a journey without necessarily sharing our same goals and outcomes. It is a different view on collaboration than, say, co-creation in which collaborators come together to achieve a common goal.

Together with introducing these two concepts, the Portfolio of Loose Ends builds on ideas and strategies explored in previous chapters to better articulate traveling as a metaphor for making. To support a process of looking backwards, forward and to the sides, we need strategies to make previous work remain actionable and open to revisit. Previous chapters proposed documentation and archiving as key activities to enable this process. This means rethinking what we consider worth putting down 'on paper', how we do that, and how we connect it to future work. In chapter 2, some of the work done at the Wearable Senses lab was analyzed through a practice of "looking forward and backwards" that allowed us to formalize the shared understanding of digital craftsmanship of our lab. In chapter 3, this idea of looking back appeared too as a practice need to join 'the search for other places', which requires sometimes looking at (old) things with new perspectives, and in the form of revisiting samples in chapter 4. Chapter 5 highlighted serendipitous encounters as drivers for collaboration, which can occur when we 'look to the sides', open to collaborate with the socio-technical system of production we are in. By making explicit how co-presence in the lab can play a role in emergent-friendly processes through the design memoirs, this chapter supports expanding how a focus on samples enable new opportunities for making with our socio-technical systems of production. At the same time, by sharing the technical specifications and vectorial files as open invitations to a broader audience for traveling with these samples, this chapter also proposes the dissemination of documentation about our material samples as an alternative to physical co-presence, turning its logic inside out. The approach to turn taking used in Exquisite Fabrication (section 5.2) can be seen as an example of how these asynchronous collaborations can take place, but other approaches can and should be explored. In any case, my hope is that the ideas proposed in this pictorial inspire others to continue to seek for new ways to articulate practice into theory in our publications.

6.1 Portfolio of Loose Ends

Published as

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ABSTRACT

Digital Craftsmanship, and other explorative design research practices using digital fabrication, depend on sample making and material exploration. Rather than describing a method of making use of the information present in samples co-inhabiting a timeline, this pictorial reports on the loose ends that may emerge out of the main journey, when taking a traveler's approach to making. By loose ends, we mean successful samples that are not suitable to the main inquiry of the present design research process, but that under certain circumstances can become starting points for new investigation lines. We describe four examples of such loose ends and introduce the concept of fellow travelers as a metaphor for describing the process of co-inhabiting a timeline and a journey while ultimately having diverging goals and outcomes.

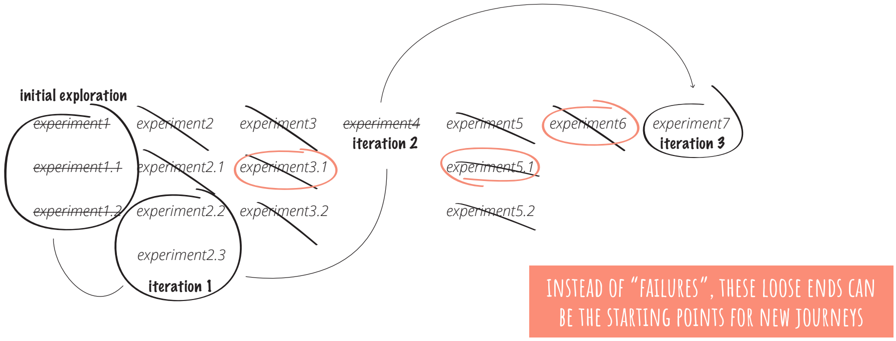
KEYWORDS

Digital Craftsmanship; Research through Design; Digital Fabrication; Design Processes; Sample Making

FROM FAILURES TO LOOSE ENDS

The field of Digital Craftsmanship has been developing at the intersection between maker culture, HCI and design research. As a result, sample making is emerging as a key area of design research [14]. In this context, sample making is a fast-paced process of thinking-through-making which investigates new materials, emerging technologies, and ways of working with and through digital fabrication machines. The deep engagement with making practices, with digital machines and with the knowledge produced through their creation process have prompted a departure from a utilitarian approach to samples and prototypes, towards more exploratory ones. This caused designers to seek theory that support more multiplicity in design work [18,22,32] and bottom-up ways of working from the capabilities of machines and properties of materials [1,2,5,10,17,24,28,29].

Making samples can be seen as is a process of itineration [22] in which each sample is both a consequence of the previous one and preparation for the next. Rather than always incremental, each step in a sample making process can explore different possibilities of fabrication and, as consequence, each sample can embody different qualities. Furthermore, making itself is a multifaceted practice in which knowledge is distributed across the whole socio-technical system (meaning the people, the machines, the software, the materials, and the outcomes) of production. Each sample offers potential insights related to application, programming, skill, technique, material and so on. Making sense of all this knowledge and appreciating the potentials of each sample is difficult, which is reflected in the reporting of such processes. Even in journeys that are not goal- or solution-driven, the difficulty of reporting material-driven processes often leads designers to describe design journeys from the perspective of the final sample as a reached goal. In order to build a clear narrative of how a final outcome is successful, samples



or experiments created along the process that directly contribute to this success are more carefully described while others are often unaccounted for or summarized as part of an exploratory phase [15]. This way of folding "failures" into iterative cycles that lead towards a successful narrative partly stems from a solutionist and functionalist standard [21].

Design researchers have been exploring alternative notions to failure in design research and practices to deal with them [3,6,8,19]. Rather than discarding such experiments, Becoming Travelers [11] proposes that we look at making as an activity akin to traveling by seeing them as opportunities of new journeys.

Traveling can be used as a metaphor for explorative practice in design projects. In both project and travel, a set of constraints, curiosities and motivations support our decision-making process over the journey. Unlike a goal-oriented design process, when we travel, we tend to allow emerging opportunities to affect our plans. If we see or learn of a cool place to visit, we spontaneously change our plans or we make plans to (re)visit another time. We take photos, and we talk about these places to friends. Why not do the same with our samples?

Making as travelers

Making as travelers requires us to observe what is at hand: what are the actors of the sociotechnical system in which I am situated? How can I collaborate with them? It also requires us letting go of strictly pursuing goals or accepting detours for the sake of emerging opportunities. We would like to propose that loose ends are the unexpected samples we make when we create time to collaborate with the sociotechnical system. They could be the "failures" of a project in that they are not suitable to the main inquiry of the present design research process, but also the quick explorations or serendipitous encounters with other makers or ideas co-habiting a timeline. We would like to propose turning so called 'failures' or (porous) dead ends [3] into loose ends, meaning samples that can be revisited and carried over to new journeys, as a strategy for staying committed to our processes without losing the chance of finding the other places.

In this pictorial, we explore the notion of loose ends as digital craftsmanship outcomes that emerge from serendipitous collaborations with people, materials, and opportunities. We illustrate this through four samples as cases of such collaborations. We present these samples and the stories behind their making as contributions to the field of Digital Craftsmanship with 1) reflections about the implications of this way of working, 2) recommendations for how to nurture explorative making and 3) a proposal for a way of documenting samples so they can be revisited within and outside the design processes in which they were created. As a result, we propose that the practice of sample making as travelers can be extended with the notion of fellow travelers as a co-inhabitant of a timeline who has diverging goals for a journey.

This pictorial also proposes a new way of sharing and publishing sample work in the pictorial format itself by embedding vector files into the layering of its digital pages. Through these files, readers are invited to become travelers and to take our loose ends forward into new journeys. Building on the growing interest in sharing more of the knowledge revolved in making (and making things well) and exploiting the potential of physical samples [9,15,20,23,30], we propose this as a way of using our publication platforms as actionable archives that are independent of external links or supplemental materials. We expect that through the telling and reflection of these stories, we can support opening opportunities for cross-pollination through samples, which in turn can lead us in the direction of turning our labs and communities into more flexible and permeable systems.

MEETING FELLOW TRAVELERS

The samples described here are all explorations created in opportunistic collaborations alongside other more goal orientated design processes. The main intention was staying lost in the thick of making and letting one collaboration lead to the next. The process of sample making followed the simple rules from Becoming Travelers [11]: create time to make things; collaborate (with people, ideas, tools and materials); and be systematic about the documentation.

In practice, this meant that time was created in between other activities to continuously make, searching for loose ends or new opportunities. This process was driven by collaborations that happened organically by working in person in our lab. This lab is populated by a community of students, researchers and occasional industry partners gathered around interests of emerging technologies and new ways of engaging with production systems. Labs are complex environments where the people working next to each other, the samples they were working on, the other machines in the lab, the materials that were available, are all prospective collaborators.

Our main finding from this process is the identification of the figure of the fellow traveler. The fellow traveler is a metaphor for describing the process of co-inhabiting a timeline and a journey while ultimately having diverging goals and outcomes. As a fellow traveler, you share the road for a bit, then separate when your paths diverge. In the context of making as a traveler, this means fellow travelers are people, ideas and machines that are available for new collaborations. In this pictorial, we focus on the processes of making with human fellows and the samples they were working on with at the time.

THE PORTFOLIO

In the following section, we share stories, told in first person, and the documentation of four samples created during an itinerative [22] processes of making as a traveler and meeting fellow travelers. These samples were selected as exemplars of different ways of traveling to support our twofold intention to reflect on the potential of this way of working and to contribute with an open invitation for future travelers to take them over into new journeys. For each of the samples, we detail how the collaboration took place and include its corresponding documentation.

Documentation form

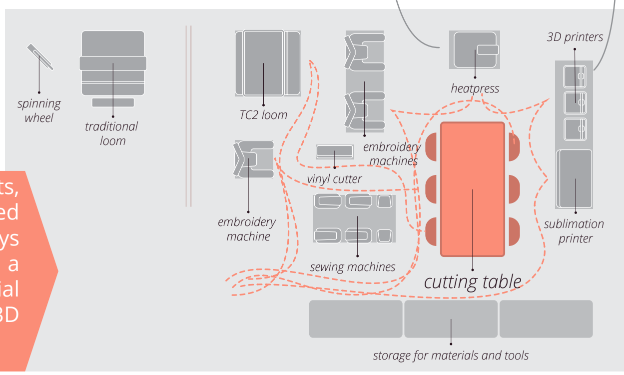
The documentation form used to document the samples was informed by existing publications documenting sample making processes and insights from the wider area of research on documentation [7,15,26,27]. We see such documentation as an actionable tool for new developments, and documenting as a lively process of reflection-in-action that can be refined over time. The form combines reporting styles from industrial and textile designers. It seeks to make explicit the data that would normally be distributed between the digital file, the digital fabrication machine, and the designer. In doing so, it also aims to facilitate revisiting samples both within a design journey and as a stand-alone sample. The form we use contains four main sections: general header, journey, on the floor and technical specifications. The fields "keywords" and "highlights" are meant to further support re-visiting samples as starting points for new journeys by envisioning searchability within an archive and giving clues for what should we know or remember about a sample to take it over into a new making process.

PICTORIAL AS AN INVITATION TO TRAVEL ALONG

This pictorial takes the form of an open invitation to travel along with us, making use of the documentation of the samples shared in the following sections. To enable this, each sample is presented through two pages. The first page takes the form of a design memoir [4]. It narrates the story of how the collaboration that led to a sample happened from a first-person perspective [31]. Annotations on the page also help to point out technical specifications directly on the embroidery designs of each sample, used as background image. This is a layered PDF. A vector file of the base design of each sample is included as an underlayer. On the right side of the page, the stitch view of the sample indicates what the embroidery design should look like. As a fellow traveler, feel free to extract and explore with the vector designs integrated into this pictorial as under layers. After editing it as you wish, export it as an .emf file to open it into an embroidery digitizing software to convert it into a stitchable design. In the second page, you can find the form used to document the process containing the stitch design details and other information about the sample.

THIS WORKFLOW WAS TESTED USING ADOBE ACROBAT, ADOBE ILLUSTRATOR AND PE-DESIGN 11

THE BEST WAY WE FOUND TO EXTRACT THE VECTOR FROM ADOBE ACROBAT PRO: OPEN "EDIT PDF" > (HIDE PICTORIAL LAYER TO) SELECT THE VECTOR > CLICK IN "EDIT USING" > "OPEN WITH" ILLUSTRATOR



The lab is populated by a community of students, researchers and occasional industry partners gathered around interests of emerging technologies and new ways of engaging with production systems. The lab houses a combination of domestic, semi-professional and industrial machines, including a range of digital machines like 3D printers, a TC2 loom and digital embroidery machines.

LIGHT EMITTING EMBROIDERY

My fellow traveler in this journey was a visiting PhD with expertise in weaving and light emitting textiles. She devoted a good deal of her time in our department learning how to get started with the TC2 weaving loom that had just arrived in the lab. Next to that, she also used our smaller hand looms to create samples related to her work with polymeric optical fibers (POF) fabrics. At the time, I was working on embroidery-based soft actuators [16], and I was pursuing a way to improve the casting process of the silicone on the embroidered fabric.

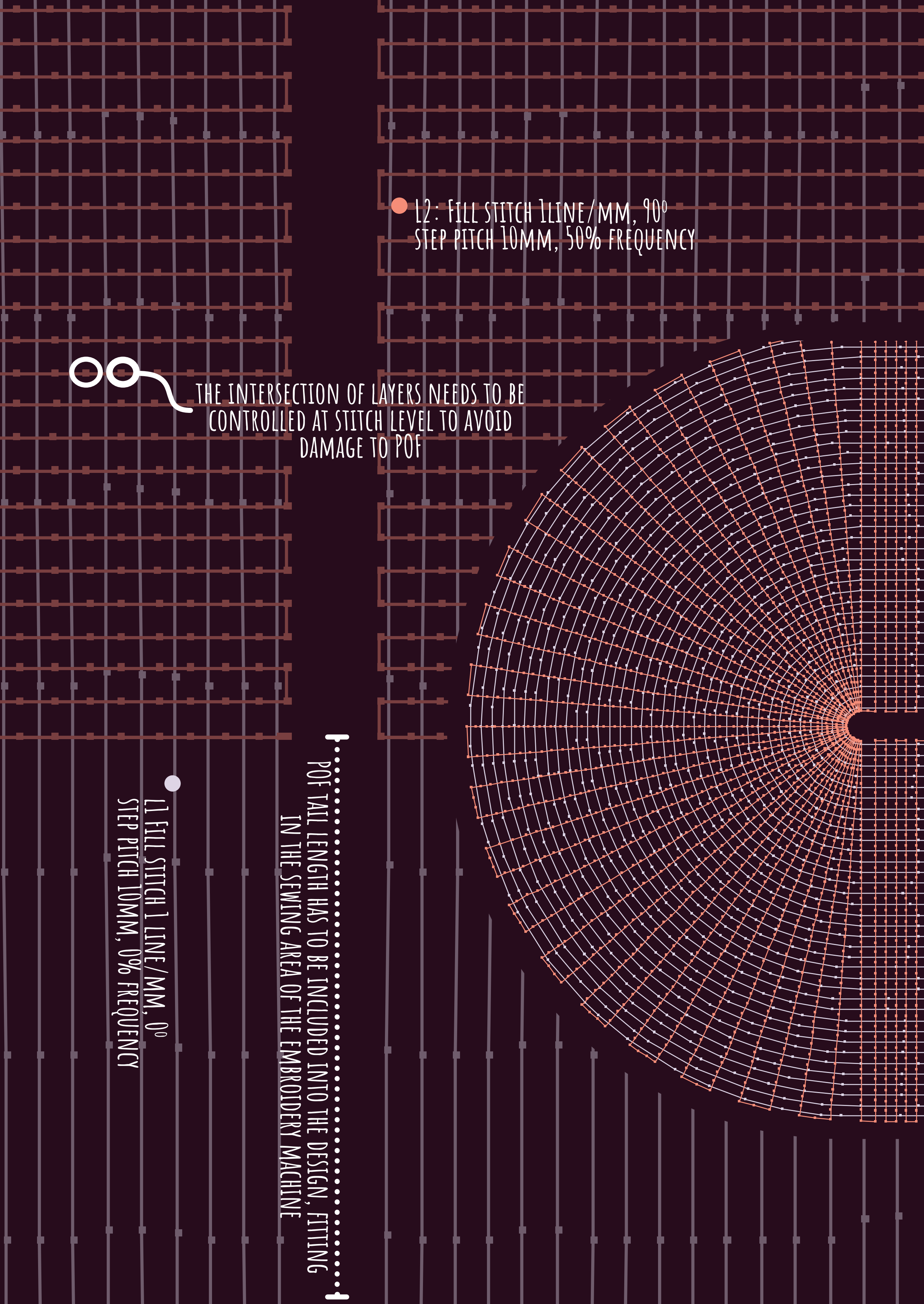
While spending a lot of time together in the lab, we had the opportunity of sharing a lot about the technical features of the crafts we used to create interactive materials. She explained to me that one of the main limitations of working with the POF fibers was that if they got too bended or damaged during processing, they could no longer emit light from the point of breakage onwards. This was the main reason, according to her, for it not being used in other techniques such as machine embroidery. I became interested to explore whether it could work, and she offered me some of the POF and the LED device she had been using to test her samples.

As obvious as it sounds, being open to (and making the time to) collaborate with others or starting experiments with completely new materials is not trivial. Having a person in the lab with the material and the knowledge (as well as the willingness to share both) made it possible for me to ask the questions I would otherwise not ask about the technique I was investigating: can digital machine embroidery combined with chemical embroidery technique offer advantages or different opportunities for creating light emitting fabrics compared to those offered by weaving?

As a result, five light emitting embroidered fabric samples were created. To reduce the chances of damaging the POF during processing, the fiber was used in the bobbin and the stitch length used was long, reducing the number of times the needle could hit it. The first three samples aimed at getting at the basic technique: how to program, stitch and what post-production would the sample need to emit light. The other two explored freedom of routing to create shapes that weaving could not as easily create.

The ends of the POF need to be collected in a bundle for the light effect to be visible. In the case of embroidery, the ends need to be included in the design within the active area of the machine, meaning that the technique is limited in the scalability of the sample. Having said that, the samples created show promise in creating shapes, such as arcs, with the integrated optical fibers. The embroidered textile with integrated optical fibers behaves similarly to a woven structure, particularly a leno weave. When carefully programmed to avoid overlapping stitches, the points in which the needle lightly damages the fiber create the effect of bright light dots on its length.

LONGER STITCHES ON LAYER 1 AVOID DAMAGE TO POF


L2: FILL STITCH 1LINE/MM, 90º
STEP PITCH 10MM, 50% FREQUENCY
THE INTERSECTION OF LAYERS NEEDS TO BE CONTROLLED AT STITCH LEVEL TO AVOID DAMAGE TO POF
POF TAIL LENGTH HAS TO BE INCLUDED INTO THE DESIGN, FITTING IN THE SEWING AREA OF THE EMBROIDERY MACHINE
L1 FILL STITCH 1 LINE/MM, 0º
STEP PITCH 10MM, 0% FREQUENCY

Project name	Light Emitting Embroidery
Project description	Exploring how to embroider light emitting fabric using POF
Sample name	20200205_POF_4
Keywords	POF, light emitting, machine embroidery, weaving

Journey

Setup

Goal	Explore the implications of making light emitting fabrics through digital machine embroidery patterns
Process & Approach	Create a two-layer construction to create a substrate similar to a woven textile

Design process - end of the day

Insights	The light shines towards the ends of the substrate (meaning most fibers were not damaged in the process)
Next steps	all-in-the-machine: explore connectting the light emitting fabric to a an embroidered LED and soft circuit OPEN INVITATION FOR FELLOW TRAVELERS

Technical specifications

Hardware

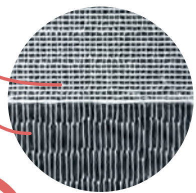
Machine	Brother PR1050x
Machine setup	POF at the bobbin (L1); polyester at the bobbin (L2)
Machine settings	400 spm (L1); 1000 spm (L2)
Materials	POF, polyester thread, water soluble film (solvy 80)

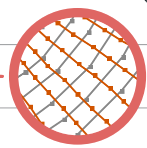
Software

L1: Fill stitch 1line/mm, 0o – step pitch 10mm, 0% frequency

L2: Fill stitch 1line/mm, 90o – step pitch 10mm, 50% frequency

Manually (re)move stitches from L2 that coincide with L1





Finish & Post-production

1. Wash away stabilizer
2. Separate and expose the POF
3. bundle POF ends together and cut for flat contact area

On the floor

Outcomes

The sample An embroidered substrate similar to leno woven structure which emits light **Properties & Behavior** The sample is flexible, but holds shape **Technique** Embroidered on water soluble film. Sewing was done in two stages. The first had the optical fibers at the bobbin, the second used conventional polyester threads.

Evaluation

Method	1p.p. explorations manually manipulating light source at the end of the fibers
Insights	light is brightest in inner arc; as contact of the fiber/LED is key, moving the light source creates a dynamic effect

Highlights

The frequency of stitches was manipulated to prevent damaging the fibers during the sewing process – especially for organic shapes, automating it would require control on stitch level

TUNABLE LACE

The Tunable Lace originated from a teaching partnership with a faculty professor passionate for generative design. For a few years, we shared a lecture about creative coding and digital machine embroidery. In these lectures, he approached Digital Craftsmanship from the generative design side while I did it from the machine side, creating a feedback loop between them.

When I began to explore the potential of revisiting samples, I went through all the samples made for the project I was working on [16], looking for loose ends. The project consisted of a series of samples that investigated different possibilities of creating soft actuators based on digital machine embroidery. As part of this series, I created an embroidered wrist-worn wearable that included six soft actuators meant to give directional cues to the body through push. Due to its complex outline, filling the design with a standard net fill stitch caused an excessive repetition of stitches on the edge of the design, causing the water-soluble film to break. This was a problem as the film was needed for creating the air chambers of the actuators during the casting process. To mitigate it, I recreated the grid in four separate layers, each with a different sewing direction.

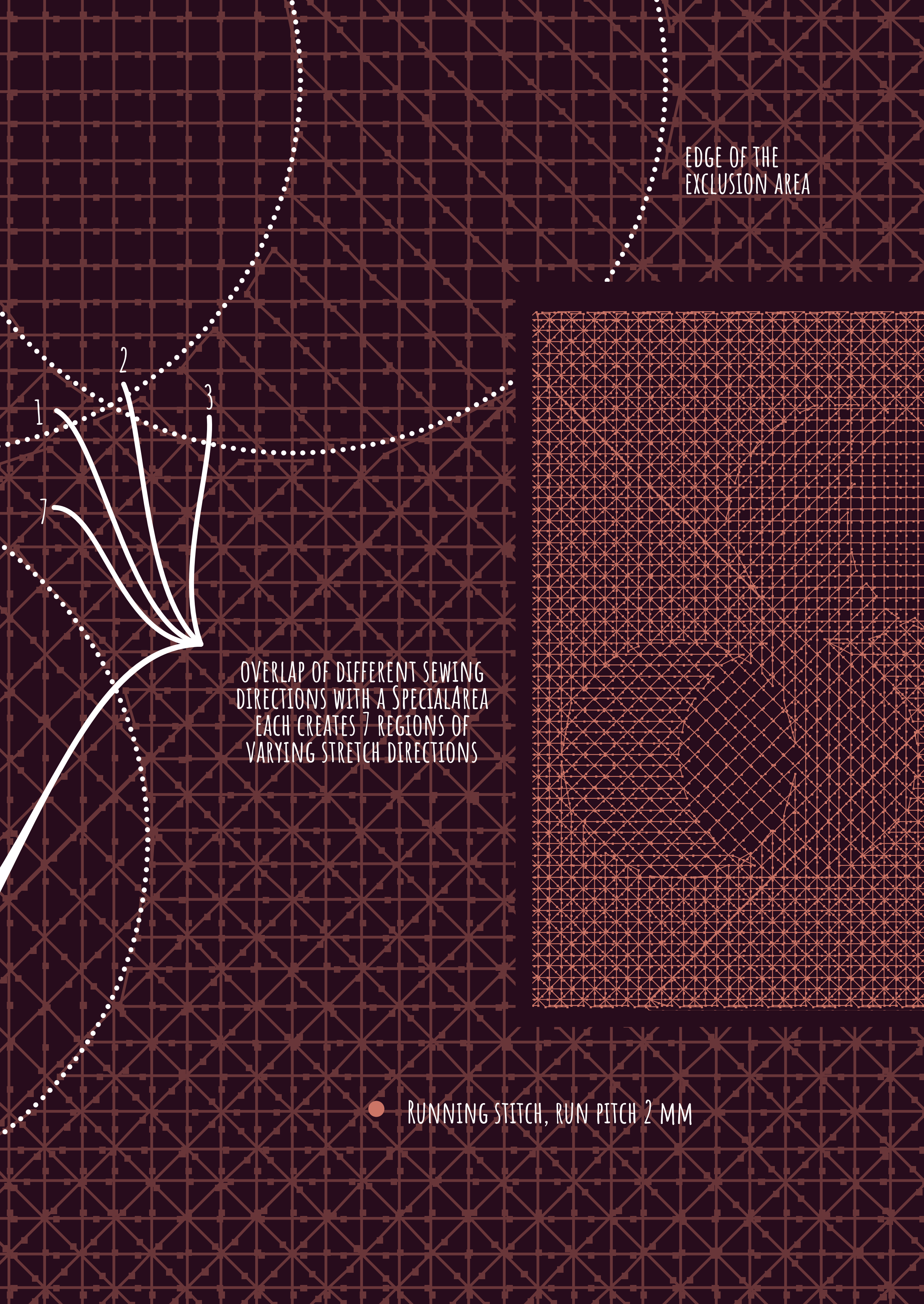
One day, my fellow traveler was embroidering designs based on a pied-de-poule tessellation while I was integrating the soft actuators into a garment. We talked about our designs and the issues I encountered before. A few days later, he called me to show a program in Processing he created to automate the process of making the layers of the net. He demonstrated it through an image he was already using in his work. The program worked by scanning a black and white image then generating the grid pattern to fill it with the rule of avoiding traveling through the edge of the design.

By watching the routing created by the program being stitched, another loose end of the original sample emerged as a possible new direction: generate areas of variable properties to create stretch to better support fit on the body, like a fully fashioned embroidery. For that, the code was updated to allow for exclusion areas in the fill of each of the four layers. The new sample created from this featured seven different types of regions within the fabric, each with different stretch directions. Taking it further into the direction of a fully fashioned embroidery remains open for revisit.

5

4

6


EDGE OF THE
EXCLUSION AREA
2
1
3
7
OVERLAP OF DIFFERENT SEWING
DIRECTIONS WITH A SPECIALAREA
EACH CREATES 7 REGIONS OF
VARYING STRETCH DIRECTIONS
RUNNING STITCH, RUN PITCH 2 MM

Project name	Tunable Embroidery
Project description	Exploring variable properties of embroidered fabrics
Sample name	20200219_TE_ SpecialAreas 02
Keywords	Processing, variable properties, stretch, generative design

Journey

Setup

Goal	Experiment with generating embroidered fabric with variable properties through Processing
Process & Approach	Create different overlaps of sewing directions (horizontal, vertical, diagonals) with exclusion areas (SpecialAreas)

Design process - end of the day

Insights	The contours of SpecialAreas are less defined than SpecialAreas 01, creating a smoother gradient between fills
Next steps	Explore variations of the SpecialAreas through overlaps, different polygons and sizes – explore gradient transitions

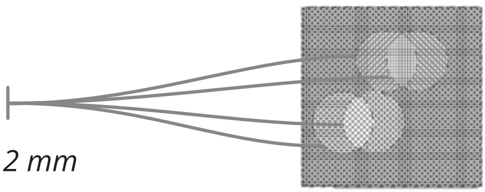
Technical specifications

Hardware

Machine	Brother Innov-is 750e
Machine setup	standard
Machine settings	650 spm
Materials	Sulky 40 (1071), Bobby, water solluble film (Solvy Ultra)

Software

DY=8; DX=8; DDY=16; DDX=16
SPECIALCONTOUR=14
specialArea1 (250,370); specialArea2 (165,370);
specialArea3 (370, 200); specialArea4 (285, 200)
[PE-Design] *Line sew type: Running stitch, run pitch 2 mm*



Finish & Post-production

Wash away stabilizer

On the floor

Outcomes

The sample An embroidered fabric with different stretch directions **Properties & Behavior** Fabric has 7 types of regions that allow for variable properties locally **Technique** Embroidered on water soluble film

Evaluation

Method	1p.p. explorations manually stretching the sample
Insights	The stretch is quite playful. Could potentially be used to create a sort of “fully fashioned” embroidered thing

Highlights

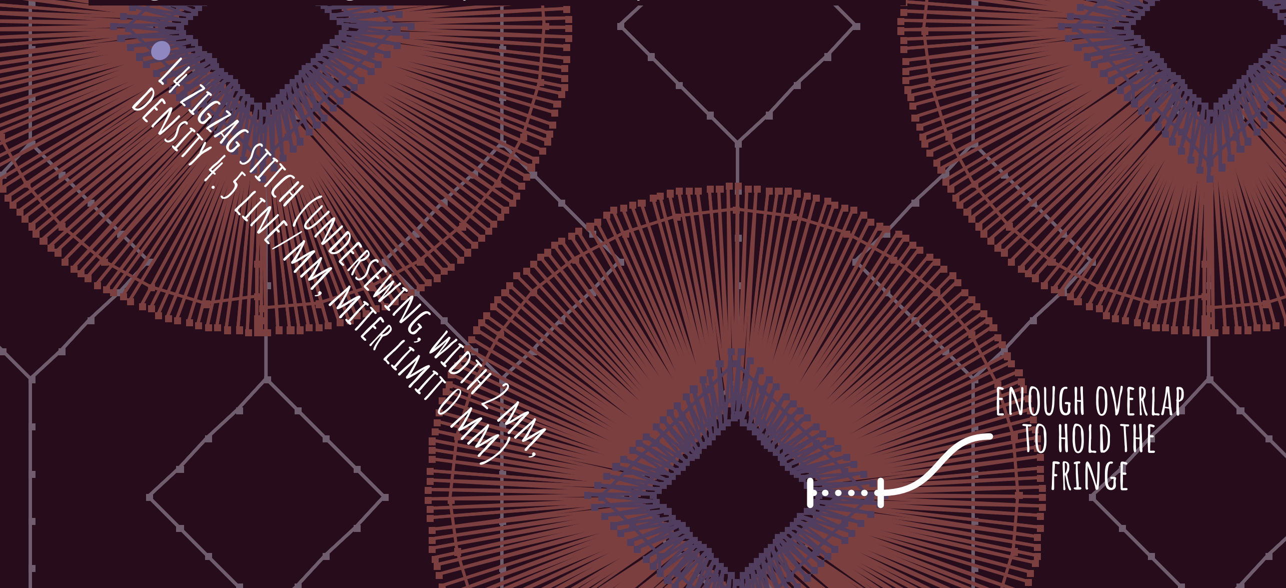
Contours of SpecialAreas are not too clear, making transitions between properties more subtle

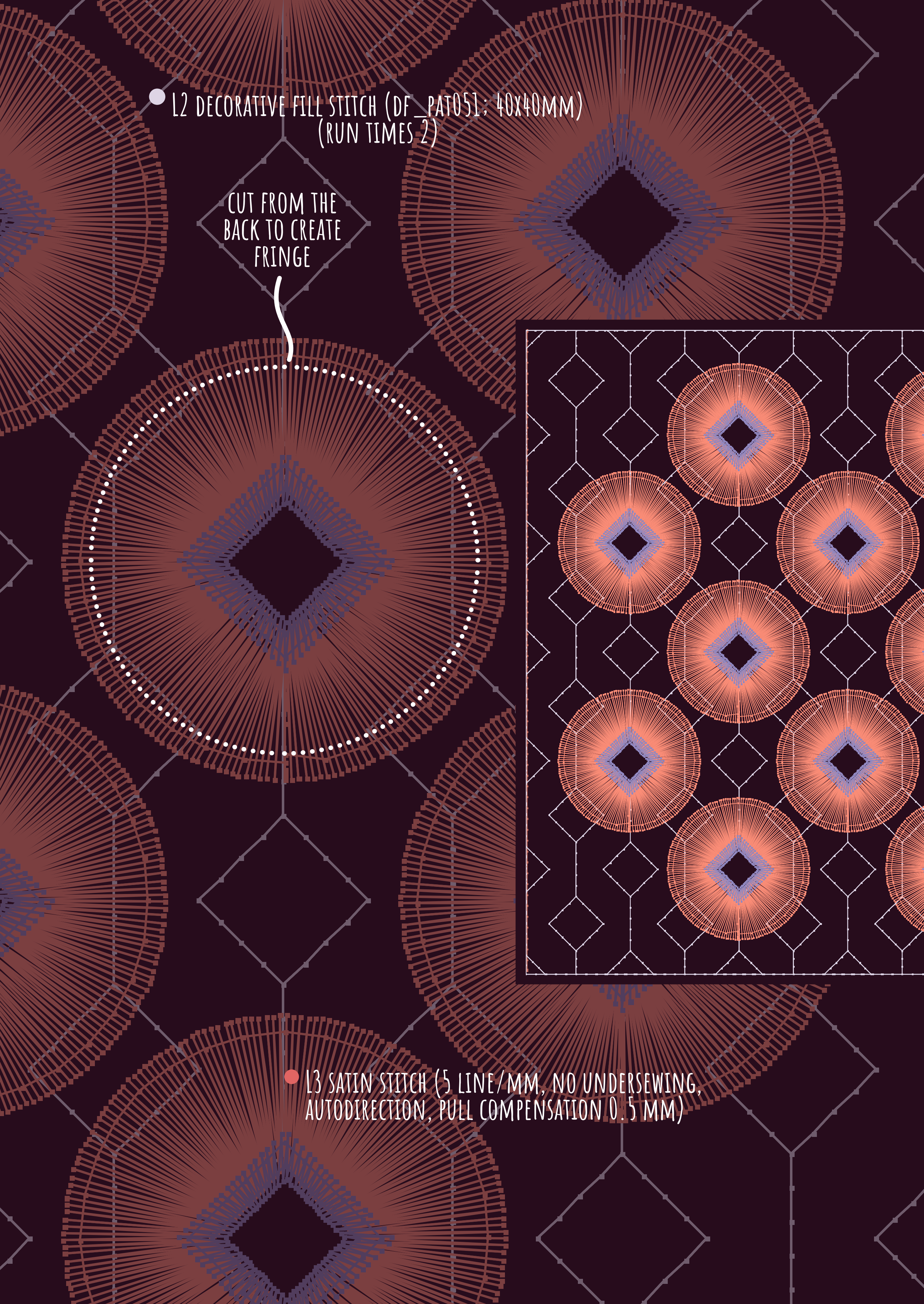
SUBLIME EMBROIDERY

The Sublime Embroidery started from a very serendipitous encounter at the lab. My fellow traveler was a bachelor student who was working on coloring the surface of 3D printed auxetic materials (materials that become wider in the transverse direction when stretched and narrower when compressed [25]) by using the heat of the extrusion to activate the color transfer from sublimation printing. While she was taking her work out of the printer, I was embroidering small samples in different colors to explore the relationship and impact of color in the embroidered fabrics covered by silicone. The finish of the colored 3D print was glossy and the deformation of the image when the sample was stretched was a great effect.

As she had also tried to create auxetic materials through digital machine embroidery before, we began to discuss what could be done to the embroidery files to improve them. The talk shifted to the possibility of mixing both experiments. She had the print ready to go and I had samples made in polyester that had both dense fill and open structure for us to see whether sublimation printing would work well on the embroidered material. An interesting finding was that the heat and pressure needed to saturate the color onto the embroidery also makes it quite silky smooth, giving it an extra shine.

For many reasons, this sample stayed as a loose end for more than a year. When I returned to it, I was already exploring fringes and floats by warping thread on a jig that fits the embroidery frame, then stitching over the warp to create a free-standing fabric. Forwarding ideas from both samples, I created a new sample to explore the combination of print with embroidery and the deformation of the image. The effect on the denser fabric was even shinier than in the small samples, making the yarn look almost metallic. The deformation of the sample, and consequently of the image, can happen both by moving the fringe around and by stretching the sample. In future revisits, I would like to further explore how the overlap of the embroidery design with the image of the print can complement each other.




L2 decorative fill stitch (DF_PAT051: 40x40mm)
(run times 2)
Cut from the back to create fringe
L3 satin stitch (5 line/mm, no undersewing,
autodirection, pull compensation 0.5 mm)

Project name	Sublime Embroidery
Project description	Exploring sublimation printing on embroidered fabrics
Sample name	20210928_SE_Floats_01
Keywords	Sublimation printing, floats, fringe

Journey

Setup

Goal	Combine techniques and explore interactive surface design possibilities, such as deforming the print
Process & Approach	Apply sublimation printing on embroidered fabric created by stitching on "warped thread" of add-on inner frame

Design process - end of the day

Insights	Image needs to be sharper; Fringe added volume and depth to print, but too short for image deformation effect
Next steps	Explore how image and embroidery can compliment each other; further explore image deformation/glitch effects

Technical specifications

Hardware

Machine	Brother Innov-is 750e + wooden frame add-on
Machine setup	Top and bottom thread the same + add-on frame warped
Machine settings	650 spm
Materials	Sulky 40, water solluble film (Solvy Ultra)

Software

PE-Design 11
L1: running stitch (run pitch 2 mm; run times 2)
L2: decorative fill stitch (df_pat051; 40x40mm) (run times 2)
L3: satin stitch (5 line/mm, undersewing, autodirection, pull compensation 0.5 mm)
L4: zigzag stitch (undersewing, width 2 mm, density 4.5 line/mm, miter limit 0 mm)

Finish & Post-production

1. Heat transfer print to embroidery
2. Wash away stabilizer
3. Cut away threads from L2 (from the back) to make fringe

STEP 3 COULD BE SKIPPED BY USING WASH AWAY THREAD IN THE BOBBIN OF L2

On the floor

Outcomes

The sample
An embroidered fabric with one way stretch
Properties & Behavior
Fabric has 3D effects, fringe can be disturbed but bounces back into place
Technique
Embroidered on water soluble film + heat transfered sublimation print image

Evaluation

Method	1p.p. explorations manually stretching the sample
Insights	The fringe and the floats have potentital to be two different playful ways to deform the image (brushing and stretching)

Highlights

Ironing the sample for the heat transfer enhances the shine of the thread; image needs to be very sharp for best results; L3 is important to keep fringe in place

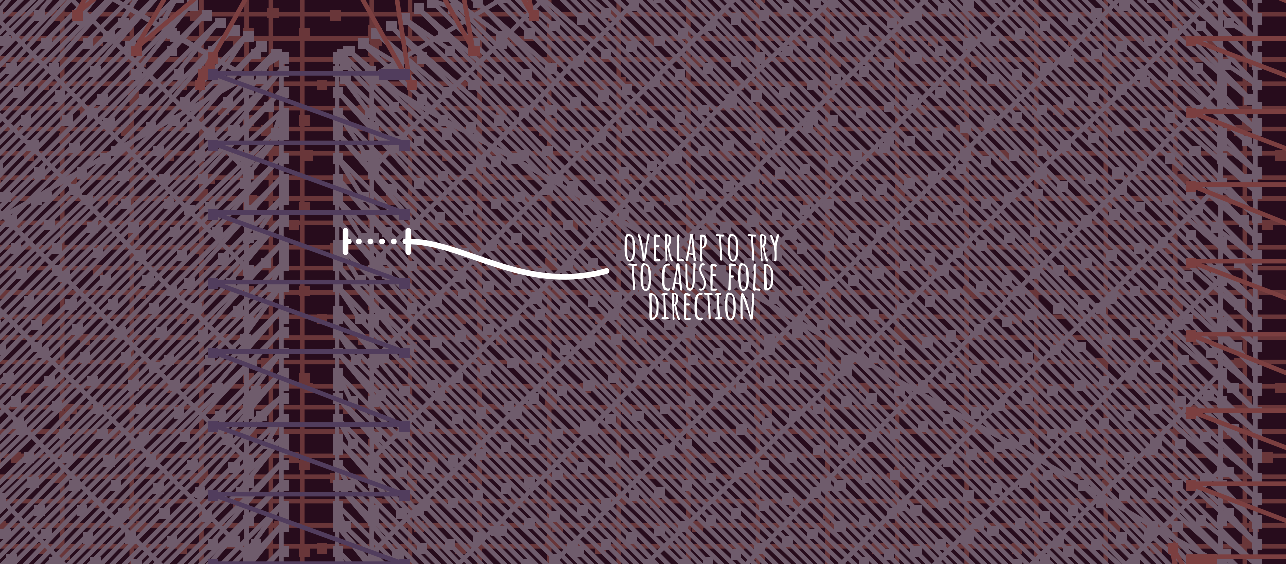
ORIGAMI EMBROIDERY

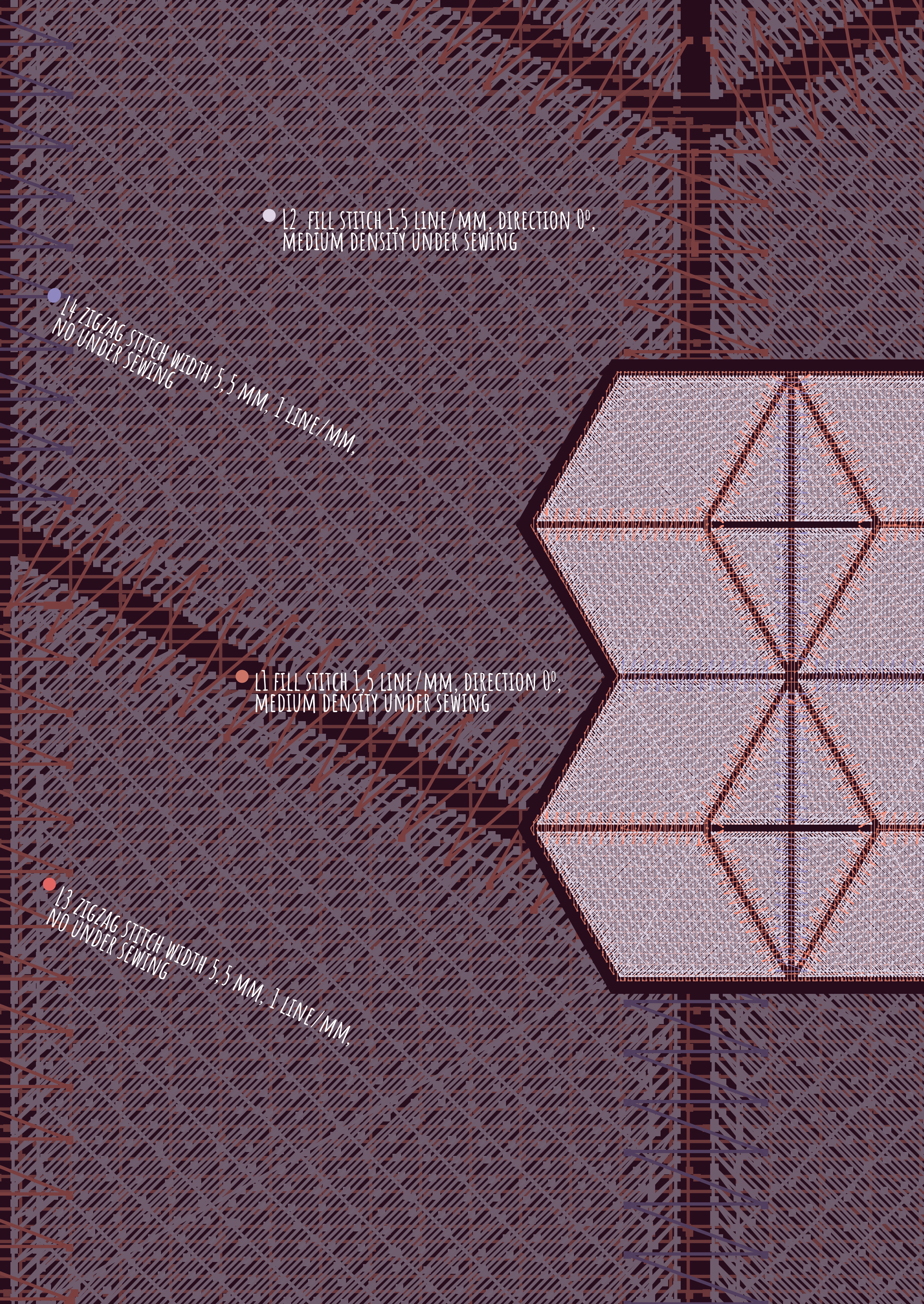
My fellow traveler in this journey was a post-doc specialized in wearable tech. She was beginning an exploration of origami technique applied to woven structures. Her goal was to define the fold as mountains or valleys based on the structure of the weave pattern, but to better understand the origami designs she began by folding and pressing origami designs made of a lightweight textile (organza). While she carefully ironed the organza in an origami pattern known as miura, I was working on the pattern of a top to investigate the potential challenges of crafting garments with integrated embroidered inflatables.

By going through our samples, we discussed turning flat textile designs into three-dimensional objects. Based on this conversation, I became curious to explore whether the fact the embroidery has a top and bottom thread could be an advantage to creating hinges with defined folding directions (mountains and valleys) in embroidered textiles. I explored this in four samples of three different designs.

The first three samples have variations in a) the construction of layers of the textile, b) the proximity between the faces of the miura pattern, c) the properties of the lines the connect the faces and d) the uses of the shrinking yarn. The fourth sample is the same design of the third sample, but made in monofilament thread which holds the memory of the folds better than polyester.

The third design was made in three layers: a base layer of the overall miura shape open sewn in low density, a second layer of separate objects forming the faces of the miura pattern and a third layer of lines in between the separate objects. The base and first layer made sure that there were well defined faces of the miura and hinges in between them. The third layer was where I attempted to define the direction of the fold by using shrinking yarn (30% shrinkage). A yarn of higher shrinkage and further exploration of how to implement it would be needed for the mountains and valleys to be programmed into the textile itself without the aid of post-production.




L2 FILL STITCH 1,5 LINE/MM, DIRECTION 0°, MEDIUM DENSITY UNDER SEWING
L4 ZIGZAG STITCH WIDTH 5,5 MM, 1 LINE/MM, NO UNDER SEWING
L1 FILL STITCH 1,5 LINE/MM, DIRECTION 0°, MEDIUM DENSITY UNDER SEWING
L3 ZIGZAG STITCH WIDTH 5,5 MM, 1 LINE/MM, NO UNDER SEWING

Project name	Embroidered Origami
Project description	Exploring hinges, mountains/valleys in embroidered fabrics
Sample name	20200223_EO_Miura03
Keywords	Processing, variable properties, stretch, generative design

Journey

Setup

Goal	Explore whether it is possible to define fold and their direction (mountain/valley) based on machine embroidery
Process & Approach	Layered strcuture of fabric + use of shrinking thread (smocking thread) on the top and bobbin of folding lines

Design process - end of the day

Insights	The direction of the folds was not clear, but the fabric holds shape very well when folded by hand/ironed
Next steps	Loosen tension of bobbin so the length of shrink yarn is the same on both sides. Look for yarn of higher shrinkage rate

Technical specifications

Hardware

Machine	Brother Innov-is 750e
Machine setup	L1, L2 Standard; L3 shrinking thread (top); L4 shrinking thread (bottom)
Machine settings	650 spm
Materials	Sulky 40, Bobby, water solluble film, smocking thread (30%)

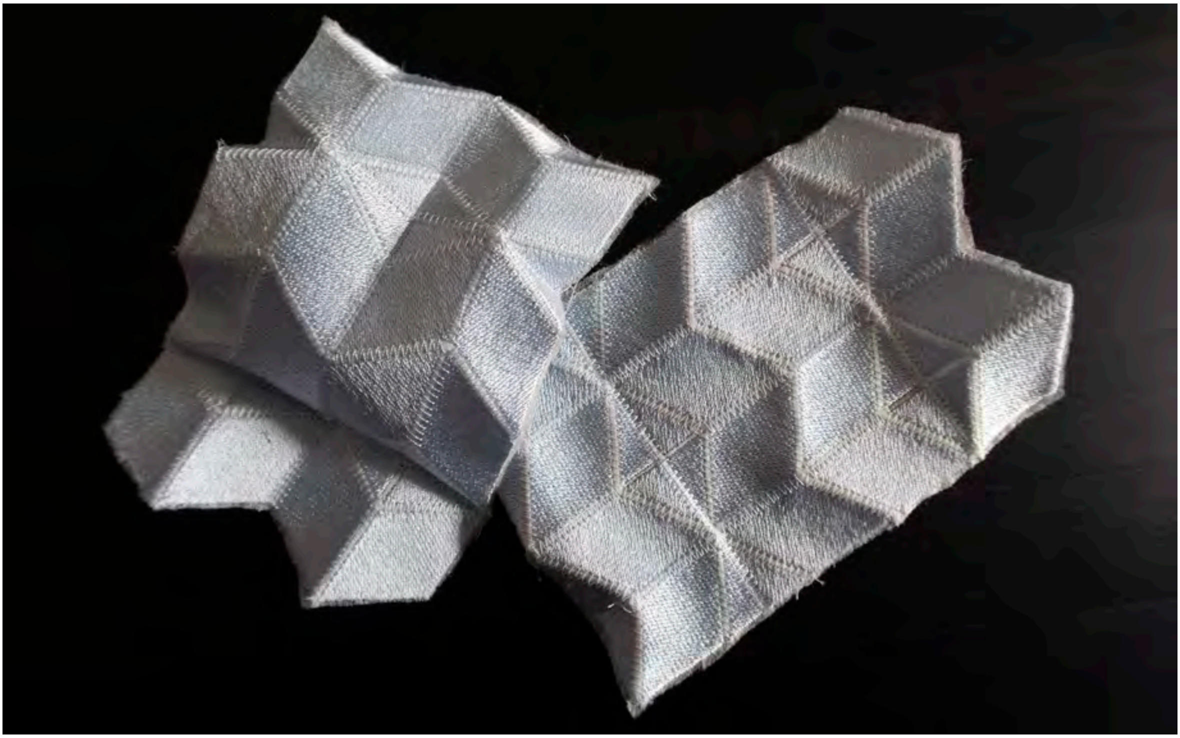
Software

L1: fill stitch 1,5 line/mm, direction 0o, medium density under sewing
L2: fill stich 4,5 line/mm, direction 45o and 135o, medium density under sewing
L3: zigzag stitch width 5,5 mm, 1 line/mm, no under sewing
L4: zigzag stitch width 5,5 mm, 1 line/mm, no under sewing

Finish & Post-production

1. Iron to shrink the smocking yarn
2. Wash away stabilizer

I RECREATED THIS DESIGN USING MONOFILAMENT. THE SHRINK YARN WAS STILL NOT STRONG ENOUGH TO DEFINE FOLD DIRECTION. HOWEVER, THE QUALITIES OF THE MONOFILAMENT MAKE FOR VERY WELL-DEFINED FOLDS.



On the floor

Outcomes

The sample
An embroidered fabric with sturdier areas and hinges
Properties & Behavior
Material contains hinges that supports folding/holding it into (origami) shape
Technique
Embroidered on water soluble film. L1 is the full part shape; L2 makes the polygon areas sturdy; L3 and L4 try to program the folding direction mountains and valleys

Evaluation

Method	1p.p. explorations manually stretching the sample
Insights	The fringe and the floats have potentital to be two different playful ways to deform the image (brushing and stretching)

Highlights

The addition of a tear away layer helped the way the folds behave (similar to paper)

DISCUSSION

The four design memoirs and the loose ends we shared in this pictorial allowed us to consider the implications of the practice of making as travelers in three aspects: samples as outcomes of a community of practice, ways of traveling, and the role of documentation.

Samples as outcomes of a community of practice

In this pictorial, we mean to unpack aspects of making that are often omitted from our accounts of projects, but that we consider crucial for enabling makers to become travelers. One important aspect we recognized is the role of the lab as a sociotechnical system that offers opportunities for new work to flourish both through its infrastructure and, more importantly, the permeability of the community of practice formed around it.

Starting from wearable electronics, the work developed in our lab has become broader in how the relationships between computation, materials and practice are negotiated [12]. We observe how the interests of individual researchers and students influence the overall work in the lab. As an example, a PhD candidate was engaged in a deep exploration of 3D printing and we saw how his presence in the lab opened opportunities for investigating tunable materials and production systems, transforming the way our fabrication machines were used in the lab in general. Although we see these waves occur, they are difficult to track. This pictorial is part of our attempt to get a deeper understanding of how these influences might happen and what they mean.

Different than "inspired by", the collaborations seen here are ideas, technique principles, and materials combined and forwarded to new samples. Because samples have very concrete properties, the exchanges are based on analyzing what is at hand. In other words, understanding the sample itself and what causes it to behave like it does, allows us to explore the possibilities and the conditions of moving the work to a new place.

Ways of traveling

The rules of becoming a traveler [11] suggest a few basic practices to nurture an attitude of explorative making. As we explored these basic practices of making, the figure of the fellow traveler emerged.

The stories shared here demonstrate different ways of being (fellow) travelers. in the Light Emitting Embroidery and the Origami Embroidery samples, we could say that the fellow travelers acted as tour guides who provided the knowledge and basic resources needed to engage with their samples. Different types of collaborations happened in the other cases. In Tunable Lace, both collaborators entered a process of turn taking between solutions and exploring new opportunities. The openness and trust built between collaborators fostered the willingness to share (knowledge, resources, responsibility, risks) needed to enter this process of traveling together. A similar relationship was built in the case of the Sublime Embroidery. However, instead of turn taking, the collaborators combined efforts and resources to let a new idea emerge. Later, the sample that was created in this collaboration became a new travel companion in a process that resulted in the sample documented in page 9.

The different ways of being a fellow traveler also demonstrate that there are many ways of traveling that include doing together, sharing advice, taking a tool for a new walk and turn taking. In the cases presented here, an important enabler for these collaborations was the physical co-presence. Standing next to each other around the same cutting table while surrounded by different fabrication machines created opportunities for serendipitous making.

The role of documentation

Understanding that making is a multifaceted process, we propose a documentation form informed by different reporting styles to support reflection-in-action, and to make explicit as much data – and as many types of data – related to a sample as possible. We expect that in doing so, makers can nurture their sensibility to the qualities of their samples and the implications of the fabrication methods used. As such, documenting should be seen as an extension of the act of making itself.

We recognize that the physical proximity in the lab and the time spent together building relationships played a big role in the collaborations shown here. These factors contribute to filing in gaps of knowledge (simply ask questions as they come) and building the intimacy needed for makers to engage with each other's work As evidenced by previous work [13], we believe that the practices of making as travelers and traveling together can happen over distance and asynchronously. However, different strategies and tools are needed to allow us to design from the samples of others. We believe the format and way of disseminating sample documentation is certainly one way of shortening this gap.

We integrated vector files of loose ends in this pictorial as a way of proposing a workflow that is supportive of learning-through-making and of getting intimacy with each sample. We hope this strategy supports others into getting more directly engaged with the samples shown in this work. These and other formats of (sharing) documentation as well as new archiving practices should be further explored to expand the practice of making as a traveler and of becoming fellow travelers.

CONCLUSION

Exploration is often used to indicate a phase of looking for a direction. Our proposal with making as travelers is to shift the notion of exploration from "not knowing where we are headed" to embracing that "we are here". This is not the same as being aimless. We believe that explorative making can be conducted even in more goal-oriented projects, provided we nurture practices that allow us acknowledging what we have at hand and coming back to it within and outside design journeys.

In this pictorial we propose different strategies of nurturing such practices through our traveling design memoirs, a documentation form and by integrating the digital file on the pictorial. We expect that the reflections presented here can prompt further investigation of strategies for sharing material knowledge and nurturing more permeability of ideas, cross-pollination of techniques, and new forms of collaboration in our field.

ACKNOWLEDGMENTS

We thank all the fellow travelers who co-habited this timeline and supported the search for the other places.

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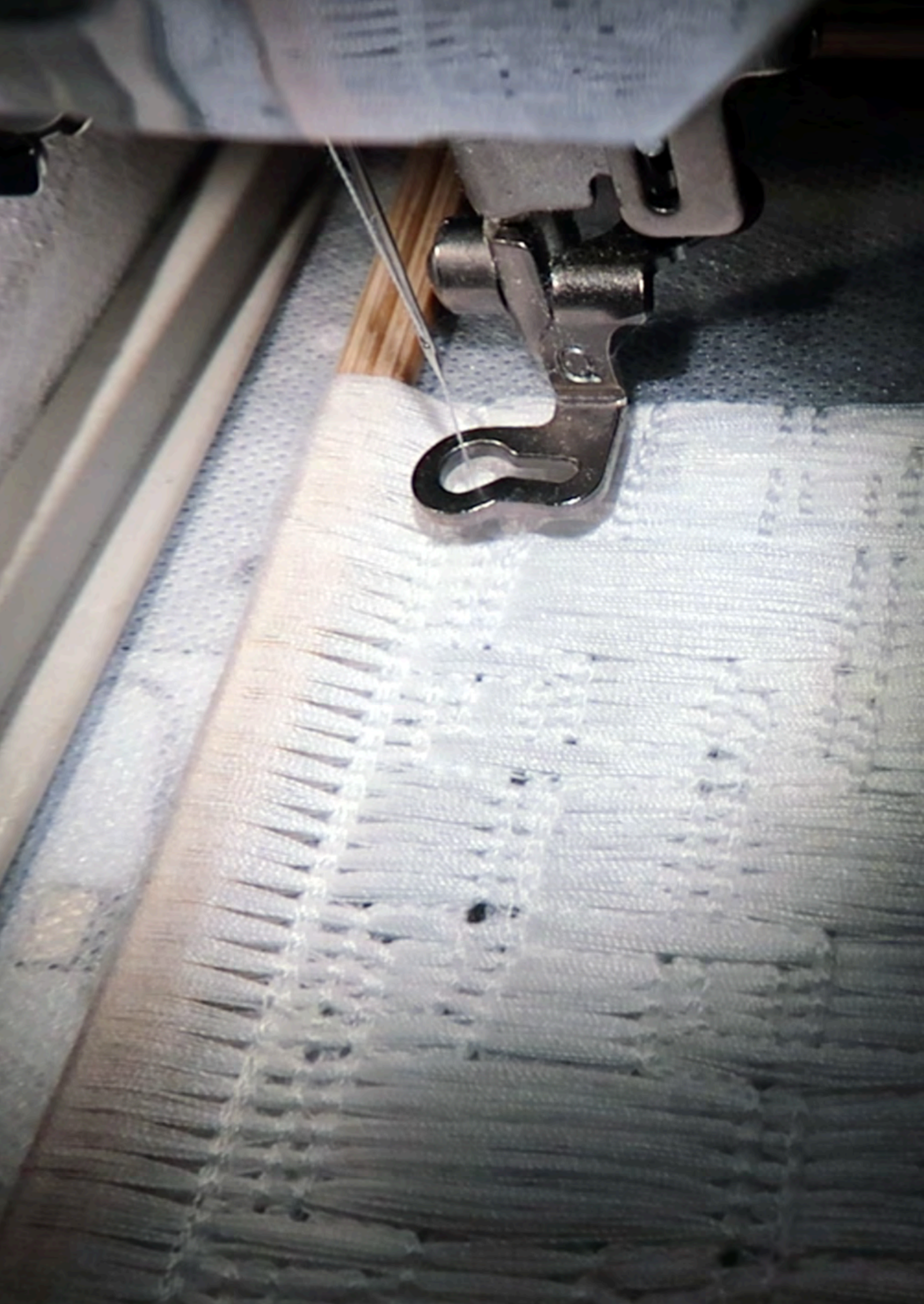

7 What happened here

As described in the introduction of this dissertation, my biggest aim with this research was to be both the researcher and the practitioner. Recognizing that emergence is an inherent aspect of design practice, I also took it as an approach to research and attempted to communicate this process as a *traveler's journey*, meaning that the detours and parallel lines of inquiry that were pursued are accounted for. Keeping in line with the ideas proposed by this body of work, rather than ending this dissertation with a closing statement, I would like to end it with an invitation to travel. Therefore, in section 7.1, I reflect on what happened as a result from taking an emergence-based approach and summarize the contributions of this doctoral research. In the final section of this dissertation, I return to the main contribution of this work, the *Becoming Traveler's* approach. I summarize the definitions of concepts I identified and developed through my engagement in *digital craftsmanship* as a form to consolidate the approach and to reinforce my call for other *fellow travelers*. Such fellows might include people engaging in *digital craftsmanship*, digital fabrication, other kinds of material-driven process, and textiles. The transferability of the perspective of *becoming travelers* is based on promoting multiplicity and richness of design outcomes. As such, this call is also extended towards a wider audience of people engaged in research through design, who might benefit from the reflections on the mindset and the conditions that promote and leverage on emergence in design proposed by this work.

7.1 Research as traveling

Through a more-than-human and relational view on making, this research through design project sought to identify aspects of *digital craftsmanship* that were obscured in the ways we describe its practice. By focusing on practices of sample making, I embraced serendipitous opportunities and the complexities (and even messiness) of material-driven processes both as a way of working and as objects of investigation. In doing so, this research joined a broader discussion on the relationship between theory and practice in research through design that has been questioning how we communicate plural designerly ways of knowing [28, 29, 45, 47], and valuing the material design outcomes produced throughout our processes as academic outputs in themselves [10, 66, 73, 80]. While any doctoral research through design project includes elements of emergence and serendipity through experimentation, these are typically considered corrections or shortcomings in terms of the convergence to a final result [48]. Rather, emergence and serendipity have been cast here as fundamental aspects that should be highlighted as drivers of exploration, and for which we needed to develop novel ways of expression and reporting. Embracing emergence as core methodology meant that the research questions evolved or emerged over time through a series of experimental projects. The collection of publications that compose this dissertation documented these projects and the evolution of our understandings of essential concepts related to *digital craftsmanship* and exploration in design research. This collection was also an exploration of how to communicate this kind of research. As result, this research contributes to the fields of *research through design* and HCI as an exemplar of research led by emergence as well as with situated accounts of sample making within complex socio-technical systems of production and reflections that support unpacking *digital craftsmanship*.

Like how machines configure our design practice in *digital craftsmanship*, publication formats configure our research practice. The formats we use define what kinds of data get documented and what kinds of knowledge are disseminated in our communities [76]. In this, formats such as the pictorial, first introduced in HCI as a Designing Interactive Systems (DIS) conference track in 2014, has been offering researchers an alternative to the dominant mode of publishing by enabling researchers to foreground image over text to articulate knowledge [8]. This format, which builds on long standing traditions of creating and articulating knowledge through visual form in other design and artistic fields [8], has been one of the main formats explored in this research. Referencing this track as a sign of a shift in design research, Odom et al. [66] sought to also create space to present and discuss design research artifacts at the CHI conference. To do so, they ran workshops in which the artifacts brought by participants stimulated discussions without the need of prompts. According to them, "there is a maturity to things — a weight, a feel, a presence, an expressiveness— that will and did steer the discussion" [66]. Perner-Wilson and Posch [73] also propose attending to the physical outcomes of design research as a way to broaden how academic publishing can be more inclusive towards different forms of design and knowledge [73]. Based on their experiences organizing swatch exchanges [39,71,72], they initiated a discussion of the implications and possibilities of considering swatches as a new form of physical publication format. The Research Through Design (RTD) conference, initiated in 2013, has been foregrounding design research artifacts through visual papers, a curated exhibition and roundtable sessions [88]. The conference has also been paying attention to documenting the event itself [87] by using different methods, such as scribing and other mediums. This documentation is envisaged as both a way to enrich the experience of conference delegates and to open possibility of engaging other audiences who may access these materials [93].

Workshops, interactive exhibitions, and physical formats are unique opportunities of experiencing design work that enable the conditions needed for designs to drive the debate on their own. While I believe it is extremely important to promote these opportunities, their reach is limited to the few individuals who can join or access the materials in person. Strategies such as the documentation of the RTD sessions can increase this reach and should be explored in different venues. However, papers will continue to be important vehicles of dissemination of research through design, as they that have a wider reach. As such, multiple and complementary strategies should be continually explored by design communities to ‘carve space’ for valuing the things we make, including efforts to expand the possibilities of our current publication systems and research programs. In this direction, the *Portfolio of Loose Ends* (section 6.1) can be seen as an exemplar of how different reporting styles can be combined to support a multifaceted analysis and dissemination of design work. It proposed an approach to exploration and collaborative practices in digital craftsmanship, while it also included the vector file, design memoirs and documentation of each sample into the pictorial. With these, this publication extends both the possibilities of pictorials and the notion of *annotated portfolios* [26] of retaining the specificity and richness of the designs through an approach that supports the analysis of each sample through different lenses. The designs remain open for reproduction, appropriation, and reinterpretation by others, who are welcome to partake in traveling. *Digital craftsmanship* was a good practice to investigate how to support emergent processes because the appreciation of the specificity and richness of the designed artifacts is inherently part of it. Further exploring how to successfully communicate the value of this kind of research can help mapping how to also appreciate and communicate the specificity of design in other fields, in which their importance might be less explicit.

By making samples the unit of observation in this research, it was possible to question the notions of failure and exploration in digital craftsmanship, which led to the proposal of an approach for explorative making. This approach, called *Becoming Travelers*, proposes that we embrace detours from our main lines of inquiry and consider our samples both within and outside our design journeys. In doing so, samples can be seen as *loose ends*, which can serve as starting points for new journeys through *revisiting*. To support this practice, ways of documenting-while-making and archiving are explored as tools that enable documenting simultaneously the journey of material-driven processes (how each experiment led to the outcome), while also promoting a practice of reflecting on each sample for their qualities. In this approach, *detours* and *revisiting* are seen as specific forms of drifting in explorative sample making processes that could be extrapolated to support designers in embracing emergence in other design practices. A detour can mean working in parallel lines of inquiry or a complete shift of focus in a design process. Through a lens of *traveling*, *revisiting* is the return to old experiments with new perspectives or picking up a *loose end* as the starting point to a new journey. We can engage with past experiments to learn new things, re-annotate our designs, maybe group them in different collections and enrich our documentation with different kinds of knowledge. This form of *revisiting* depends on the ability to document our processes while preserving the design work open to reinterpretation, appreciation, and appropriation.

Beyond these conceptual and methodological contributions, this body of work also contributes:

Documentation form. The assumption that the use of digital assets and digital fabrication machines guarantees that designs can always be reproduced shifts our attention away from the decisions, preferences, and insights embodied by them. The knowledge generated in *digital craftsmanship* is distributed across the whole socio-technical system of production. This means knowledge can remain hidden in digital files or potentially lost in processes that were not documented. Therefore, this dissertation proposed a documentation form for *digital craftsmanship* (chapters 4 and 6) that supports making this knowledge explicit and enables the appreciation of each sample within and outside projects. Informed by different reporting styles, this form combined technical specifications, situated accounts of the design journey and a reflection on the qualities of the sample (*on the floor*). Although sustaining a rigorous and consistent practice of documentation of each sample can be difficult due to time or other restraints, as discussed in chapter 4, I believe that it is a valuable exercise to increase one's sensibility towards the *intra-actions* embodied by samples. Different techniques and kinds of projects might configure practice differently and have very different needs regarding the kinds of data that need to be documented. As such, this form should be seen as an invitation to experiment with multiple reporting styles rather than a standard of documentation.

Technical solutions for crafting interactive materials and research products based on digital machine embroidery. This research contributes to the field of wearable computing by extending the possibilities of employing digital machine embroidery to develop high fidelity soft wearables and soft applications. By exploring the accuracy of the machine and stability given by the embroidery frame, it was possible to create the textile substrate in the shape of parts of the wearable and integrating technology through the same process of fabrication. As demonstrated during the development of the Smart Sock (chapter 3), variables of the design can be isolated and precise changes can be made between prototypes both for optimization but also as a means of exploring alternative solutions. Due to the high fidelity of the prototypes created, it was possible to evaluate and explore each research product in different conditions. Differently than in iterative processes, this level of fidelity enables other kinds of comparisons between prototypes which supports identifying the range of possibilities of a technique together with progressing toward a project goal. This kind of approach can be applied to other developments beyond wearables as well as to other digital fabrication techniques. The family of embroidered elements and techniques developed in this work can be appropriated and extended by others in the field.

Strategies and conditions for combining fabrication processes into a single workflow. Building on the experience of combining embroidery and casting in the fabrication of the *Embroidered Inflatables*, chapter 5 contributes with two projects that combine digital fabrication techniques. These projects, *FabriClick* and *Exquisite Fabrication*, present different strategies that machines can be combined into a workflow. *FabriClick* supported precision in the fabrication of parts and their assembly through the creation of a jig system. *Exquisite Fabrication*, on the other hand, aimed at flexibility of the fabrication system through a combination of software to facilitate the alignment of the sample in each machine and through practices that create the conditions for *turn-taking* with machines and other designers. With these, we open the possibility of engaging our whole labs to reflect on the future of manufacturing. Digital fabrication machines already support manufacturing on demand, high-quality small-to-large scale production, and personalization. The examples presented in this body of work can support us, for example, in envisioning future systems of production that enable local fabrication by trading off the precision and optimization of dedicated production lines for flexibility and improvisation in (shared) fabrication facilities.

7.2 A traveler's guide

I expect that this body of work can be seen as a provocation to seek ways to open our processes to new interpretations and to each other, fostering permeability of ideas, cross-pollination, *turn-taking*, and collaboration with and through our material samples. To support this, I summarize the definitions of concepts I identified and developed through my engagement in *digital craftsmanship* as a form to consolidate *Becoming Travelers* as an approach to explorative making.

Digital Craftsmanship

Digital craftsmanship is a design research methodology concerned with generating knowledge through making with socio-technical systems of production that include digital fabrication tools. As making is the main strategy used for this kind of research, samples are important material outcomes of design processes in this practice. This making with process is itinerative (each sample is both the result of a previous development and preparation for the next) and informed by the real implications of the fabrication systems and materials involved. As result, this knowledge, which is embodied by physical samples, is rich, multifaceted, and situated. Agency is decentered from the designers to be distributed across the socio-technical system of production. Digital craftsmanship is practiced through a workmanship of risk [59], meaning that the outcomes of the process of sample making cannot be predetermined and the quality of the outcomes of the whole process is continually at risk. In other words, emergence is inherently part of the practice. This is evidenced by the design process of the Embroidered Inflatables, in which new directions emerged from each series of samples. The work done in Exquisite Fabrication (chapter 5) shows a different exploration of risk in digital craftsmanship through a trade-off between accuracy and flexibility, but also in the relationship between makers and machines. Differently, the Portfolio of Loose Ends (chapter 6) demonstrates a more extreme form of digital craftsmanship by means of explorative making, in which we include the whole community of co-inhabitants of the lab as potential collaborators.

Samples

In digital craftsmanship, the term “samples” refers to the material outcomes of the process of making with socio-technical systems of production. Samples embody intra-actions between all entities that constitute digital craftsmanship – meaning the entanglement of machines, designers, materials, ideas, and environment. Samples are created through processes of itineration, in which each sample is both a development of the previous and its analysis is the preparation to the creation of the next. When the material properties and interactive possibilities of a sample created through digital machine embroidery are examined, for example, code, structure, thread, and tension cannot be considered separately from each other. As such, samples can be considered instantiations of the socio-technical system of production within which they are created. The complexity of these relationships enables us to look at them from different perspectives. Therefore, each sample offers potential insights related to application, interaction, programming, skill, technique, machines, material, collaborators and so on. Such potentials can be appreciated on the individual samples or through collection of samples, which might be curated based on a particular perspective or variable. This complexity also means that the qualities and properties of the outcomes of making processes, as well as the knowledge generated through them, are not predictable. Upon engaging with a sample, we may discover that more than the (interactive) qualities we planned on materializing are present. When judged based solely on our intentions, a sample may be a failure or a success within our journey towards a specific goal. Yet, that does not eliminate its other qualities, and consequently, the other opportunities they embody. Under this perspective, analyzing a sample is an exercise of seeing “what’s at hand?” by unpacking the intra-actions that compose it, seeing each sample for what it is and does on its own right. This kind of analysis supports seeing samples both within and outside the context in which they were created. In turn, this distributes agency with samples and unlocks their potential of pointing to new directions of exploration. In essence, if we embrace emergence in the way we evaluate samples, they become both embodiments of past journeys (the process that originated them) and invitations for future ones.

Becoming travelers

This dissertation proposes that we see the making process as akin to traveling. The proposal of becoming travelers extends the digital craftsmanship methodology through an approach for explorative making that seeks to expand the material repertoire of design.

“When we travel, we tend to allow emerging opportunities to affect our plans. If we see or learn of a cool place to visit, we spontaneously change our plans or we make plans to (re)visit another time. We take photos, and we talk about these places to friends. Why not do the same with our samples?” (Section 6.1)

As an extension to digital craftsmanship, the traveler’s approach is based on collaborations with our socio-technical systems of production. The core of the approach is understanding that samples are instantiations of this system and open for renegotiations of meaning. As such, they can answer other questions than the ones we asked when creating them. Making as travelers requires nurturing practices that enable the appreciation of what was made, recognizing the potentials of each sample, both within and outside design journeys. This means a departure from a solutionist approach towards one that is driven by emergence, actively welcoming detours from the main inquiry of a given project and making time to pursue them.

Traveler’s mindset

To enter the traveler’s mindset, it is important to: create time to make, collaborate with, be systematic (section 3.3). The first two are inherited from the practice of digital craftsmanship. Creating time to make is allowing ourselves to get lost in the process of making itineratively. Collaborating with is recognizing that making is relational and situated.

The understanding of what being systematic means is particular to supporting the practice of making as a traveler. For the traveler, ‘being systematic’ is achieved through an attitude of care towards the things we make, which means staying responsible for their future becomings [50]. Documenting-while-making is a strategy to nurture such care, making time to appreciate and reflect on each sample or experiment for what they are, how they contribute to the current project and how they can lead to other journeys. By documenting-while-making, a practice that has been well-known to maker communities to generate instructions for open-source platforms and is an integral part of the education and research model proposed by Fablabs [56], it is possible to capture a good deal of the richness of the process, including technical details that contributed to specific outcomes, and support a reflective practice. In turn, this can support making loose ends explicit and actionable. This dissertation introduced one format for this documentation as an invitation for further investigation of this area. The sections proposed in the format mean to describe types of data that could be captured and to emphasize the need to make the knowledge integrated into digital assets and their connection with the physical outcomes explicit. The ways of capturing such type of data remain open to be investigated. Different techniques and the level of access to machines might affect the time designers have to reflect on the work at hand and so require different strategies for documenting. As discussed in chapter 4, digital tools and photos can be used to capture a lot of data that would otherwise be difficult to recall afterwards or time consuming to write/type down, such as machine setup or settings. Along with finding ways to effectively capture more data with less effort and time, new ways of documentation should find means to retrieve this data in the future and to acknowledge factors that contribute or limit findings, such as the expertise of the maker, type of technique, field of application. These can support investigating why specific phenomena is happening but also open opportunities for future inquiries. Therefore, documentation in this field should be lively and open for revisit as much as the samples themselves. The way we archive – or, instead of archive, live with – our samples can complement this practice. The choice for surrounding ourselves with certain material samples facilitates transforming them into collaborators in future journeys. Treating and presenting a collection of samples all at the same level allows identifying qualities and opportunities beyond 1) what we aimed to explore when conceiving them and 2) beyond the judgement we made of them during a given design process.

Conditions for emergence (to support collaborating with)

In engaging in making through the traveler's mindset, different notions or strategies that support the practice of making as travelers were identified:

> **Looking backwards and forwards** – Acknowledging the work - first identified in chapter 2, this idea inspired the notion of *revisiting* samples which was further explored in chapters 3 and 4. This notion considers that "the finding of new things also means looking at old things with new perspectives" (section 3.3 [32]). This is made possible through an exercise of appreciating samples for their qualities and interactive possibilities. This reflective practice of seeing what is at hand, which is assisted through documentation, supports identifying ***loose ends*** in sample making processes as well as activating them in other journeys. Loose ends are samples that might not have contributed for the main line of inquiry in which it was created but that embody possibilities for new starting new

journeys. In an ongoing process of making as traveling, loose ends can also be created as deliberate detours within a given process, taking advantage or creating the of circumstances to pursue different outcomes and parallel lines of inquiry at the same time.

Looking sideways – Acknowledging co-inhabitants of a timeline – introduced in chapter 5, to "look to the sides" means acknowledging the value of co-inhabitance of a timeline in a shared working space, widening our view of who and what is part of our socio-technical system of production. Our samples are not observation-independent objects, and they are not created within independent, isolated spaces. Directly or indirectly, the ideas, samples, people, and machines that co-inhabit the lab in a timeline rub off on each other. *Looking sideways* is an exercise of identifying possible ***fellow travelers*** and seeking for opportunities for collaboration with the socio-technical system of production. Collaboration between *fellow travelers* can take many forms include making together, sharing resources, and *turn-taking*. *Turn-taking* was explored in this work as a particular form of collaboration in explorative making and as the mechanism that supports the process of *itineration* in sample making. This notion first appeared in this work through the string figuring metaphor [37] to support my understanding of sample making through a relational view (chapters 1 and 2). The game of string figuring is played by two pairs of hands taking turns in reconfiguring an entangled string. In chapter 5, this notion was reintroduced as a specific form of collaboration that enables shared risk, agency, and ownership between collaborators. Through the notion of *turn-taking*, drift and opportunity are emphasized in the design process by allowing the capabilities and skills of others (non-human and human, respectively) to contribute and redirect the process of making.

Throughout this dissertation, I have explored making through the lens of itineration and traveling. This journey has taken me to a different understanding of collaborative practices, exploration and sample making in the context of digital craftsmanship. I hope that through this body of work, I have gotten closer to understanding how to pay attention to the physical things made in design research. I see this work as directly linked to the broader fields of fabrication and design research as a way of rethinking the way we approach design practice and knowledge dissemination in HCI. My hope is that becoming travelers can support design communities to devise systems and to inspire other approaches that open our making processes and material samples to new interpretations and to each other, breaking boundaries between fields.

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Curriculum Vitae

Bruna Goveia da Rocha was born in Curitiba, Brasil, on the 10th October 1990. She studied product design at Universidade Positivo. In 2015, she received her master's degree from the department of Industrial Design from the Eindhoven University of Technology with the project "Flow: In the path towards embodied guidance". After her studies, she worked as a design researcher within the Wearable Health team of the department of Instrument Development Engineering & Evaluation (IDEE) of the Maastricht University, creating soft wearables for healthcare in interdisciplinary teams.

Bruna started her PhD research at the Eindhoven University of Technology as part of the i2-CoRT project, carried out within the context of Interreg V-A Euregio Meuse- Rhine from the European Regional Development Fund, in 2018 with results presented in this dissertation. During her doctoral research, she supported education in the Industrial Design Wearable Senses Lab, Health squad and Crafting Everyday Soft Things squad as a lecturer and coach. Her research through design practice has been dedicated to reflecting on sample making practices and its outcomes through a more-than-human perspective. In her work, she collaborates closely with other designers, materials and production systems to explore emerging technologies and cross pollination between techniques. Dissemination of this work has included exhibiting projects at Dutch Design Week exhibitions and the Kantfabriekmuseum, as well as through publications in international conferences and journals, including design exhibitions and publications at the International Symposium of Wearable Computing, the Intersections Conference, the Journal of Textile Design Research and Practice, Temes De Disseny Journal, ACM CHI Conference in Human Factors, the ACM DIS Designing Interactive Systems (Netherlands), and the ACM TEI Tangible Embedded and Embodied Interaction. She is currently doing postdoctoral research at the Amsterdam University of Applied Sciences within the context of the Erasmus+ TRANSITIONS project which aims to support the skilling and upskilling of professionals towards the circular and digital transition in fashion and textile fields.