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Exploring Prototyping Tools for Interactive Fashion Design

by

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Abstract

Interactive garments enable new forms of communication between our bodies and with other people. In electronic fashion (eFashion) design, interactive garments on high fashion runways envision how people might use interactive technologies to enhance our clothing with new sensing and output capabilities. Researchers and fashion designers have since explored new interactive textiles that enable aesthetics-driven, interactive, and new material properties to explore on clothing. While there exist physical tools to implement interactive garments and software tools to create the visual aesthetic of a garment, these tools cannot yet enable designers to use new eFashion technologies in their garments because they require engineering expertise and specialized laboratory equipment. In this thesis, I explore the use of computer-aided prototyping tools to develop interactive eFashion garments. I present case studies with makers and two experienced eFashion designers about their design practices and formulate design guidelines for prototyping tools. I then present two prototyping tools for implementation and exploration of interactive garments. Finally, I discuss future work for physical and virtual prototyping tools in eFashion.

Preface

This thesis is original, unpublished, independent work by the author, Kevin Ta. The case studies reported in Chapter 3 were covered by Ethics Certificate number REB16-2332, issued by the University of Calgary Conjoint Health Ethics Board for the project "Understanding Practices and Evaluating new Technologies for Creative Communities" on September 21, 2017.

The system reported in Chapter 5 was published in the Designing Interactive Systems 2018 conference as a provocation paper and poster titled "Bod-IDE: An Augmented Reality Sandbox for eFashion Garments" by the authors Kevin Ta, Ehud Sharlin, and Lora Oehlberg. My co-authors assisted in the editing and review of this work. The provocation paper's contents, along with additional details and discussion, have been reproduced here in this thesis. See Appendix D and this thesis' accompanying materials for a reproduction of the poster.

Acknowledgements

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Chapter 1 Introduction

In this thesis, *I explore physical and virtual prototyping tools to enable electronic high fashion designers in envisioning the behaviour of interactive components in an electronic fashion garment before physically implementing their designs*. The prototyping tools I develop help electronic fashion designers explore interactivity on garments to know what is possible before investing their efforts into a physical implementation. I discuss the opportunities presented by these prototyping tools, as well as their limitations and the implications for future prototyping tools for electronic fashion.

My goal is to help electronic high fashion designers to explore new interactive experiences and showcase them on the fashion runway. Thus, designers can envision new communicative functions for interactive clothing. In my research, I formulated design guidelines from a brief quantitative analysis on makers and the practices of two electronic high fashion designers to inform the creation of prototyping tools. From the guidelines, I built a physical prototyping tool and discovered limitations towards conceptually developing an interactive garment. I then built an augmented reality prototyping tool that helps electronic fashion designers envision and refine a garment behaviour before it is physically implemented. I discuss implications for future work in prototyping tools for interactive garments.

1.1 Motivation

Why do people have clothes? People have communicative needs for clothing, and fashion designers help meet those needs. Cultural theorists like George Sproles (1979), defined several communicative functions of clothing by examining consumer behaviour. To meet the communicative demands for clothing, fashion designers have design principles that they can use to express the basic elements of clothing design. By varying the basic elements – silhouette, lines, and texture (Jones, 2011) – fashion designers can create vast varieties of clothing to meet consumer demand.

Interactivity as a new design space in fashion. With the development of new electronic technologies, fashion designers now have interactivity as a new way to express the basic elements of clothing design. As a result, a new field has emerged known as Electronic fashion (eFashion), where fashion designers combine electronic components and clothing to augment and dynamically change garments to meet the communicative needs demanded by consumers of fashion.

Processes to disseminate fashion ideas. Getting new fashion ideas directly into retail stores to purchase is challenging and can be only be done indirectly through existing channels like high fashion runways. High fashion is a discipline where fashion designers develop artistic and experimental clothing for fashion runways (Jones, 2011). Once designers disseminate their ideas by presenting garments on runways, fashion magazines and mass media (e.g., television and internet) then review and report on the ideas presented on the runway, which can inspire consumer demand for different styles of clothing. Commercial fashion designers then work with market reports, fashion magazines, and trade publications to fulfill retail demand, thus allowing fashion ideas to reach consumers.

eFashion is exciting for both designers and researchers. In the research literature, designers and technology researchers are exploring new fashion ideas and technologies on interactive garments. Researchers are interested in eFashion technologies because they provide new exciting challenges and opportunities to solve on interactive garments. Researchers have developed new kinds of technologies such as waterproof and stretchable circuit boards (Nagels et al., 2018) helping make electronics more durable on clothing. There is also interest in developing new methods for actuating fabrics on clothing using pneumatics (Perovich, Mothersill, & Farah, 2013) as an alternative to rigid shape memory wires. eFashion designers benefit from the researchers by building use case scenarios to envisioning their technology in various social situations (e.g., *Robotic Spider Dress* (Wipprecht, 2015)). Both researchers and designers have desires to explore eFashion beyond the runway in new functions of interactive clothing.

1.2 Problem

eFashion is not for sale. In eFashion, few interactive garments exist in retail stores despite having international eFashion runways like MakeFashion. There already exists products like smartwatches and fitness monitors, that indicate demand for interactive wearable objects. eFashion designers continue to build new prototype garments on international runways and researchers continue to develop new eFashion technologies.

There may be many reasons for eFashion not exciting demand thus far (e.g., cost, new production processes). Though perhaps the amount of technical skills necessary makes it so (1) only a few people can be a part of this field, and (2) only a limited amount of garments can be created a time given how time-consuming it is to build these interactive garments. I believe that by allowing designers to envision their ideas before implementing their designs (i.e. creating custom circuitry, soldering electronics, programming the underlying software) designers can determine what is physically possible and how they can realize their vision as a garment, which will save them time and effort in implementation and exploration, and thus increase their output.

Current eFashion prototyping tools lack interactivity prototyping. Current means to prototype eFashion is limited to exploring, iterating, and refining interactivity on physical garments. There are garment-friendly technologies that eFashion designers can use to explore opportunities but are often challenging to use without specialists or require building a finalized garment leaving little room to alter the concepts. Technologies like touch sensitive textiles (Poupyrev et al., 2016) and artistically expressive soft displays (Devendorf et al., 2016) grant eFashion designers new varieties of technology but require specialists to help integrate. Physical prototyping tools like Arduino LilyPad (Buechley, Eisenberg, Catchen, & Crockett, 2008) enable designers to build interactive garments but cannot make it easier use new eFashion technologies in their designs. Various Fashion CAD (e.g., Tuka3D[1]) tools support the visual aesthetic of a garment but do not yet support interactive components on garments. Thus, there are opportunities to develop improved eFashion prototyping tools that support the design of interactive behaviours on an eFashion garment.

1.3 Thesis Statement

In this thesis, *I explore physical and virtual prototyping tools to enable electronic high fashion designers in envisioning the behaviour of interactive components in an electronic fashion garment before physically implementing their designs*. I explore different ways to support eFashion designers with prototyping tools that support implementation and exploration of interactivity on garments. My perspective is that of a computer scientist and computer system designer: I am interested in building prototyping tools that support fashion designers to author

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[1] http://www.tukatech.com/3D-fashion-design-software/TUKA3D

and test interactive behaviours on garments. By envisioning interactive behaviours, eFashion designers can know what interactive behaviours are possible before committing time and resourcing building their garments.

The remainder of this chapter will provide some background on the computer science context that fits the research, introduce existing work on eFashion prototyping tools, state the research goals in greater detail, and outline the rest of the thesis.

1.4 Context and Scope

This research is a contribution to the field of Human-Computer Interaction (HCI), a discipline of computer science and design. The research is the intersection of eFashion, toolkits and prototyping tools, and augmented reality. I explore the use of physical and virtual prototyping tools to enable electronic high fashion designers to author interactive garments. Figure 1 summarizes the scope of this research.

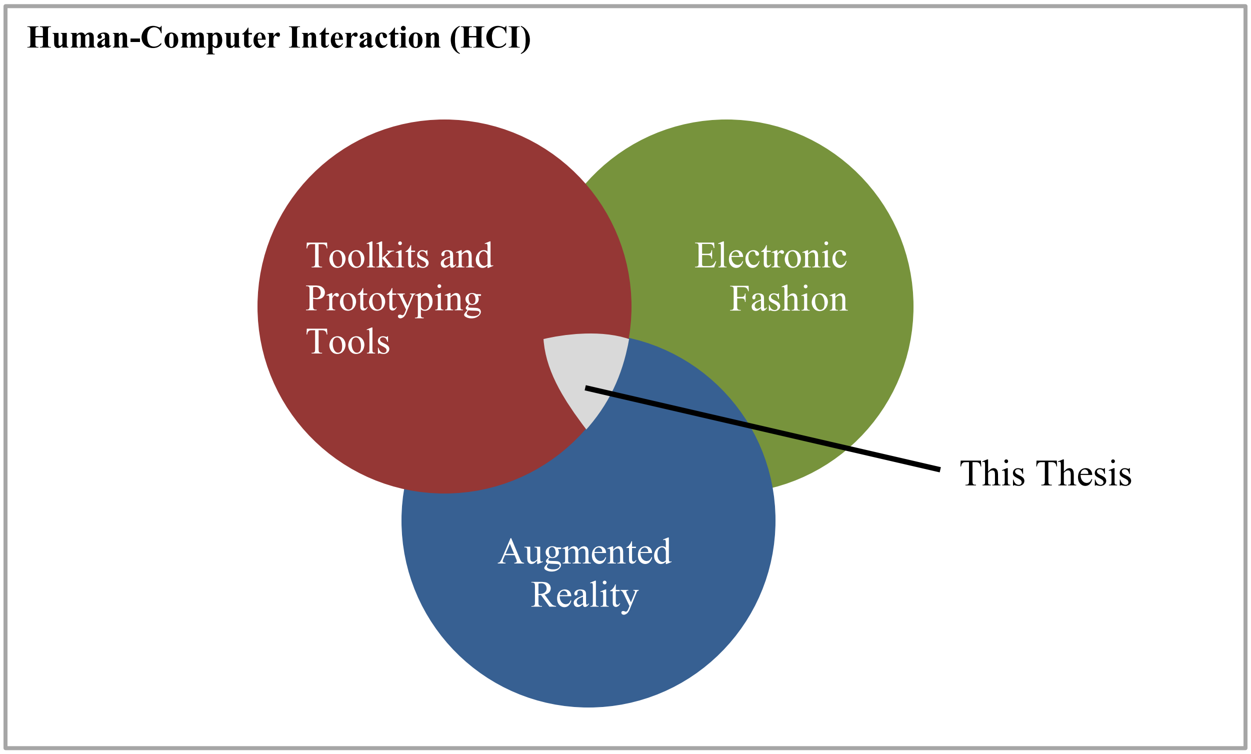

Figure 1 Research scope: this thesis is in the intersection of toolkits and prototyping tools, electronic fashion, and augmented reality.

Electronic Fashion is the creation of interactive garments which concerns the field of wearable computing. A traditional computer interface typically consists of interacting with elements on a rectangular screen on a desk using a mouse and keyboard. As computing technologies evolve to new form factors – such as smartphones, internet of things (IoT) devices, and wearable devices – interfaces must now adapt to new environments such as the user's body. In garments, interactive technologies - like heart-rate sensors, accelerometers, vibration motors, and light emitting diodes (LEDs) - can be embedded onto garments. The design of interactive garments can be challenging because interacting with electronic components inherit the context of the wearer's internal state, abilities, and environment. It is of interest for computer scientists to help support the design of interactive garments so that eFashion designers can generate new functions for wearable technologies.

To help eFashion envision new wearable technologies, I use ideas from prior work in *toolkits and prototyping tools*. Toolkits are the study and development of tools that support designers that provides an environment with many building blocks, structures or primitives that afford a "path of least resistance" (Ledo et al., 2018). Examples of these tools are Makers' Marks (Savage, Follmer, Li, & Hartmann, 2015) and ReForm (Weichel, Hardy, Alexander, & Gellersen, 2015) which help designers integrate electronic components into physical objects. This research looks at developing prototyping tools for applications in eFashion. Prototyping tools can help fashion designers by facilitating some aspect of their prototyping process so that they can focus on exploring, realizing, and evaluating ideas they are interested in developing. For example, Fashion Computer Aided Design (Fashion CAD) software helps fashion designers create and refine the look of their garments by rendering previews of the imagined garment (e.g., Tuka3D[2]). These previews help fashion designers iterate on their designs faster by removing low-level implementation like physically sewing the garment.

Lastly, this research also concerns the field of *augmented reality*. Augmented reality is a technique to overlay virtual objects in the real world in real time (Azuma, 1997). In Bod-IDE (chapter 5) (Ta, Sharlin, & Oehlberg, 2018), I used augmented reality to develop a prototyping tool without material constraints and embed interactive virtual components on garments. Augmented reality has previously been used to support early electronics prototyping (Somanath, Oehlberg, & Sharlin, 2017) and can theoretically generate limitless components that need not

[2] http://www.tukatech.com/3D-fashion-design-software/TUKA3D

conform to real-world physics. Virtual stand-in components make augmented reality ideal in a prototyping tool because physical constraints like weight, electronic wires, power, and sensors can be ignored to focus on refining interaction on garments. In this work, augmented reality serves as a means to envision eFashion garments and their possibilities without physically building them.

1.5 Research Goals

To realize this thesis of exploring prototyping tools to enable electronic high fashion designers to envision the behaviour of interactive components, there are two main goals that needs to be achieved: (1) understand fashion designer's practices to inform the design of eFashion prototyping tools, and (2) developing and exploring prototyping tools that author interactive garment prototypes. For each goal, I then address the following research questions:

Research Goal 1: develop design guidelines for prototyping tools in eFashion design practice

Research Question 1. **What are the challenges and opportunities in an eFashion designer's practice that an interactive garment prototyping tool can support?**

To develop a prototyping tool, I first need to understand how fashion designers currently develop their interactive garments. By understanding what conceptual development and implementation challenges eFashion designers face will help inform opportunities to support their practice. To do this, I will conduct a quantitative analysis and collect a small set of interactive garments that makers already make with LilyPad. This sample will help understand the current limitations of the platform and determine potential "building blocks" (Greenberg,

2007) in a prototyping tool. Next, I will conduct and present detailed case studies on eFashion designers who have experience producing eFashion garments for a high fashion runway. I will then synthesize these findings in the form of design guidelines which will help inform the creation of prototyping tools that author interactive garments.

Research Goal 2: develop prototyping tools that create interactive garment prototypes

A prototyping tool can create garment prototypes in both physical and virtual worlds. There are physical prototyping tools help implement interactive garments physically (e.g., LilyPad) and virtual tools to develop the garment's aesthetic (e.g., Fashion CAD). I build on the physical and virtual prototyping approaches to help designers implement and explore their garments respectively. Thus, I address two research questions about prototyping tools:

Research Question 2A. **How might a prototyping tool support the exploration of physical implementation and behaviours on an interactive garment?**

Using the design guidelines developed in RQ 1, I will develop and explore a physical prototyping tool for developing interactive garments. Given the popularity of prototyping tools like Arduino LilyPad, the goal for building this prototype is to enable eFashion designers to explore eFashion technologies. The purpose of this tool is to gain understanding on how designers currently implement their garments and what aspects of the process to support. I will discuss this tool against the design guidelines and evidence gained RQ 1. I will discuss this tool against current low-fidelity tools like sketching and paper prototyping to contrast against the approach.

Research Question 2B. **How might a virtual prototyping tool support eFashion designers in envisioning their interactive garment designs and knowing what is possible before physically implementing such designs?**

Using the design guidelines formulated in RQ 1 and addressing limitations from RQ 2A, I will develop another prototyping tool to support virtual garment prototyping. Using the Fashion CAD approach, I will develop a system that authors interactive garments virtually. Current Fashion CAD tools do not yet support interactive components on garment design. The goal is to extend this capability in a new prototyping tool. By authoring virtual interactive garments, eFashion designers can explore and envision interactive components before they physically implement their garments. I will evaluate this prototyping tool using techniques common in toolkit evaluation (Ledo et al., 2018), specifically using *demonstration* by using "'how-to' scenarios", *usage* by using "walkthrough demonstrations", and *heuristics* following Olsen's outline (Olsen Jr., 2007). The evaluation will highlight the tool's strengths and features to improve.

1.6 Contributions

My research contributes the following: (1a) a detailed examination into two eFashion designer's practice building interactive garments for the fashion runway; (1b) a set of design guidelines for building prototyping tools to support said eFashion designers; (2a) a physical prototyping tool that allows designers to quickly start experimentation at garment-wearable scales; and (2b) a virtual prototyping tool that allows designers to explore and envision the behaviour of interactive components.

1.7 Research Approach

The goals of this thesis are to (1.) develop design guidelines for prototyping tools in eFashion design practice and (2.) to develop prototyping tools that create interactive garment prototypes. Here I outline my research approach in greater detail: form case studies to examine eFashion design practice, develop and evaluate a physical prototyping tool, and develop and evaluate a virtual prototyping tool.

To inform the creation of prototyping tools for eFashion, I develop two sets of case studies with makers and two high eFashion designers and developed prototyping tools in response. The approach I take is similar to what other researchers have done in the past such as d.tools (Hartmann et al., 2006) and DENIM (J. Lin, Newman, Hong, & Landay, 2000) by understanding the users that the tool is intended for. In this thesis, I conducted interviews with eFashion designers to inform the design of prototyping tools and built tools to support the fashion design practice. I first develop case studies with makers to understand what is typically made on platforms like Arduino LilyPad to determine potential “building blocks” (Greenberg, 2007) for a prototyping tool. Then I develop case studies with two eFashion designers with experience in eFashion to build design guidelines to determine how a prototyping tool can support the design of eFashion garments.

Using the design guidelines from the case studies, I then build two prototyping tools: one that authors physical garment prototypes and one that authors virtual garment prototypes.

For this thesis, I am focusing on high fashion designers because their field is most supportive in creative prototyping and that by supporting them they will have a higher overall impact on eFashion. As a discipline, high fashion is the most supportive in creative prototyping and is open to generating ideas about the role of interactivity on clothing. Furthermore, targeting eFashion designers who have existing experience in technology to examine how they think about technology on garments and how they used their knowledge to explore alternative interactions. By supporting their ability to prototype with technology will allow eFashion to gain more influence on the runway. More influence in the high fashion world means inspiring fashion designers to create more eFashion, create more consumer demand for eFashion, and generate innovations in new eFashion materials and goods.

To develop the case studies, I focus on what makers currently produce using LilyPad and examine the eFashion designer practice. To inform the case studies, I first conducted a quantitative analysis on what makers already make using Arduino LilyPad. The small set of projects informs how the tool is currently being used and determine potential building blocks for a prototyping tool. Next, I develop case studies with eFashion designers who have presented an interactive on a high fashion runway. I will examine their most recent project on how they conceptually developed their garment and the implementation challenges they faced. The goal is to synthesize these findings into design guidelines to inform the creation of prototyping tools that author interactive garments.

Using the design guidelines formed from the case studies, will then explore and develop two prototyping tools to address physical implementation and virtual prototyping. I will create a physical prototyping tool to explore how eFashion designers implement their garments and opportunities for physical garment prototyping.

I will also explore the use of a virtual prototyping tool based on the approach of Fashion CAD tools that allow manipulation and previewing of patterns. The goal of this tool is to help designers explore interactive components before they physically implement their garments.

I will then evaluate the virtual prototype toolkit through *demonstration* and *heuristics*, two common approaches to evaluating toolkits (Ledo et al., 2018). Using demonstration, I will describe a "'how-to' scenario" of how an eFashion designer uses the tool and how they might work with the tool (Ledo et al., 2018). To illustrate what the toolkit does, I will describe some examples of what was previously difficult to do (e.g., connecting a fan to an accelerometer) and provide novel examples of what the toolkit can do. Then I employ a usage evaluation by conducting a "walkthrough demonstration" to laypeople to determine the value of the tool. I will also perform a heuristics evaluation using Olsen's (2007) guidelines. These heuristics will reveal what the system currently excels at but also reveal limitations to improve the system further.

With these prototype tools and their design reflections, I then conclude the thesis in chapter 6 with a summary of my findings, contributions, and discuss future work for the prototyping tools I developed.

1.8 Organizational Overview

The following section will briefly describe the contents of each thesis chapter.

Chapter 2: Background & Related Work

I present a detailed background on the challenges and tools that eFashion designers currently face. I show what fashion designers are trying to do with interactivity and how they distribute new clothing ideas in the fashion world. I show various existing technologies that eFashion designers can use to explore interactivity on clothing and the current tools to support implementation with those technologies. I then outline my research approach in further detail.

Chapter 3: Forming Design Guidelines – eFashion Designer Case Studies

I investigate how makers currently use LilyPad to build their interactive garments and I examine how eFashion designers develop their garments for the runway. I provide a context on what is currently being made by makers using LilyPad to inform the building blocks for a prototyping tool. I also present how eFashion designers they conceptually develop their ideas and the challenges they faced in implementing their interactive garments for a high eFashion runway. I then discuss design guidelines for a prototyping tool to support their practice.

Chapter 4: Exploring Physical Prototyping Systems

In this chapter, I developed and explored a physical prototyping tool to address RQ 2A by using design guidelines formulated in Chapter 3. TortillaBoard is a wearable zipper sleeve for implementing easily-alterable and experimental interactive prototypes. I then discuss two design lessons: physical implementation leaves little room for interaction exploration and low-fidelity techniques (e.g., sketches, paper prototyping, junk prototyping) are difficult to use to communicate interactive behaviour.

Chapter 5: Envisioning Interactivity with Augmented Reality

I discuss the design of Bod-IDE – an Augmented Reality Mirror for prototyping interactive garments on-the-body and address RQ 2B. Using a commodity IR camera, display, and easy-to-produce physical tags.

Bod-IDE helps eFashion designers explore interactivity through a virtual prototype of their garment. Using augmented reality, designers can wear their virtual prototype to explore and test their garment's interactions. Using physical stand-ins for electronic components allows designers to explore alternative interactive behaviours before physically implementing their garments. I discuss the evaluation of Bod-IDE using demonstration and heuristic type toolkit evaluation.

Chapter 6: Conclusion and Future Work

I conclude this thesis by outlining the main findings and contributions. I also discuss future work for the prototyping tools TortillaBoard and Bod-IDE. I also discuss other considerations concerning how to evaluate the utility of these systems with eFashion designers.

Chapter 2 Background & Related Work

In this chapter, I provide an overview of the existing literature and related work underlying eFashion in support of this thesis. To understand what the state of eFashion is, existing processes the tools used to author interactive garments, and the tools used to develop eFashion, I present this literature review as context for this thesis. I examine the core principles of fashion design, designing electronic fashion, electronic garment prototyping tools, and my research approach. I then show the current tools and approaches that fashion designers can use to explore interactive behaviour and existing eFashion technologies on their garments. From this body of work, I describe, I identify a gap in the state-of-the-art prototyping tools, which is the few ways that eFashion designers have to refine and iterate interactive behaviours on their garments.

2.1 Core Principles of Fashion Design

In this section, I describe the core principles of fashion design and how eFashion designers distribute their fashion ideas to end-wearers. I examine the communicative needs of clothing, how designers meet these communicative needs through three basic principles of fashion design, interactivity as a new dimension to express the three basic elements, and disciplines in fashion and the processes that disseminate fashion ideas.

2.1.1 Designing Clothes for Consumption

In the context of this thesis, I define several terms: clothing, garments, wearers, and accessories. Clothing are objects that people use to cover their bodies. *Clothing* is a collective term to describe objects that people can wear on our bodies, usually made from sheets of fabric.

A *garment* is a physical item (e.g., pants, shirts, dresses, costumes) that can be worn on the body; it is typically made using sheets of fabric. A *wearer* is a person that wears garments. *Accessories* are removable items (e.g., belts, hats, suspenders) can enhance the visual appearance of clothing but are not clothing themselves and are easily removed. Fashion design concerns the creation of clothing and accessories. In this thesis, I will only address fashion design for clothing.

In the modern world, consumers now have communicative needs for clothing. In *Consumer Behaviour Towards Dress*, cultural theorist George Sproles suggested a model of the primary functions of the utility of clothing (Sproles, 1979). According to Jones (2011), Sproles suggested the following primary functions of clothing: utility, modesty, immodesty, adornment, symbolic differentiation, symbolic affiliation, psychological self-enhancement, and modernism.

These functions of clothing, except utility, suggest that consumers have communicative demands for clothing and fashion designers design clothing to meet some of those needs. For example, a police uniform uses consistent colors and lines to help *symbolically differentiate* themselves from a crowd and to communicate authority. Further examples include: Swimwear can be designed to enhance the appearance of body parts or hide imperfections (*immodesty/modesty*). Mass produced clothing are designed to be mixed and matched so that individuals can have more combinatorial choices to express themselves (*psychological self-enhancement*). Clothing of a common theme like western-themed clothing (e.g., cowboys) can suggest belonging to a western-themed community (*social affiliation*).

Consumers thus have communicative needs and fashion designers meet these needs through the design of clothing.

However, how do fashion designers express and communicate these functions through textiles? I discuss in the next section.

2.1.2 Elements of Clothing Design

Using three basic elements of clothing design, fashion designers can express a large variety of clothing. As Jones (2011) suggests, designers use the following three basic elements of clothing design they can alter on a garment: silhouette, line, and texture.

Silhouette refers to "the overall outline and shape of the worn garment as its silhouette… Silhouette is almost always the first impact of a garment, as seen from a distance and before the details can be discerned" (Jones, 2011).

Lines can be "hard or soft, implying rigidity or flexibility. It can move in various directions, leading the viewer to look across, up, down or in a sweep around the body. It can emphasize or disguise other features. It can create illusions of narrowness or fullness. The most common use of line in fashion is in the seaming of the pattern pieces and in fastenings" (Jones, 2011).

Texture refers to the fabric or material the garment is made with. "It is both the visual and sensual element of fashion design" (Jones, 2011).

To express the basic elements, fashion designers have several design principles they can vary to make different garments. There are several ways that fashion designers can manipulate the three elements through the following design principles: "*repetition, rhythm, graduation, radiation, contrast, harmony, balance and proportion*" (Jones, 2011). Using clothing design elements and design principles, a fashion designer has various ways to combine textiles to achieve different looking garments.

2.1.3 Interacting with Clothing

Interaction is a design principle that designers can express in the three elements of clothing design. In addition to the design principles mentioned, some garments can dynamically change the main elements of their design as the wearer goes about their daily activity. Using the wearer's body to supply mechanical movement garments can alter different aspects of the garment. For example, in Figure 2 a wearer could raise their arm to alter their garment's *silhouette*. The wearer lifts their arm pulling the skirt upwards and covering their underarm with an extended manifold of the skirt. More examples of dynamic clothing effects include: zippered sweaters, when zipped or unzipped changes the number of visual *lines*; and two-sided jackets with smooth and furry sides that can be turned inside out to change *textures*.

Figure 2 The skirt of this dress is attached to the wearer's arm. The wearer can alter the silhouette of by moving their arm.[3] Photo Credit: Jones (2011).

Electronics can provide access to new kinds of input data and output techniques without limiting the designer to the mechanical movement sourced from the wearer's body. Using electronics, fashion designers have new tools to augment the three basic elements without using the human body's mechanical movement. An electronic-enhanced garment can, for example, pull

[3] © Central Saint Martins College of Art & Design. (Jones, 2011).

the fabric attached to the wearer's arm in Figure 2 by using motors and cables based on the number of people in the room without the wearer's body moving or having the wearer mentally count. Fashion designers can also use other input sources (e.g., ambient brightness, the wearer's heartbeat) to allow the wearer to interact with their garment in different ways. Thus, eFashion came about as fashion designers explored new ways to interact with garments through electronics. I discuss more on how eFashion designers make interactive garments in section 2.2 Designing Electronic Fashion.

Fashion designers thus have many ways to express the basic elements of clothing design. By experimenting with different design principles, designers can address the communicative demands of clothing. Once a designer has developed a garment, they will need to distribute their garment's design. In the next section, I discuss how ideas in fashion are disseminated.

2.1.4 Disseminating Fashion Ideas

In this section, I describe processes that allow fashion designers to disseminate fashion ideas, the different disciplines within fashion, and the processes that enable the realization of fashion ideas to be produced and sold. I also discuss the challenges that eFashion designer face when disseminating their fashion ideas.

Commercial fashion designers respond to market demand. Designers in commercial fashion develop clothing according to market reports on consumer demand leaving little room to experiment with different ideas in fashion. Clothing in commercial design perhaps has the most ubiquity in all of fashion. Commercial fashion designers make clothing to be mass produced and marketed to different groups of consumers. Commercial fashion designers typically make clothing in standardized sizes, also known as ready-to-wear (Jones, 2011). These garments come in separate pieces such as shirts and pants which can be mixed and matched, satisfying the demand for *psychological self-enhancement.* These are clothes that are sold as-is and in a finished state. Designers are expected to design clothing for company brands, or to market reports of in-demand clothing (Jones, 2011).

High fashion designers develop experimental clothing. While high fashion garments are not considered affordable for consumers, it is a venue where designers can artistically develop, experiment, and present new fashion ideas. In contrast to commercial fashion, high fashion (also known as haute-couture), is a discipline where fashion designers can create one-off experimental clothing to explore new ideas in fashion. High fashion tends to hold high prestige because of skillfully hand-made one-off garments (Jones, 2011). High fashion designers typically showcase their experimental work on fashion runways, venues with a long stage that fashion models walk on while wearing the designer's garments.

Fashion journalism and media disseminate fashion ideas. Fashion magazines and mass media report on ideas showcased on fashion runways influencing market demand for new fashion styles. According to Jones (2011), ideas in fashion can exhibit the "trickle-down effect". Fashion ideas make their way towards mass dissemination through mass media (television, magazines, internet) and word-of-mouth, starting with music-bands, celebrities, and elite high-culture. Ideas make their way through trade shows, fashion leaders, and magazines excite consumer demand for new styles. Commercial fashion designers pick up this demand through their market reports and fulfill this demand for retail clothing stores.

An example of the impact of high fashion runways. One example of high fashion runways influencing consumer demand was in the debut of relaxed-fitting clothes from Japanese fashion designers on international high fashion runways. In the 1980s, Japanese fashion designers made their debut on international runways in Paris with their alternative fashion philosophy. They presented women's clothing designed for modern living as opposed to the already established notions of western style. Despite receiving mixed responses by fashion critics with their "bag lady" or "ragged chic" looks, they inspired a new trend towards high-quality textiles and relaxed fitting style clothing (Marra-Alvarez, 2010). American retailers soon found customers adopting the relaxed fit style of clothing from the Japanese clothing brand *Comme des Garcons* due to their thoughtful use of high-quality fabrics and the relaxed fit style that gave the wearer's body new freedom of movement compared to existing clothes at the time (Marra-Alvarez, 2010). By experimenting and showcasing their ideas on the runway, the Japanese high fashion designers managed to influence market demand for their relaxed fit style of clothing through high fashion runways.

One-off garments can be made by makers too. The practice of creating one-off custom-made garments is not exclusively for high fashion designers, but makers can participate as well. Makers are a community of do-it-yourself creators. Within makers, there are people capable of making their garments for themselves (e.g., cosplay, knitters). Makers can also make clothing and can freely experiment with clothing design.

High fashion designers showcase on different venues than makers. Unlike makers, high fashion designers have different production goals for their garments. High fashion studios fund designers and have goals to showcase their work to gain manufacturer interest, to secure exclusive clothing collection productions, or to develop experimental art (Jones, 2011). Makers have few options to showcase their work outside of online communities and typically must fund themselves to develop their clothing.

Dissemination of eFashion through high fashion runways. Through high fashion, an eFashion designer has the highest chance of influencing market demand through fashion runways. Runways like MakeFashion fund eFashion designers to develop and showcase original one-off electronic garments. They have extensive collections of eFashion garments including *Lumen Couture* (Klukas, Corner, & Nylund, 2017), a hat that projects images onto clothing; and *Gamer Girls* (Housego et al. 2016), a pair of dresses with a built-in multiplayer video game. These electronic garments envision a possible future vision of how technology can integrate with fashion design. Since 2013, MakeFashion has conducted many shows throughout Canada, United States, and China providing competitive funding for fashion designers looking to develop eFashion garments. Their international presence provides a venue from which eFashion garments can build demand and inspire fashion designers.

eFashion design implementation challenges. Despite international runways for eFashion, there commercially exist few eFashion garments. There may be many reasons for eFashion not existing in retail stores such as: the cost of an eFashion garment may be too high or that significant changes are needed in the commercial fashion production process to accommodate the production of electronics embedded on clothing.

An approach to using prototyping tools. I believe that by helping high eFashion designers overcome the technical skills necessary to build eFashion garments, they can explore new interactive garments and increase their output of new eFashion ideas. Currently, only a few designers and garments can be a part of a high fashion runway because of the high cost and skill needed to create the exceptional quality expected. Furthermore, implementing an eFashion garment incurs additional skill and time requirements to create custom circuitry, solder electronic components, program behaviour, etc. I believe that by allowing Fashion designers to envision the interactive behaviour of their garments before overcoming these technical requirements will save them time and effort and helping them explore new expressions of interactivity in elements of clothing design on the runway.

In the next two sections, I will examine the technical challenges of implementing an eFashion garment in greater detail. In the next section (2.3) I examine the challenges of integrating electronics into garments and the current garment technologies that eFashion designers have access to integrate on their garments. Then in section (2.4), I examine current eFashion prototyping tools and the lack of interactivity prototyping on garments.

2.2 Designing Electronic Fashion

In this section, I will examine technologies and tools that support the implementation of eFashion. I will explain in greater detail the requirements to integrate electronics onto garments, a sample of output technologies for garments, a sample of input sensors for garments, and a sample of textiles with new material properties. I then describe in greater detail why these technologies are difficult to access by eFashion designers.

2.2.1 Communicating Meaning on Interactive Garments

eFashion is an emergent field in fashion that concerns the design of garments that feature electronic components. In eFashion, garments use electronic sensors and components to allow its wearer to interact with the garment. In this thesis, an interactive garment is one produces some output in response to some inputs. Computers or microcontrollers on the garment interpret the garment’s sensors (e.g., buttons, heart rate) and communicate back to either the user personally (e.g., vibration) or on the garment itself as a public display (e.g., LED displays).

The way the garment behaves in response to input data can alter the way people interpret its actions. For example, the *Robotic Spider Dress* (Wipprecht, 2015) and *enVella* (H. Lin, Coleman, Ip, & Man, 2011) both communicate differently about how open the wearer is to other people for conversation.

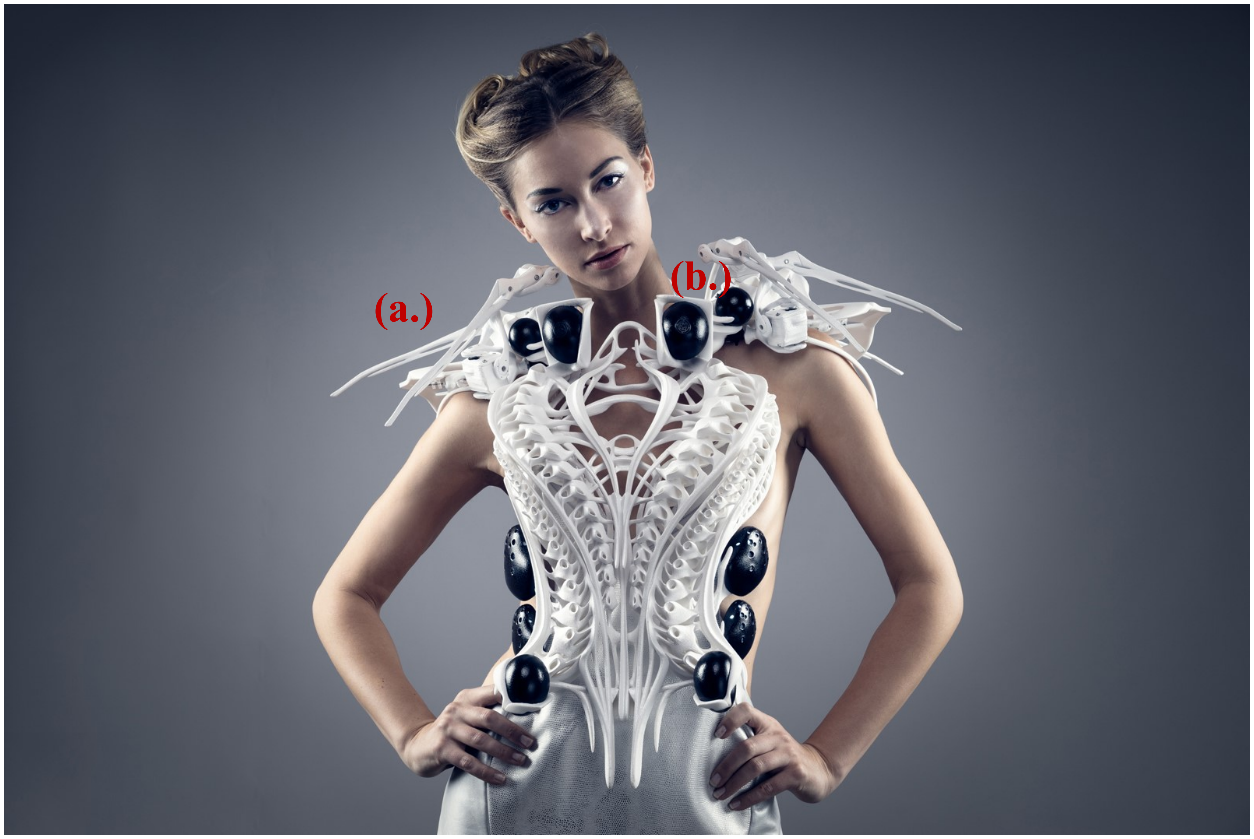

Figure 3 The *Robotic Spider Dress*. Using proximity and skin sensors, it lunges its legs at others who that invade the wearer's personal space. (a.) legs of the spider dress that lunge forth, and (b.) the black orbs containing the proximity sensors. [4] Photo source: Kaplan (2015).

Wipprecht's (2015) *Robotic Spider Dress* is an example of an interactive eFashion garment that uses proximity sensors and the wearer's anxiety to protect its wearer's personal space actively. When a passerby approaches too closely to the wearer, the dress's legs – located

[4] Photo source: Kaplan (2015)

at the shoulders (Figure 3a) – would lunge outwards of the wearer to intimidate the intruding person. The distance at which the dress begins its defensive positioning is related to the wearer's stress levels (Kaplan, 2015). The lunge effect alters the silhouette of the garment both visually and practically to defend its wearer. All the wearer needs to do is wear the dress, and the dress responds based on the information from its wearer and nearby people. In contrast to non-electronic clothing, the wearer would have to continually monitor when other people are nearby and manually actuate the spider legs themselves.

Figure 4 enVella covering its wearer with fans[5].

enVella (H. Lin et al., 2011) is another similar concept dress, but it defends its wearer without using aggressive techniques. When the wearer's body temperature and heart rate increases, the dress opens out fans that cover and protect the wearer's face. Like the anxiety

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[5] Image source (video): https://youtu.be/QOx2D5_6coc | (H. Lin et al., 2011)

response of the robotic spider dress, enVella protects its wearer from potential harm. However, enVella protects its wearer by covering their face (Figure 4). This difference shows that the way an electronic garment behaves can be made to communicate different meanings, in this case, aggressiveness, despite similar functions.

In the following section, I describe some advances in form factors for electronic components that enable designers to integrate electronics onto garments and what technology exists to explore interactivity in eFashion design.

2.2.2 Integrating Electronics in Garment Aesthetics

eFashion demands electronics to either be hidden or integrated into the aesthetics of the garment, making it technically difficult to produce a visually appealing garment. In the *Robotic Spider Dress* (Wipprecht, 2015), the electronic components – such as the servos actuating the legs and proximity sensors – on the dress have been designed to be hidden away or integrated into the visual aesthetic. Electronic parts thus need to be made in new form factors that are suitable for visually demanding applications such as high fashion and be physically durable to withstand movement and washing.

Electronic components on garments also need to be safe to wear and washable. Desirable properties of electronic components are: mouldable to the wearer's body, stretchable, safe, comfortable, durable and washable. Unlike consumer electronics – which are typically in rigid protective boxes – interactive garments may require electronic components to fit or stretch around the contours of the human body. Furthermore, eFashion garments need to be comfortable and safe to wear since electricity may cause bodily harm. The garment's parts (electronic and non-electronic) also need to be washable and withstand continued use. These example requirements show the need for electronics in eFashion to be designed to withstand new environments and new aesthetic use cases.

Technology researchers have been developing new form factors for electronic components that allows them to be integrated into the garment's visual aesthetic. The Arduino LilyPad (Buechley et al., 2008), is a slim low profile microcontroller that designers can sew onto clothing. The microcontroller interfaces to other sewing compatible LilyPad components using conductive thread. This innovation allows fashion designers to embed their electronics into the design's aesthetic and hide them in-between seams or under different layers. Other commercially available wearable electronics kits like StitchKit[6] are designed to withstand daily wear on clothing. Buechley & Eisenberg (2009) developed a collection of methods that describe how to implement fabric printed copper boards (fabric PCBs) that can directly interface with integrated circuits. Their methods allow electronic components to integrate more seamlessly with the garment.

Material science has also been developing soft PCBs that enable electronic circuits to be stretchable, soft, and flexible. Silicone Devices (Nagels et al., 2018) allows makers to use commodity fabrication tools to create soft-stretchy silicone devices without the need to access special laboratory equipment or materials. These custom silicone devices can be washable and skin friendly for clothing used daily.

With these new form factors, eFashion designers currently have the means to integrate electronics in an aesthetically pleasing way onto their garments. In the next section, I review some output technologies that designers can use to express on garments.

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[6] http://www.stitchkit.io/

2.2.3 Output Technologies

Output technologies are discrete components that allow computers or electronics to communicate with its wearer or other people. Researchers have been looking at developing technologies that are attractive and more accessible for applications on clothing. There is also interest in developing techniques to allow garments that move on their own.

Researchers have been developing output devices that blend or try to mimic the affordances of textiles. Ebb (Devendorf et al., 2016), is a woven fabric textile embedded with thermochromic ink. It is a display device that updates at 30-second time intervals. The fabric display was appealing to fashion designers since light-emitting screens (e.g., LCDs) had negative associations likened to "entryway into a 'world of hurt'" and that Ebb offered a more "painterly" use of technology (Devendorf et al., 2016). Fabric folding (Moere & Hoinkis, 2006) is another fabric display technology that uses actuated folds to reveal an underlayer in the garment.

There is also a variety of ways to add motion to fabrics. Shape memory alloys can be heated to return to a predefined a shape but can be challenging to work with since designs often need to be reversible and to account for the large amounts of power to heat the alloys to change. Textile researchers are also interested in finding new methods of actuation. Awakened Apparel (Perovich et al., 2013) is a method of embedding pneumatic air tubes to actuate textiles. Awakened Apparel offers a softer and faster alternative to creating shape changing clothing. Combining traditional sewing techniques, Filium (Kono & Watanabe, 2017) is a method of actuating drawstrings using precision servo control. This method allows movement actuation using traditional sewing techniques and minimal electronics outfitting.

Designers can also experiment with robotics and automation on clothing. As output technologies become more behaviourally complex, technology can make clothing appear to be automated. In Rovables (Dementyev et al., 2016), a garment-crawling robot can draw lines on clothing, actuate fabric, move accessories, provide tactile feedback, and provide a means for input. Rovables can act as a personal assistant by receiving a wearer's incoming phone call and move a microphone towards the wearer's ear.

With these output technologies, eFashion designers have a variety of ways to express the state of the garment through new qualities of electronic components. In the next section, I review input technologies that eFashion designers can use to create behaviour in their garments.

2.2.4 Input Technologies

Interactive garments will need to react to the wearer's state, activities, and context to interact with its wearer. Output technologies can enable garments to interact with the wearer, but input technologies can enable garments to know the wearer's environment. In this section, I review input technologies that designers have adapted to for use on garments.

eFashion designers have explored input technologies on interactive garments such as sensing how the garment is tied, wearer's internal state, what the wearer is thinking, internet data sources (e.g., social media), and to make garments behave in new meaningful ways. Scarfy (von Radziewsky, Krüger, & Löchtefeld, 2015) is a scarf that can sense how it is tied. It uses flex sensors embedded in the scarf to its state and can respond with actuating shape memory to display the wearer's notifications. Monarch (Hartman et al., 2015) uses electromyography (EMG), or muscle sensors, to measure the wearer's movements and responds by actuating folded flaps on the wearer's shoulders. *Common Experience* (Blair & Blair, 2014) is a dress that makes uses of Electroencephalography (EEG) to visualize brain activity levels through the garment's lights and actuate parts of the garment (Klukas, 2014). *Positive Feedback* (Blair & Blair, 2015) is a party dress that visualizes the wearer's social media activity ("MakeFashion | Positive Feedback," 2015) helping the wearer show off their online popularity.

These examples of how eFashion designers use input technologies on garments and show that there is interest in using information and data from beyond the wearer's body. In the next section, I review some more technologies that can give new material properties to garments.

2.2.5 Electronic and Non-woven Textiles

In addition to output and input technologies, researchers have also developed new textiles that feature new material properties. These properties enable designers to explore new behavioural and interactive functionality on clothing. In this section, I review some of these textiles.

Throughout fashion history, access to new textiles has influenced new fashion styles. The invention of Spandex in 1959 initially started in fitness wear, but it solved the sagging and bunching problems of nylon. It had abilities to mold itself around the wearer's body without restraining it, making spandex popular in aerobics (Genova & Moriwaki, 2016) and eventually became common in everyday clothing (O'Connor, 2011). Today, new textiles researchers are developing new textiles with new material properties compatible with electronics.

With the development of new electronic textiles (eTextiles), textiles can now interface with electronics and have interactive capabilities. Unlike the discrete input and output devices technologies discussed previously, eTextiles exhibit properties of a fabric such as being stretchable, flexible, and store digital data. Google's Project Jacquard (Poupyrev et al., 2016) can sense touch using conductive threads woven into a grid-like pattern. Ebb is a textile that changes color using thermochromic ink and heat elements built into the fabric (Devendorf et al., 2016). Sphelar Power Company has developed a textile with solar power harvesting capabilities ("The world's first energy-harvesting textile with micro spherical solar cells - News - Sphelar Power Corporation," 2012). NASA has also developed a textile that can store digital data (Rajan, Garofalo, & Chiolerio, 2018). Furthermore, a wide variety of fabric-based input sensors have been developed using fabric components such as fabric tilt sensors, fabric bend sensors, fabric buttons, and fabric stroke sensors (Satomi & Perner-Wilson, 2011). These sensors have been built with conductive fabrics and can be made to flex and stretch with the underlying textile.

Using new fabrication techniques, designers have access to new non-woven textiles allowing them to produce textiles with computer-precision specified properties. It is common for eFashion designers to use translucent fabrics to diffuse LED lighting on their garments. With the invention of new textiles and production methods (e.g., 3D printing), designers can specify exact parameters to define textile properties and the property's effect strength. For example, *Kinematics Dress 1* (Rosenkrantz & Louis-Rosenberg, 2013) is a dress that was 3D printed as a single folded sheet of nylon and it flexes via hinges between the interlocking triangles (Rosenkrantz, 2014). BioCouture has developed a textile that can be grown from cellulose producing bacteria (Fairs, 2014). Sekine et al. (2018) built a dress that uses sheets of liquid crystal film and uses electric signals to change the opacity of the film.

Non-woven textiles introduce new textile properties that can be used to augment the effects of existing eFashion technologies. Thus, designers have access to many technologies for output, sensing, and textiles. However, how do designers access these technologies for use in their garments? I discuss in the next section.

2.2.6 Accessing eFashion Technologies

Many of the eFashion technologies mentioned in this section are difficult to access by eFashion designers. There already exists many kinds of output, input, and textile technologies for eFashion designers to explore interactive garments. The eFashion input, output, and textile technologies I discussed are custom-made research prototypes. These prototypes are not necessarily mass produced which and may be challenging to explore and access by fashion designers due to custom engineering processes. On the fashion runway, dissemination of electronic fashion ideas would be challenging without access to reverse engineering specialists.

One approach to making these devices more accessible to eFashion designers is by developing prototyping tools that facilitate interfacing fabrics with electronics. In the next section, I review electronic garment prototyping tools to discuss why it is challenging for eFashion designers despite tools to access these technologies.

2.3 Electronic and Fashion Prototyping Tools

In this section, I examine various fashion prototyping tools and how they may be used to prototype interactive garments. In the previous section, I examined the output, input, and textile technologies that researchers developed but are difficult to access by eFashion designers due to one-off custom engineering processes. The tools I examine here may help fashion designers prototype their garments. I examine digital garment design tools, physical eFashion prototyping tools, and augmented reality prototyping tools.

2.3.1 Virtual Garment Design Tools

Virtual prototyping tools like Fashion CAD, help designers prototype the look and feel of their garments using virtual sewing patterns before producing the garment physically. Fashion computer-aided design (Fashion CAD) is software designed to help fashion designers create designs (patterns) to be later exported as a pattern to manufacture. Example software includes: Seamly2D[7], Optitex ODev[8], CLO[9], and Tuka3D[10]. Fashion CAD software helps designers create sketches, design patterns, and generate pre-set clothing sizes. There are also built-in template patterns built into the software to help designers quickly start with a style of garment (e.g., low-cut pants, tank tops) and make alterations to its aesthetics. Software like CLO also has tools to add interactive non-electronic hardware like zippers, buttons, and elastics.

[7] https://valentina-project.org/
[8] https://optitex.com/solutions/odev/3d-production-suite/
[9] https://www.clo3d.com/explore/features
[10] https://www.tukatech.com/3D-fashion-design-software/TUKA3D

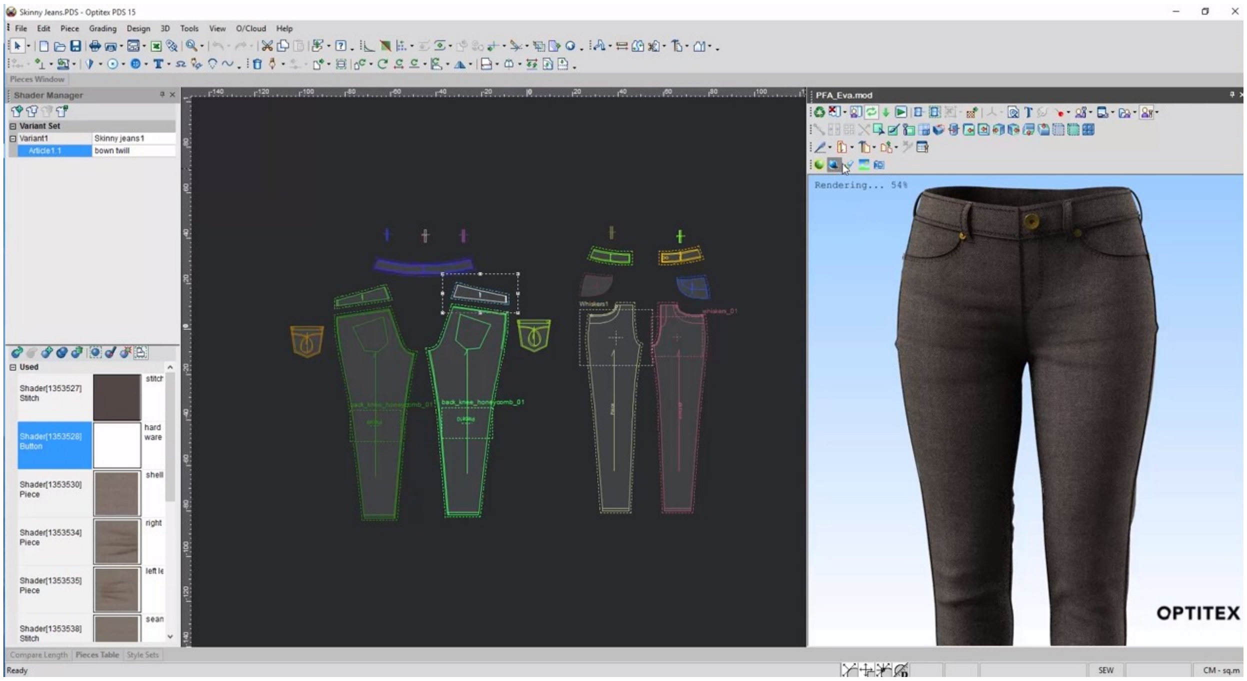

Figure 5 Optitex Fashion CAD software, with realistic garment renderings of a pattern for a pair of jeans[11].

Some software (e.g., Optitex ODev and CLO) can generate 3D renderings of the garment patterns on a virtual mannequin allowing the designer to make real-time changes to the design (Figure 5). CLO takes this virtual mannequin further by simulating stresses on the human body to show areas of discomfort. CLO and Tuka3D can also support 3D models of males and females. Tuka3D can also simulate human body movements such as cycling in a bicycle or walking on a runway. Real-time garment simulation can be useful for rapid prototyping, previewing designs before committing time and resources to sew the garment.

One key advantage of Fashion CAD software is that it can allow a designer to preview renderings of their garment's visual appearance. In commercial fashion design, designers are expected to submit high-quality finished illustrations (also known as *croquis*) of their garment

[11] Image Source (video): https://youtu.be/BFz4UXj8N3E | Website: https://optitex.com/solutions/odev/

designs to their clients (Jones, 2011). These illustrations are meant to emphasize elements of the garment's mood, texture, or the appearance of the intended wearer. Fashion designers use watercolors, paints, wax and other illustration materials to emphasize the intended texture, lines, or silhouette of the fabric on their garment. Computers are increasingly popular tools to supplement these illustrations as it can improve the level of detail and the variety of textures without relying on hand-drawn skill. Furthermore, designs can be exported as patterns and be later used to directly operate machinery or sent to a manufacturer for production review.

All the mentioned Fashion CAD tools support prototyping for the look and feel of the garment but have not yet supported the design of interactive garments. There is potential for Fashion CAD to extend to interactive garments since there exist similar design tools for prototyping user interfaces on computers (e.g., Moqups[12]). Using drag-and-drop interactive components, designers can add interactive widgets to their garment patterns. However, there does not yet exist commercial tools for developing interactive garments in CAD software.

While virtual garment prototyping tools can help designers develop their garments, they do not yet support interactive components on garments. In the next section, I examine physical eFashion prototyping tools as an approach to prototyping interactivity on clothing.

2.3.2 Physical eFashion Prototyping Tools

Physical eFashion prototyping tools are tools that allow eFashion designers to integrate interactivity onto their garments using hardware. Through special form-factor electronics designed to embed onto fabric, physical prototyping tools help eFashion designers integrate

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[12] https://moqups.com/

electronics with minimal aesthetic impact without the need to modify existing hardware to fit. Arduino Lilypad (Buechley et al., 2008) – intended for implementing complete interactive garments – allows designers to integrate sewing-compatible microcontrollers and electronic components onto clothing. However, designers need to make semi-permanent connections and hide or integrate the components into the garment's aesthetic limits alterations. MakerWear (Kazemitabaar et al., 2017) uses reconfigurable magnetic hexagonal pieces that form a wearable physical programming language; this kid-friendly platform offers a non-permanent way to define the behavior of wearable technologies. However, it aesthetically constrains eFashion designers to its hexagonal grid.

Some toolkits also help designers solve engineering problems early in the design process. Stitch Kit[13] is an Arduino-based board that has been designed to be solderless, durable for everyday use, and communicate with other existing component kits like Grove[14]. They also have modified existing components like the LED strip to be easily sewn onto fabric. Thus, helping designers address some aspects of the look and feel in their prototype.

Physical eFashion prototyping tools are useful tools to consider when building prototypes to support implementation. These tools can offer a wide variety of input and output components to build vast combinations of interactive behaviours. They also help designers solve several engineering and aesthetic integration challenges associated with the implementation of an interactive garment.

Despite enabling designers to embed electronics on to garments, these toolkits still require the designer to implement their garments physically. Designers still need to consider low-

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[13] http://www.stitchkit.io/
[14] http://wiki.seeedstudio.com/Grove_System/

level implementation details like soldering electronics, integrating electronics into the aesthetic of the garment, and programming the underlying hardware. Working with electronics thus takes a considerable amount of time before the designer can reach a functioning prototype to iterate on the design. Furthermore, designers will require engineering those custom research prototypes to compatibly interface with the tool.

There are ways to combine the Fashion CAD approach and physical approach to allow designers to explore interactive technologies on garments – without physically implementing them – using augmented reality. In the next section, I review some augmented reality techniques for prototyping virtually.

2.3.3 Augmented Reality Prototyping

Augmented reality can allow eFashion designers to create virtual interactive garments before physically implementing their garments. Augmented reality (AR) is a technique that overlays virtual assets on top of real-world objects in real time (Azuma, 1997). Often through camera-enabled devices – like mobile devices (e.g., Vuforia[15]) or head-mounted displays (e.g., Microsoft HoloLens[16]) – computer vision algorithms track real-world objects and add extra content on top through the device's screen. AR components are particularly useful for eFashion design because AR can add interactive virtual objects on garments without physically soldering, powering, or programming the components. Virtual interactive components is therefore ideal for exploring alternative garment behaviours because of the low cost to alter them.

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[15] https://www.vuforia.com/
[16] https://www.microsoft.com/en-us/hololens

Augmented reality has been used as physical stand-ins for electronic components when developing prototypes. Polymorphic Cubes is an AR system that allows virtual stand-in components that can interact, behave, and integrate in-place of the physical electronic component. Mirror Mirror (Saakes, Yeo, Noh, Han, & Woo, 2016) is a virtual fitting room mirror that allows a designer to create shirt print patterns on top of their bodies. Using physical gestures, designers paint on top of their bodies to create T-shirt designs in real time. Designers can explore the look and feel of their garment with Mirror Mirror, but the system does not yet allow a designer to explore how their garment behaves.

Augmented reality has also been used to support Fashion CAD functionality as well. DressUp (Wibowo et al., 2012) is a physical tool for generating garment patterns using various physical wands on a mannequin. Designers use different wands to cut or generate virtual surfaces on a physical mannequin which then renders a preview of a virtual garment on a virtual mannequin.

Researchers have also experimented with using augmented reality on the body, as a source of input and overlaying information on top of it. Body As Canvas (Hoang, Ferdous, Vetere, & Reinoso, 2018) is an Augmented reality system that allows the body as both input and display. It uses a body posture sensor and a fitness wristband to overlay visual information (e.g., a beating heart on top of one's chest) on top of its user. Body as Canvas is a technology that can be used by eFashion designers to display information and use the body as input. The focus of this work is to enable eFashion designers' greater access to explore these kinds of input sources and output methods on interactive garments.

Virtual prototyping tools present two opportunities: it allows eFashion designers to develop garment prototypes they can rapidly alter and they allow designers to explore interactive garment technologies with little cost. In a similar approach to Fashion CAD tools, eFashion designers can rapidly iterate on their designs through a virtual prototype of their garment without the need to physically implement their garment. Interactive components can be embedded and simulated onto virtual garments at little cost to implement. By using virtual components, eFashion designers can explore custom research eFashion with reduced engineering costs.

I believe that by allowing designers to envision interactive behaviours on their garments before physically implementing them will help them explore new interactive technologies. There are opportunities in physical and augmented reality to develop prototyping tools for interactive garment design. In the next section, I describe my research approach to developing prototyping tools.

2.4 Chapter Summary

Through high fashion, eFashion designers can explore and inspire new visions for interactive garments. Interaction is a new dimension that fashion designers can use to explore new expressions of the main elements of clothing design. By showcasing their explorations in interactive garments on the fashion runway, eFashion designers can envision new communicative functions for clothing and thus potentially generate consumer demand for purchasing eFashion.

Garment technology and tools are however difficult to access by eFashion designers. Fashion designers and researches have already built vast varieties of output, input, and textile technologies but these technologies are difficult to access since they are one-off custom research prototypes and require specialists to work with them. While there exist some eFashion prototyping tools to help build garments (e.g., Arduino LilyPad), these tools support the implementation of an eFashion garment which leaves little room to experiment with the behaviour of the garment. Other tools like Fashion CAD can support the look and feel but these tools do not yet support adding interactive elements onto garments. One approach is to use augmented reality to prototype the interactive behaviour of a garment before physically implementing it. Using a similar approach to Fashion CAD, a designer can use virtual prototyping to explore interactive behaviours on garments in real time. Augmented reality presents an opportunity to develop a virtual prototyping tool that both allows fashion designers to explore interactive building blocks on their garments before physical implementation. Thus, saving them time to explore and refine their garments, and increasing their output on fashion runways.

To develop a prototyping tool for eFashion design, I must understand the skills and practices of eFashion designers. What is currently not known is how eFashion designers currently develop their garments, what techniques they use, and the challenges that they face. Knowing these insights about their practice will inform the design of a prototyping tool and its role in developing eFashion. In the next chapter, I will develop an understanding of what kinds of eFashion garments that designers make with the current eFashion tools and develop case studies on high eFashion designers to understand how they currently develop and explore technology on clothing.

Chapter 3 eFashion Design Case Studies

In this chapter, I present and discuss a quantitative analysis on the context of how makers currently use eFashion tools, and case studies on two eFashion designers and how they conduct their practice. In the previous chapter, I determined that existing prototyping tools currently do not yet support prototyping interactive behaviours on garments. Thus, there are opportunities to improve existing fashion design tools to support eFashion design. The objective of this chapter is to find challenges and describe opportunities in an eFashion designer's practice that can be supported by an interactive garment prototyping tool. These insights will then become a starting point to develop prototyping tools in eFashion design.

To understand what eFashion designers currently make in eFashion, I first present a quantitative analysis on what makers already create with Arduino LilyPad to determine meaningful building blocks for a prototyping tool. This sample provides a context into what kinds of eFashion garments are currently being made using an existing eFashion tool.

I then illustrate two examples of eFashion designers and how they develop eFashion garments for the runway. Both analysis and the case studies will then help develop design guidelines to inform the creation of prototyping tools based on the challenges that eFashion designers face when implementing their interactive garments.

Before conducting the interviews for the case studies, I sampled a small set of instructables projects on what eFashion makers currently make with the Arduino LilyPad platform as a context to inform the design guidelines. I examined interactive garments on instructables.com that used LilyPad for what components they used and the intended use case for the garment. The findings provide some ideas for meaningful building blocks in a prototyping tool.

I then examine two eFashion designers that have presented on an eFashion runway show. I show how they developed one of their most recent garments from when they conceptualized the idea for a garment, to brainstorming ideas, and to the challenges of building their garment.

Finally, I end this case study chapter by synthesizing the findings into design guidelines to inform the creation of interactive garment prototyping tools. These guidelines reflect on the challenges the eFashion designers faced when implementing their garments and potential ways to address them in a prototyping tool.

3.1 Examining LilyPad on Instructables

Before interviewing eFashion designers, I sampled a small set of LilyPad projects on the website Instructables[17] to determine what projects are already being made by makers on the platform. In this search, the goal is to determine potential building blocks for a prototyping tool. I searched on Instructables – an online community for do-it-yourself instructions – for “lilypad” to find wearable projects. User posts on the website are intended to help readers build projects, but they are also detailed build artifacts. These instructional posts have lists of materials, the steps to recreate the build, and pictures or videos of the project. LilyPad is a well known, commercially available eFashion platform. These project instructions are valuable to understanding what the process of building an eFashion garment is like and the intended use case for their interactive garments.

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[17] https://www.instructables.com/

In this search, I analysed what kinds of garments people made, the components they used, and the intended use of their garments. I sampled 39 projects total (38 from Instructables, and 1 from Hackster[18]) that used Arduino LilyPad and can be worn on-the-body. This sample includes 17 garments (e.g., shirts, hoodies, pants) and 22 accessories (e.g., gloves, scarves, slippers). As accessories are not the scope of this thesis, I will only talk about the 17 garments.

[18] https://www.hackster.io

3.1.1 Findings

In this section, I present the findings from the sampled projects. Data for all 17 projects examined can be found in: Appendix C: LilyPad Projects. In the appendix, each project is numbered and I will refer to the projects as P1, P2, P3 and so on.

Use cases of garments. I categorized projects into nine categories by the author's intended use of their garment. The *garment* category is for projects that are intended to be worn casually where the primary means of interaction is the visual admiration of the garment.

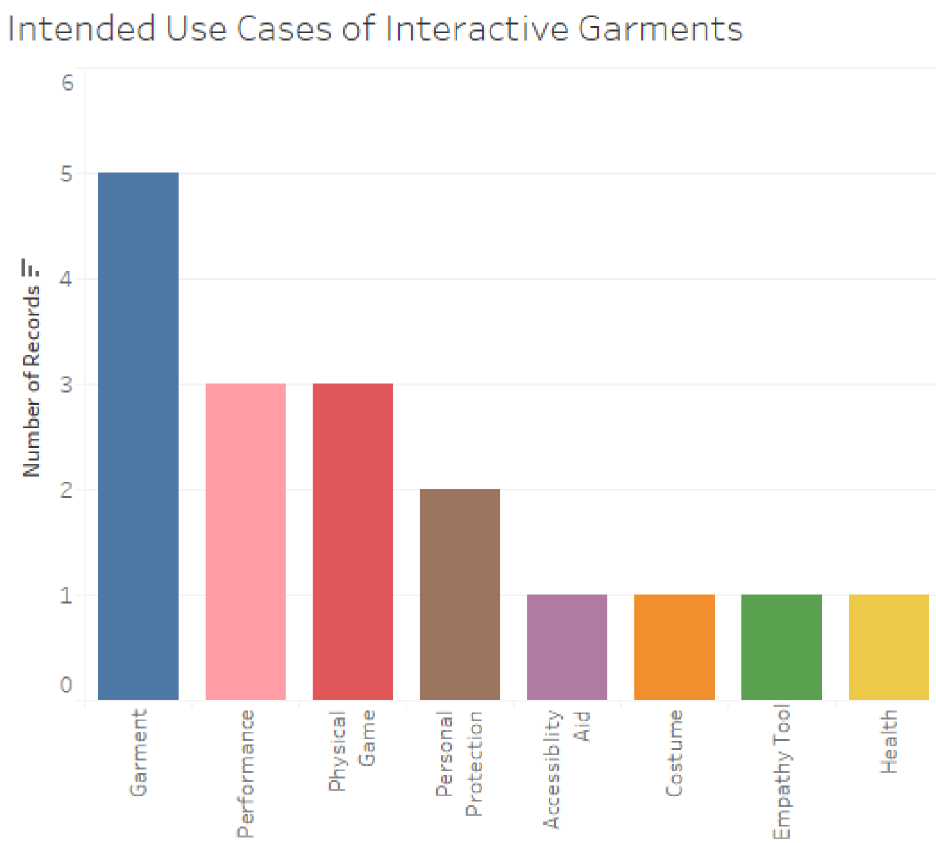

Figure 6 Intended use cases of interactive garments sampled on Instructables.com (N=17)

I discovered 12 projects that are garments that have interactions intended for use outside of visual appeal (Figure 6). The 3 *performance* projects are garments that enhance the performance of an actor or dancer. One project enabled a swordplay choreographer to instruct their students using visual cues on her shirt rather than verbal cues (P12). The 3 *physical game* projects are games designed to be played using the body. One project was an exercise shirt that encouraged exercising by playing music only during physical activity (P11). There were also 2 garments offered *personal protection* and safety for its wearer. An example of one project enabled a cyclist to display turn signals on their jacket. There was an *empathy tool* that simulates the effects of weight gain on the wearer (P9). The one *disability aid* project was a bat-themed jacket intended to help a visually impaired person navigate using a sonar (P8). One project addressed *health* issues through an interactive shirt help the wearer be more aware of when their body is in a poor posture (P10).

Popular components. Most projects used LEDs and conductive thread, while also needing to be powered by batteries. The most popular components that makers used were LEDs, with a total of 15 projects, 10 projects used them decoratively and 5 projects used them to indicate system status. Conductive thread was used in 16 different projects to connect and embed components onto garments. Conductive thread was also used on two projects to make zipper-switches that turns the project on when a zipper is zipped up. The 2 other non-LED projects used vibrations to give feedback to their wearer. Makers also used sound output from piezo buzzers and audio speakers combined a total of 4 projects. All projects used a small portable battery to power their projects featuring both rechargeable and non-rechargeable battery types. A single project used an XBee wireless module to wirelessly map a dancer's movement to control the frequency of a sound on stage (P6).

Electronic Components used in LilyPad Garment Projects

Electronic Component	Number of projects used in
LilyPad (any model)	17
Conductive thread	16
LEDs	16
Lithium polymer battery (rechargeable)	10
Non-rechargeable battery (e.g., alkaline, coin cell)	7
Vibration motor	4
RGB LEDs	3
Speaker*	3
Solar panel*	2
Buzzer	1
XBee wireless module*	1

Table 1 Output, power, and control components used in LilyPad garment projects (N=17). A single count represents a distinct project where that component was used least once. Each (*) represents a component that is currently not offered as a LilyPad component[19].

Input components. Among the input components, all 17 projects used some input component for interacting with the garment. 6 distinct projects had switches and buttons. A total of 12 distinct projects also explored a variety of different sensors outside of switches and buttons. A total of 8 projects used input components that are not part of the LilyPad component set.

[19] https://web.archive.org/web/20161012085708/https://www.sparkfun.com/categories/135 | October 12, 2016 archive. Retrieved August 20, 2018

Of the 12 non-garment projects, 7 of had additional input components that the Lilypad component set did not offer.

Note: one project used both flex sensors and pressure sensors, hence the counting differences.

Input Components used in LilyPad Garment Projects

Input Component	Number of projects used in
Switch	5
Button	2
Flex sensor*	2
Light sensor	2
Zipper-triggered switch*	2
Accelerometer	1
Conductive fabric (capacitive touch)*	1
Joystick*	1
Pressure (force) sensor*	1
Pulse sensor (heart-rate)*	1
Rotary encoder*	1
Temperature sensor	1
Tilt Sensor*	1
Ultrasonic range finder*	1

Table 2 Input components used by projects (N=17). A single count represents a distinct project where that component was used least once. Each (*) represents a component that is currently not offered as a LilyPad component[20].

[20] https://web.archive.org/web/20161012085708/https://www.sparkfun.com/categories/135 | October 12, 2016 archive. Retrieved August 20, 2018

3.1.2 Discussion

From the findings, I determined two opportunities for basic building blocks in a prototyping tool: supporting visual output and including a wide diversity of input components.

Common basic output components that should be considered building blocks in a prototyping tool are: LEDs, sound, and vibration. Makers used LEDs in nearly every LilyPad project; 10 using them decoratively on their garments. Therefore, a prototyping tool should consider having LEDs as a must-have building block. Sound and vibration can also be included as a building block since they are the next popular set of output components.

Nearly all projects also used conductive thread to connect and embed LilyPad components. Connecting with conductive thread suggests that there need to be ways to permanently attach electronics to clothing or to make connections look aesthetically pleasing.

Makers also explored many kinds of sensors which are diverse and varied in many different garment utilities. In the sample, more than half (13) of garments explored many kinds of input sensors for their project. Of the 13 projects, 8 projects used input sensors outside of LilyPad suggesting the need to use other kinds of input on interactive garments. By supporting a wide diversity of input sensors also allows makers to explore even more utilities of garments.

3.1.3 Forming Questions

This sample of projects provoked a series of questions for interviews: how ideas are conceptually developed (motivation), the challenges they face, and the strategies they use to implement their garment. Instruction posts do not consistently reveal answers to these questions since they are written to help the reader build a specific project. However, they provoked some questions to develop in a detailed examination into the eFashion design process.

It would help to know the *motivations* for implementing the project and how they use that motivation to design an interactive garment. Knowing the motivations that guide eFashion designers will inform the features that a prototyping tool should support and how they use the tool to accomplish their goals.

Knowing the challenges will help reveal the strategies and ways they refined their garment design. In instructional posts, challenges when implementing the garment refining the garment were not always clearly described. In P15's post, they warn that: "*** *THE WHOLE CIRCUIT WILL BE MUCH EASIER IF YOU JUST USE WIRE, THE CIRCUIT IN THE SECOND PART GETS MUCH MORE DIFFICULT WHEN USING CONDUCTIVE THREAD****". Meaning the author wanted to use conductive thread but found it difficult to use in the implementation process. It would also help to know what strategy they employed to overcome these problems and ways they refined their solution. Knowing what strategies designers use to overcome these challenges would help inform features to support those strategies.

In the next section, I answer these questions of motivation, challenges, and strategies with two eFashion designers.

3.2 Case Studies: MakeFashion

In this section, I present two case studies on two eFashion designers and their practice. From the Instructables sample, I was not able to answer questions like what motivated their projects, what challenges they faced, and how they refine their designs. These case studies will now help answer these questions. The goal of these case studies is to illustrate how they conceptually develop their garments and the implementation challenges they face physically implementing their garments. First, I will provide a background for the MakeFashion group that the two eFashion designers developed garments for. Then I will present the two eFashion designers and their practice developing garments.

3.2.1 MakeFashion Background

To learn more from people with direct expertise in making eFashion garments, I contacted designers from MakeFashion[21], an eFashion group consisting of designers, artists, and technologists. They organize annual high eFashion shows where "high tech meets high fashion". On the runway during their shows, eFashion garments are presented with an informational card on a large projected screen to describe each garment and how the wearer interacts with them. MakeFashion has headquarters in both Calgary, Alberta and Seattle Washington. Since 2013, they have conducted annual eFashion galas on fashion runways in Canada, the United States, and in Shenzhen China. The group provides competitive funding (for travel and garment making) for those who want to develop an eFashion garment through project proposals. Prospective members may also join existing teams with accepted proposals.

MakeFashion provides funding for accepted proposals through their website. In their call for submissions they ask for (to quote the 2018 submission guidelines[22]):

- a lead teamate's CV or Resume
- images of previous work
- contact information
- project title

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[21] http://www.makefashion.ca
[22] http://www.makefashion.ca/call-for-submissions-2018/

- list of team members with their skills
- list of required experts or support
- project proposal document

In the project proposal document, designers are expected to (to quote):

- provide a brief design overview
- detailed creative and tech overview
- bill of materials
- a timeline for the project
- a sketch of the proposed garment

Project submissions are also expected to be durable and compete for funding. Proposed projects are expected to be built withstand travel to multiple venues and models. Submissions are submitted online through their website. MakeFashion accepts submissions on a competitive basis through an expert panel of engineers, designers, makers, and industry partners. A submission is judged based on its creativity, innovative use of technology, and the team's overall experience.

3.2.2 Participants

I recruited two eFashion designers (2 female) through personal relationships. Both designers have completed a runway-ready garment and presented at a MakeFashion runway show. I conducted a semi-structured interview where I asked them to talk about their most recent project (see Appendix A). I asked questions about how they went about conceptualizing their ideas, exploring possible designs, collaborating with stakeholders, whom they work with, and the challenges they faced in their work.

The questions I used to conduct interviews with these eFashion designers can be found in Appendix A: eFashion Design Interviews: Semi-Structured Interview Questions.

3.3 Sydney: From a Single Vision

Sydney is a Ph.D. student in Computer Science studying human-computer interaction. When she was a child, she liked arts and crafts, and wanted to be a fashion designer. However, peer pressure and monetary career prospects drove her to pursue computer science in university instead. She then took a senior level Human-Computer Interaction II course where she enjoyed working with physical interfaces using Phidgets (Greenberg & Fitchett, 2001). She found physical interfaces "*really fun building something with my hands. Because I started off really liking art you know. So I would make things like crafts and stuff like that when I was a kid*". Through personal connections, she found her way into Archeloft, a design workspace where MakeFashion resides. There, she developed technical skills in eFashion design through collaborations with other experts in eFashion. Although she is not an expert seamstress or dressmaker, MakeFashion enables her additional sewing support for her garments. So in the end, as an eFashion designer with a background in computer science, she found her way back into fashion.

She enjoys creating interactive garments for High Fashion because "*high fashion is just so much funner. It is more of a creative outlet. It is like art*". However, she did not design White Wolf to be comfortable: "*yes it was definitely not made for comfort. The idea was to look kinda see-through so don't know how many people are comfortable going with that [white wolf dress] on*". Although money limits her abilities to create grand garments, she thinks of her fashion design career as "*more of a hobby than a profession*". While Sydney is comfortable with a sewing machine, enough to make White Wolf entirely with assistance, she has no formal training in dressmaking.

This case study focuses on Sydney's piece White Wolf, a proximity-based interactive dress that connects her with her dog Bentley. I examine how her initial guiding vision helped shape the design of her dress. Her envisioned garment guided her aesthetic choices for her dress and helped her make selective material choices for lighting effects. Finally, I discussed some challenges she faced when implementing her garment's technological and textile aspects.

3.3.1 eFashion Piece: White Wolf

Figure 7 (a.) Sydney (left), Bentley (middle), and her co-model (back), modeling in White Wolf, at the MakeFashion Gala 5.0. The dress glows blue when she is at the '*near*' distance away from Bentley. (b.) Sydney kissing Bentley on his head, this triggers the '*close*' distance setting turning the dress pink.[23]

[23] Photos courtesy of the participant Sydney Pratte

Sydney's inspiration for the White Wolf (Pratte, 2017) dress comes from her relationship with her dog Bentley: "*Whenever I see my dog, I light up, so I wanted to make a dress that did the same thing*". Her dog is a Malamute, a northern breed of dogs weighing around 100 pounds (45.4kg). Sydney was inspired by Bentley's breed – which originated from northern territories like Northern Canada and Alaska – and decided to emulate the northern lights (Aurora) effect in her dress.

The dress changes color based on the distance between Sydney, who also modeled for her dress, and Bentley. When she is at her normal distance (~1.5-3 meters) away from Bentley the hoop skirt of her dress glows blue (Figure 7a). As she approaches Bentley to a very close distance (~0.3 meters), close enough to kiss Bentley on his head, her dress turns pink (Figure 7b). When she is far away (~3 meters or more), her dress turns off. Bentley's collar remains pink regardless of distance.

The dress and collar were implemented using the ANT+ Bluetooth low energy sensor. The proximity sensor provided basic measurements in ranges of close, near, and far. Bentley's collar constantly emitted a Bluetooth signal. The dress meanwhile receives the signal from the collar and measures the distance between the receiver module to the collar's emitter module. Then based on the distance sensed, a microprocessor then changed the colors on the LEDs located on the hoop skirt. Sydney hid the LEDs, microprocessor, power supply, and wiring behind wide metal bands on the hoop skirt and behind the waistband of the dress.

3.3.2 Presenting on the Runway

To demonstrate the effect of proximity on the runway, Sydney made two copies of the dress for herself and a co-modeling friend. Sydney was reluctant to have regular fashion models handle her dog because "*I did not feel comfortable giving a 100-pound malamute to a 90-pound model who didn't know him, 'cause malamutes are very stubborn. So he needed to be with people he knew. Which hence why I picked myself and my friend who has known him since a puppy"*. During practice, "*We definitely had to practice quite a bit because we were in 4-inch heels with a large dog [Bentley] who is extremely strong. So getting that like synchronization down, and figuring out how we're gonna like handle this dog and pass him off to each other and how like the three of us are gonna be like on this runway*". Furthermore, she feared unexpected reactions from Bentley in the presence of lights, cameras, music, and sound. The two rehearsed with Bentley many times despite practicing without lights or the audience: "*He was fine in the rehearsal, but we didn't have the lights for the rehearsal and we didn't have all the people. I think that was the hardest part was like training with her [co-model] to make sure we got that routine down and were in sync with our music. Just have that confidence to go out there with him*".

Part of the design required Sydney to build a second dress such that its message could be told on a runway in front of a live audience. The requirement to communicate clearly on the runway influenced the decision to make a second copy of the dress to demonstrate the proximity. According to Sydney, to design for the runway, "*you really have to think about how other people are seeing it for the very first time. Because if you have something that just has a bunch of flashing lights and it doesn't really work well with the music, then people are just gonna think it's a bunch of flashing lights. They're not gonna realize it's in sync with the music*". Thus, Sydney had to design the dresses to demonstrate the proximity effect clearly and develop a routine to ensure the safety and control of her dog on stage and to demonstrate the dress correctly.

The routine Sydney had developed involved showcasing two copies of her dress on the runway; she repeated the routine twice to demonstrate proximity. Having two dresses on stage, Sydney and her co-model can show how being near or far away from Bentley changes the stage of the garment. The added repetition in her routine also helped enforce the relationship with proximity to Bentley as the focus of the interaction. Her routine went as follows: *Sydney and her co-model both walk down the runway together with Bentley. Around the middle of the runway, her co-model stops while Sydney continues walking with Bentley to the end of the runway. The co-model's dress turns off and Sydney's dress remains blue. Sydney kisses Bentley on the forehead and her dress turns pink briefly. Sydney then walks back to her co-model, still standing in the middle of the runway. Both their dresses glow blue. Sydney then passes Bentley off to her co-model and the co-model walks to the end of the runway repeating the kiss Sydney had done. Her co-model meets Sydney back at the middle and the two continue off the stage with Bentley.*

In the next section, I show how Sydney's vision for her garment guided her garment design choices.

3.3.3 A Guiding Vision

Sydney had a vision for White Wolf which influenced the aesthetic goals for her dress. As mentioned, Sydney had a guiding message for what she wanted to communicate through her garment: *"Whenever I see my dog, I light up."*. She had already wanted to do something with her dogs: "*I knew I really wanted to do something with my dog. I'm obsessed with my dogs… I do dog shows with them all the time. So, I knew he'd do well on stage*". The visual theme of her dress inspired the lighting color choices for her dress: "*so I went with the like northern lights kinda colors [blue-green]. So, I knew what kind of colors I was looking for, and I knew what* *kind of effect I wanted the lights to have with the fabric"*. Sydney also decided "*that I was going to do something based on proximity and light"* thus committing to exploring proxemic interactions in the dress. With these visionary guidelines in mind, she begins conceptually developing her project.

3.3.4 Conceptual Development

Sydney used sketches and online references to develop concepts that aligned with her vision. Sydney's exploration began as sketches into "*different themes, different light placements, different styles of garments, and then how it [the implementation] would work*". She also explored "*the design of the trigger on my dog [collar]. So like different collar ideas and things like that*". She liked "*doing exploration in sketches because you can do quick fast ideas and kind of play with that and run with it*". Sydney also used online communities like Pinterest[24] to help her create variety in her sketches. She collected various styles of dresses on Pinterest and took elements of those dresses that she felt aligned well with the northern lights visual and her relationship to Bentley.

Experimenting with a variety of alternative designs was a common technique when Sydney developed the visual aesthetic of her dress. She was most concerned about how to realize the aesthetic of her dress: "*probably the hardest part was definitely like the fashion design part… I played around more with the style of the dress rather than the technology and how I go about that*". She thought about having a long flowing skirted dress, but after exploring sketches with the hoop skirt, she felt the hoop skirt best communicated her idea.

[24] https://www.pinterest.ca/

The Feasibility Barrier

When developing the MakeFashion proposal, Sydney decided to pursue a design simple enough that she can sew with the skills and resources that she had. One limitation Sydney faced when designing the dress' aesthetic was her sewing ability. When I asked her what she would request the most from a hypothetical perfect assistant, she replied "*sewing*" since she "*could do a lot of more intense things I guess and not limit myself to simplicity*". She found patterns online that she felt that she can accomplish on her own with some assistance.

She had other ideas such as putting pressure sensors on Bentley's feet to visualize his gait and additional lighting on the torso of the dress. Sydney thought about these ideas shortly after the proposal but decided not to pursue them due to the lack of time.

3.3.5 Prototyping Challenges

In this section, I present the challenges that Sydney faced when implementing her White Wolf dress. I show some of the challenges she faced, and some strategies she used to overcome them. I examine the following challenges: physically exploring materials helped her explore materials at the body-scale, low-level technological details hinder implementation, having sketches helped her get catered sewing assistance, and refining is best done when seeing the garment at body-scale.

Exploring materials at different scales

To refine the look of her hoopskirt, Sydney explored materials physically but required a wearable body-scale version of her dress to refine the visual aesthetic. To prototype the northern lights effect, Sydney brought a string of lights to a fabric store and shone the lights through various fabrics. Sydney says that she is a decisive person and once she "*explored a bunch of them [fabrics] using the lights. And I found the one that I thought would get my idea across my idea the best and got that one [fabric]".*

However, when she needed to anticipate what the lighting effect with interference from the hoop skirt's rigid structure, Sydney needed to have a complete version of her dress to refine the look further. The hoop skirt held the lighting elements behind a "*see-through*" fabric that would reflect light in such a way to imitate the northern lights effect. Because the hoop skirt structure casts a shadow, choosing the right rigid material was important to get the best lighting effect according to her garment vision. She found experimentation challenging "*[because] that part I had to build quite a few prototypes for that before it actually panned out the way I wanted it to be. I made a few [prototypes] and the effect was okay but it wasn't quite the effect I wanted. So, I played around with different materials until I got what I wanted*".

To get the right effect, Sydney needed to try several different hoop skirt materials before purchasing the final material. Here, it was important to Sydney that she tested various hoop skirt materials on her completed dress because "*once I got the dresses made, then it was a lot easier just to make the structure [of the hoop skirt] after that. Because then I can actually prototype it or like test it with the lights and all that until I got it the way I wanted"*. She tried using bare wires, but that revealed the LEDs too much of the structure. She tried hiding the LEDs in the plastic pipe, but the lighting was too subtle. Eventually, she found a material called *hoop skirt boning*, a wide piece of metal used to make hoop skirts. Although the material was more expensive than the other methods she tried, "*it made the right shape I wanted. I put the LEDs all along the inside of that [hoop skirt] ... so it all looked like it was shining inside the dress*".

Low-level technological details hinders implementation

Sydney found low-level electronics details hindered her implementation progress due to poor documentation. In her dress, she had to combine proximity, lights, microprocessor, and power which are not necessarily compatible out-of-the-box. "*I guess just making sure that all of your pieces work well together. 'Cause not all these sensors and processors and etc are compatible or they can be compatible but not really compatible. A lot of this kind of technology, there is very little documentation. So most of this stuff you have to like just figure it out*". Sydney needed to figure out low level electronics details like power requirements, ensuring proper voltage to communicate with different modules, and how to communicate with the modules. It frustrated her to work on this near the end of her project deadline.

Sketches help get catered and specific assistance

Sketches helped Sydney get sewing assistance catered specifically for the dress she is making. Sydney asked seamstresses to for advice on how to sew portions of her dress. While Sydney considers her sewing skills at the hobbyist level, she managed to build a most of the dress on her own. However, on the portions of the dress that were difficult to sew (e.g., dress fitting), having sketches helped her talk about her dress in without the terminology needed: "*I may not know the terminology, but I can show them what I want... They [seamstresses] knew a lot of stuff. I said: 'okay I want this bottom part to fit the body like this [pointing to a sketch]'. So, they said 'okay now we need we need to add these darts in'. And they knew what kind of technique that needed to be done… for like pinning out the sides, getting the right shape in the* *skirt, they suggested certain kinds of folds in that and stitching it in place. Which was super helpful and [I] wouldn't have guessed that"*.

Refining is done when seeing the garment at body-scale

Sydney's refinement approach involves her reflecting on the current progress of her dress and build on top of what she has done. Similar to her material effect experimentation approach, Sydney needed to see her dress at body-scale to refine the aesthetic. When her dress was near completion, she felt that her dress was a little plain. She added a belt, but it did not have the right effect. She then bedazzled the belt by hot-gluing hundreds of little plastic diamonds on it. Reflecting on the design of the garment and making incremental changes is a common approach in her own practice because "*once I see it all together, then I can see what's missing and then I can play around from that*". For Sydney, design reflection enables her to explore different realizations of her garment is important; it follows with her strategy when experimenting with different material effects and determining if that effect aligns with her desired vision.

3.4 Kath: Inspirations from Discussion

Kathryn (Kath) is an artist with roots in technology. She is a Master's of Fine Arts (MFA) student with a background in visual arts. Before her undergrad, she had programming experience in PHP, HTML, and CSS. With her programming experience in art, she realized that she "*can make weird art things that like do stuff in the physical world that aren't just graphical*". She pursued physical computing projects in her undergraduate and went on to make several electronic garments for MakeFashion. Although, she has no formal training in textiles or electronics: "*all of my knowledge about electronics is because I was interested in it and I wanted to make weird stuff. So I have like not formal training in any of those [electronics] things. And I also don't have any formal sewing training*".

For Kath, she is interested in interactive garments to discuss how technology effects our perception of the world. Interactive fashion, to Kath, is "*this new way to think about something because you can control things [using sensors] in a different way or you can have this responsive item*". She is interested in technology because it allows her to make meaning in different ways than she can with static materials. One of the reasons wearables are interesting to her is because of the proximity of the garment to one's body: "*That is a way to talk about how technology changes our world in a really direct way if you include the body in it because you can't get out of your body. It is the vehicle by which you experience the world itself... It makes stuff easier to relate to and makes stuff way less abstract*". For her, eFashion is a way to discuss the relationship between garments, technology, and the wearer's experiences.

This case study focuses on two of her MakeFashion dresses *Automata* and *Positive Feedback* as examples of how she develops eFashion garments. Kath draws inspiration for her dresses from her conversations with other people and self-motivated research. Ideas evolve and change throughout the development of her dress as she refines her garment's aesthetic and motivating ideas.

3.4.1 eFashion Piece: Automata

Figure 8 Automata on a dress-form mannequin. (a) the front of the dress with LEDs diffusing under the skirt, (b) the "wigglers" attached to a cam arm system, (c) a flower that opens and closes at fixed intervals, and (d) Kath wearing the EEG brain activity sensor.[25]

[25] Photos courtesy of the participant Kathryn Blair

Automata (Blair & Blair, 2017) is a dress that visualizes brain activity of the wearer. The visualization of the brain activity is "*about being able to compare brainwaves, and how like our moods interact with and impact each other*". The garment uses an electroencephalogram (EEG) headset that measures brain activity (Figure 8d). The headset measures attention level and activates three different parts on the dress: the back-flower piece's open and close interval (Figure 8c), "*wigglers*" that move up and down through cam arms (Figure 8b), and the light color range on the skirt and flower. The intensity of these movements and the range of colors is correlated with brain activity. The higher the activity, the higher the speeds and the "*warmer*" (red) the range of colors.

The dress was implemented using Arduino, a MindWave[26] (EEG) headset, and Bluetooth. The MindWave headset is a brain activity monitor that uses EEG to measure attention level. The headset then sends the level to a Bluetooth enabled Arduino located on the dress. The Arduino then switches states based on the data altering the flower's movement speed, light patterns on the dress, wiggler movement speed, and twirling spinner speed.

To demonstrate her dress Kath prepared her dress by setting it into a scripted demonstration mode. The demonstration mode was scripted to the runway routine to demonstrate the different modes on the dress. Kath had a model wearing the dress. The model wearing *Automata* did a catwalk routine with the assistants walking with the model down the stage. She also had information projected on a large display on the runway to inform the audience of how the dress worked.

[26] https://store.neurosky.com/pages/mindwave

3.4.2 eFashion Piece: Positive Feedback

Figure 9 Positive Feedback on a dress-form mannequin. (Left) the dress in a low social media activity popularity, the skirt is lowered. (Right) the dress in a high social media popularity state, the skirt is raised.[27]

Kath made a social media dress that visualizes the wearer's popularity level by getting "*fancier*". *Positive Feedback* (Blair & Blair, 2015) is a party dress that visualizes social media activity on the dress in the form of lights and vertical movement of the skirt's hemline. As the wearer receives social media activity through Facebook or Twitter, the dress "*gets fancier*" by lighting up and lifting the skirt to reveal sparkling ruffles (Figure 10) underneath ("MakeFashion

[27] Photos courtesy of the participant Kathryn Blair

| Positive Feedback," 2015). Kath did not intend for the dress to be used to attract social media attention: "*it was supposed to be a dress that visualizes how active you are on social media. So, you weren't supposed to use it as a way to get people to interact with you*".

Figure 10 The ruffles on *Positive Feedback* are revealed under the skirt when the dress is in high social media popularity mode. [28]

The dress was implemented using Arduino, Wifi, and "sail winch servo" motors. Using Arduino, the dress connects to Twitter via WiFi and calculates a popularity score using followers, tweet activities, and other events.

A high popularity score raises the skirt, while a low popularity score lowers the skirt. Raising and lowering the skirt was controlled by sail winch servos attached along the waist of the dress. The servos raised a metal band at the bottom of the skirt.

[28] Photos courtesy of the participant Kathryn Blair

To demonstrate *Positive Feedback*, Kath wrote a demonstration script to demonstrate the capabilities of the dress on the stage. Kath wrote a pre-scripted demo script because it made communicating the story of the dress easier without relying on unpredictable audience input. Using a dancer as a model, she had her model show that "*she was being really 'big'*" when the dress is in the 'popular' state and "*shy and reserved*" in the less popular state. Using the runway's projector screen, she projected information about the dress to inform the audience about how the dress reacts to social media activity.

3.4.3 Inspirations from Discussion

For Kath, ideas are born out of discussions that she has with her friends, colleagues, and professors. These discussions are unfocused sessions and not strictly about Kath's current eFashion project. These discussions are "*usually conceptual things, like what does it mean that we have technology that does this or that, what if this happened, what if that happened, what do you think about XYZ technology, what could we do with that*". Her ideas "*don't develop in a vacuum*" and that "*other threads come from different parts of life*". Figure 11a, shows the discussion loop, and as Kath mentions, these discussions happen over many encounters over days, weeks, and months.

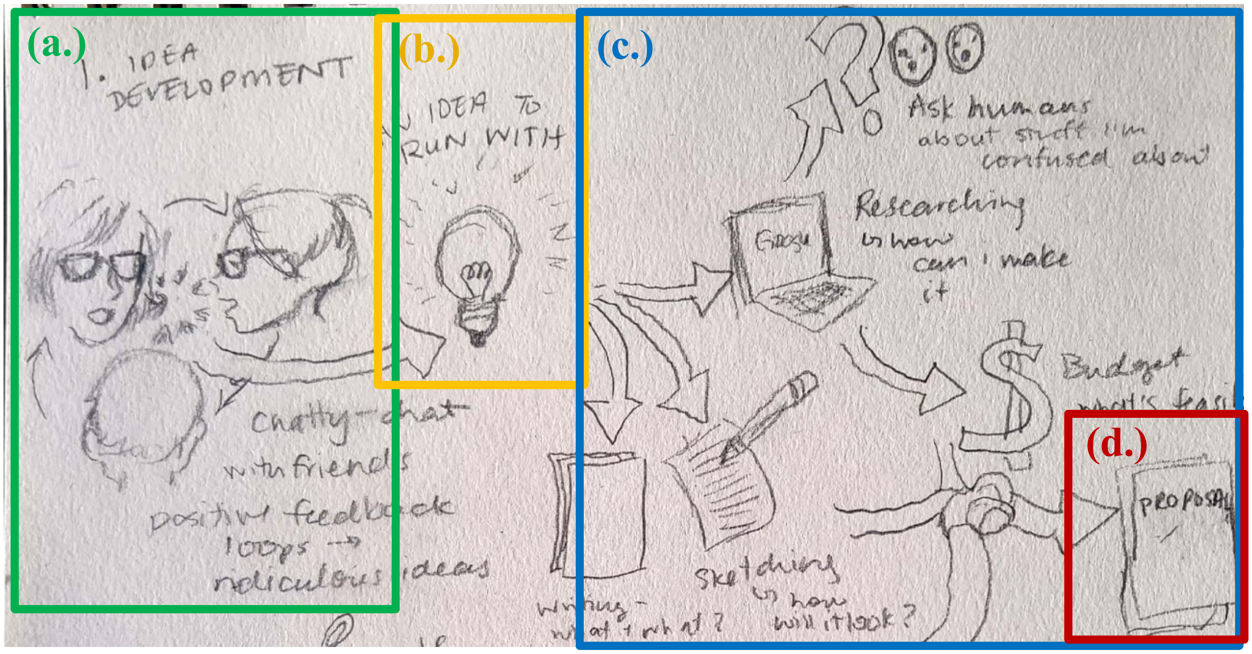

Figure 11 The "Idea Development" stage, an excerpt of sketch provided by Kathryn Blair. (a.) Discussion phase with friends and colleagues, (b.) "An idea to run with", (c.) research and conceptual development, and (d.) proposal milestone. [29]

"*An idea to run with*" (Figure 11b) eventually results from many discussions when she decides that her idea is interesting enough to pursue as an interactive garment. This threshold starts with "*what is interesting that is worth bothering to say*", what is technically reasonable, what she thinks she can do, and having a venue to make it for (e.g., MakeFashion). When she is interested in pursuing the idea further begins the starting point for the next phase: conceptual development.

3.4.4 Conceptual Development

Once Kath has an idea developed through her discussion, she then "*runs with the idea*" and conducts several research processes to determine if the idea feasible to implement as a

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[29] Photos courtesy of the participant Kathryn Blair

garment. She needs to realize her ideas prove to both herself and the venue to support her motivations to build a garment: technical, conceptual, and physical. To realize her ideas, she uses the following techniques: writing, research, and sketching (Figure 11c).

Writing allows Kath to articulate ideas so that she can communicate her idea clearly and to help convince other people that the idea is worth putting in a garment. Through writing, it is "*often just exploring ideas and possibilities, making lists, and figuring out how stuff will go together technically*". Writing helps Kath ensure her that what she imagines aligns with how she is communicating her idea: "*writing helps me make that concrete so that I can then refer that into like 'okay what is the dress actually doing. Does that potentially match back up to what I said I wanted to say'… and you also need to do that to convince anyone that they should let you show it in their thing [venue]*".

Research is a process where Kath looks for resources on what techniques she needs to realize her garment technically. Kath initially does some research to determine if her project is at all feasible to do. Then she does a more detailed search to examine: "*how will I actually do this, what [materials] would I need, will I need help, who could I ask for help*". The research ultimately helps her know what she needs to do to build the garment. She uses online resources such as Google[30] and Instructables[31] to support her research.

Kath will also use physical experimentation as part of her *research*. She will attempt to build a small portion of her envisioned dress to experiment with different fabric materials and electronic components. The experiment helps her decide what kind of material or electronics

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[30] https://www.google.ca/
[31] https://www.instructables.com/

implementation approach she will use to build the garment. Here she also explores the look of her dress by examining, for example, how fabric diffuses an LED light.

Figure 12 A proposed sketch to realize the intended physical appearance of the Automata dress by Kathryn Blair [32]

Sketching is used to help her physically realize how the dress will look in the physical world. Sketching for Kath usually comes after *writing* and helps her imagine how her dress physically looks. Sketches also serve to help fuel more *research* to find feasible patterns to make, additional dress elements, or experiment with materials. "*so like based on a sketch I will go like find a pattern I could use, or like make my own pattern if I were going to do that [element of a garment], or start draping on a dress form*".

[32] Photos courtesy of the participant Kathryn Blair

3.4.5 Prototyping Challenges

Following the proposal, Kath begins implementing her garment. In this section, I illustrate some of the challenges that she faced when building either *Automata* or *Positive Experience*. I examine the following challenges: physical materials cannot perfectly approximate her garment's vision, demonstrations help with communication between collaborators, and anticipating technical challenges allows more time for refinement and iteration.

Physical materials cannot perfectly approximate the vision

Kath is limited to the materials and their variations that the real world offers and thus finds it difficult to realize the right material aesthetics physically. Despite having sketches to Kath needs to experiment physically to find the right effect: "*I can just sketch anything, but that doesn't mean I'm gonna be able to like make that thing [look like the original sketch] … The fact that I could sketch it doesn't help me realize it*". When implementing parts of her dress, she is also trying to refine the visual effect physically which is often different from her original sketches. Using small experiments that she calls "*mockups*", Kath builds small functional pieces of her dresses to test different materials on, for example, lighting effects. However, Kath finds it difficult to get LED lights to diffuse through fabrics to look visually appealing on a dress. She finds that because diffusing LEDs requires "*so much [fabric] space and I never have space for it. So then I just have to be like: 'whatever they're just going to look like twinkling lights' I'm okay with that. But then I am like never 100% sure that I am actually okay with it… I try a bunch of different stuff but I'm not necessarily ever super happy with the like final result*".

Demonstrations help with communication between collaborators

Having different ways to express or explore complex garment or object behaviours would help Kath communicate with her collaborators. In *Automata*, her original idea for the back piece was to have a "*some mechanical thing that moves like a brain and it kind of undulates*". To build the brain, Kath enlisted her husband – a mechanical engineering technologist – to help her build the mechanical motion of the brain. It was hard for Kath to give her husband enough information to make prototypes of the brain motion because her husband was expecting to get exact specifications on what linkages, at what size, and how the system should move. But Kath cannot give that information because "*that's what I need you [husband] for, I don't know that… I don't know all the factors that you know, so you just have to pick this for me*". How they got over this challenge was when Kath asked: "*okay, well what could we actually make that would move and then he [husband] was like: 'these things'. And I was like: 'okay, make those'*". Her husband then showed two prototypes that he could make: an umbrella style linkage where the insides moved up and down and the sides would fold in and he also showed a set of cams that moved the "*wiggly things*". With her husband's proofs-of-concept, Kath was able to communicate what she wanted her back piece to do and her husband had a reference object to refer to when fabricating the back piece.

Anticipating technical challenges allows more time for refinement and iteration

It is difficult for Kath to anticipate the difficulty of her garment's technical implementation, thus in favour of getting her garment to function, she reduces her garment's behavioural features. During the brainstorming phase, Kath is often excited by "*big ideas*". In *Automata*'s proposal, she originally had listed three EEG headsets. The three headsets would allow the model and two other VIP audience members to interact with the dress. The extra headsets would allow the audience to "*compare brainwaves*" as initially envisioned. However, implementing technology can be challenging and take a lot of time: "*I'm really excited about [ideas] that are really big and I don't know how technically difficult they're gonna be to implement … So, I'm just trying to be like okay what are the changes I can make that will improve this [implementation] quickly*". Ultimately, Kath presented *Automata* with only one headset on the model.

Another example of having requiring time for refinement was through implementing the raising skirt in *Positive Feedback*. Kath also had technical difficulties in trying to ensure the hem would rise properly. Kath faced challenges dealing with friction between the cables and fabric, having the hem raise or lower easily. She needed to ensure that that the cables did not tangle in the dress while the model walked in it. "*when you're pulling using clothes it's like a lot harder to ensure that it won't get tangled because the clothes like will have friction with each other, and then you're like on a body or a person who's walking around*". After much experimentation, she solved her problems using a metal ring at the bottom of the skirt to add weight and to keep the cables taught.

3.5 Discussion

Through these two case studies, I aimed to find out more about the motivations, challenges, and strategies that eFashion designers encountered. In this discussion, I examine common challenges and practices between the two eFashion designers that may be used to inform the creation of a prototyping tool. Here I discuss how the two designers conceptually develop, what challenges they face in implementing their garments, and barriers to refinement.

3.5.1 A Guiding Vision and Ideas From Discussion

In this section, I examine the contrast between the two designer's approaches: a guiding vision and ideas from discussion.

In the conceptual development phase, a guiding vision approach can support designers by helping them align concepts and materials to their vision, while a discussion approach can be supported through exploring alternative garment behaviours. Sydney adamantly adhered to her guiding vision's themes for the northern lights and relationship to her dog. She explored alternative aesthetics on Pinterest and used elements of them on her dress towards realizing her vision. Kath meanwhile is inspired by her discussions with her friends and colleagues about the world around her and works towards realizing her ideas through writing, research, and sketches. Kath garment's vision can be flexible, adjusting to the technical challenges of the situation; allowing her to alter *Automata*'s brain theme to the mechanical flower. A prototyping tool ought to consider these two approaches to design. A prototyping tool can support Sydney by helping her find the right materials that align with her guiding vision. A prototyping tool can support Kath by allowing her to explore different kinds of garment behaviour.

3.5.2 Implementation Challenges

Here I discuss implementation challenges and assistance strategies: designers need to find physical materials that best approximates their vision and designers can get catered assistance from their collaborators when they explain with demonstratable design artifacts.

Experimentation with materials at body-scale is important for the two eFashion designers to ensure that the physical implementation aligns with their original vision. To decide what material should be used on a garment, experimentation was employed to search for the right material. Exploring and experimentation with different materials was a common technique used by both Sydney and Kath because it helped them find materials that can realize their vision. The problem, however, is that envisioned garments and their behaviours do not always have a perfect physical analog. This difference leads the two designers to find approximating materials. In a computer prototyping tool, it is easy to simulate materials of different properties and strengths in virtual reality. Ultimately, they will need to transform a virtual prototype into a physical garment using materials that already exist. A prototyping tool could help match designers to similar materials or help produce materials that do not yet exist.

Sketches and other conceptual design materials help the two eFashion designers get project-specific assistance. When developing a prototyping tool, the prototype authored can help eFashion designers communicate across disciplines. In Sydney's case, she used sketches helped seamstresses give her catered advice for her dress. Kath's husband found value in showing Kath movable objects that he has experience making. Through the umbrella-like mechanism, Kath understood what her husband is capable of and they both had a shared object to refer to when engineering the back-flower piece of Automata. Likewise, a prototyping tool can potentially author prototypes that help designers demonstrate garment behaviours to other collaborators what they want to build and how they can assist in the process. Authoring these demonstratable artifacts can also be useful to give eFashion designers more ways beyond the runway routine to help disseminate their ideas through existing fashion channels (e.g., virtual online demos).

3.5.3 Barriers to Refinement

Here I discuss two barriers to refinement: refining garments need to be done at the body-scale and allowing designers to access what is technically feasible may help them explore more interactive or visual features.

To refine their garments, the two eFashion designers often needed to see and have their garments worn on their bodies before making refinements to their designs. Experimentation ideally should be on a body-scale garment, but often is not possible in the early implementation stages of the garment. Both Sydney and Kath utilize small-scale experimentation to explore different material effects early while implementing their dresses. Later, when Sydney was searching for the right the hoop skirt structure material, she needed to test the material on a body-scale garment to see the completed effect. A body-scale garment allowed Sydney to test the lighting effects that the structure introduced. Some Fashion CAD tools (e.g., Tuka3D, Optitex ODev) help designers generate 3D previews of the garment's pattern making refining the garment's aesthetic easier without needing to implement their dresses physically. However, Fashion CAD software currently does not have functions to enable designers to add interactive components. A virtual prototyping tool can help designers make rapid changes to both the aesthetic and interactive behaviour of their garments.

When designers can assess what is technically feasible, they may be able to explore more interactive or visual features on their garments. Sometimes the designers are limited by their assessment of what is "feasible" to implement. Sydney avoided complex patterns and elements for her dress based on what she felt like she could sew. She said that if she had more time to work her dress, she would have added lights on the torso of her dress to building boots for Bentley to visualize his walk pattern. For Kath, it was difficult for her to predict if her designs are technically challenging and lead her to lose time to refine her dresses. A prototyping tool can help by lowering technical barriers or help designers anticipate technical challenges so that designers may be more confident to pursue and explore more interactive or visual features on their garments.

3.6 Design Guidelines

To inform the creation of a prototyping tool for interactive garments, I distill the following three design guidelines with the aim of synthesizing the two case study's findings. These guidelines are not meant to be absolute rules, nor do they represent all eFashion designers and makers, but they inform the decisions of prototyping tools presented in this thesis. In the following design guidelines, eFashion prototyping tools should allow users to:

1. **Explore** alternative physical and interactive realizations on garments
2. **Reduce** low-level implementation details
3. **Build** demonstratable and alterable artifacts

Exploring alternative materials is important to help designers align garment visions to physical realization. Whether they have a conceptual sketch or a virtual demo of their garment in action, designers will eventually need to approximate their vision with physical materials or components. This principle does not require designers to explore physically, but to help them explore alternative realizations of their garment to prepare for physical implementation. The designer ideally should be able to see their explorations at a body-scale version of their garment and support comparisons between different versions or materials. Exploring different alternatives help designers find the best physical approximation to their garment vision.

When exploring different interactive components, it is important to support visual output devices and a wide variety of input sensors. As informed by the sample projects on makers, a prototyping tool should provide building blocks that include visual output devices like LEDs, include sound and vibration, and include a wide variety of input sensors. These components are commonly used in LilyPad interactive garments and help support exploration into a wider range of garment utilities.

A prototyping tool should help designers *reduce* low-level implementation challenges to help them focus on refining their garments. When the two eFashion designers explored alternative materials or refined the aesthetic of their garment, they often spend time with low-level implementation details such as wiring components, communicating with components, debugging programs, and determining component ratings. By lowering these barriers to implementation, the designers will have more time to explore alternative materials and refine their garments, thus increasing their output.

Allowing designers to *build* demonstratable and alterable versions of their designs will help communicate with other collaborators and help them refine the concept of their garment. As observed in the case studies, both designers used sketches or demonstratable objects to help them communicate with other collaborators and experts to get assistance or communicate their ideas.

Prototyping tools should allow designers to build demonstratable or interactive versions of their garments either in virtual or physical realities. These demonstrations should also allow the designer or their collaborators to alter an existing prototype garment to allow design input from all stakeholders.

3.7 Chapter Summary

This chapter began with an examination into to what kinds of garments makers create using LilyPad. I concluded that most garments used visual output from LEDs and that makers use a wide variety of input sensors to supplement their design. Makers using LilyPad built garments for a large variety of functions outside of being visually pleasing. Suggesting that there are opportunities to develop tools to help makers access interactive input components to make more diverse garment utilities.

The two eFashion designers case studies presented in this chapter show two different approaches to designing eFashion. One where the vision is clear and their exploration of materials helped them approximate the vision as closely as possible. The other approached their vision with an openness to ideas and allowing different discussion threads to refine the design of their garment throughout the project. These approaches show the need to explore alternatives to both approximate what they set out to do and to consider alternative ideas.

To summarize the findings, I formulated three design guidelines to inform the creation of prototyping tools for interactive garments: explore physical materials on garments, reduce low-level implementation challenges, build demonstratable and alterable artifacts.

A prototyping tool should allow designers to *explore* alternative interactive or aesthetic realizations because they need to approximate their visions through physical materials. This exploration ideally happens on a body-scale garment to maximize the approximation to the final garment. When exploring alternative components, basic building blocks should include output components like LEDs, sound, vibration, and a wide variety of input sensors to explore the vast potential diversity of garments.

A prototyping tool should *reduce* the low-level implementation details to allow designers more time to refine and develop their garments. Low-level implementation details include wiring electronics, programming and debugging programs, and determining component ratings.

Finally, a prototyping tool should allow designers to *build* demonstratable and alterable artifacts to communicate their ideas to collaborators and stakeholders. Demonstratable artifacts will allow designers to get assistance when implementing their garments and to communicate their ideas through existing fashion channels.

From these design guidelines, I now have opportunities and challenges to address with an interactive garment prototyping tool. To start the exploration into an eFashion prototyping tool, I choose to address some of the physical implementation challenges. From the case studies, working with physical materials is important because designers need to translate their visions into a physical garment. A physical eFashion prototyping tool should enable eFashion designers to explore different materials and components at the body-scale. Unlike the physical prototyping tools in chapter 2, the goal of this tool is to enable material exploration rather than implementation. By getting to a body-scale prototype, designers can then see the totality of their experiments and physically interact with their garments to refine its aesthetics. However, the there are many physical prototyping tools in the literature and the approach may be inherently flawed if these eFashion problems still exist. In the next chapter, I discuss a physical approach to prototyping interactive garments and why the physical prototyping approach may be limited.

Chapter 4 Exploring Physical Prototyping Systems

This chapter provides a detailed overview of a physical prototyping system that I developed to address the design guidelines outlined in chapter 3. The research question I will address in this chapter is: *How might a prototyping tool support the exploration of physical implementation and behaviours on an interactive garment?*

In this chapter, I developed a physical prototyping tool: TortillaBoard. TortillaBoard is a wearable sleeve that allows designers to quickly get started with building electronic components on top of their bodies. It builds on the findings from chapter 3 by enabling eFashion designers to explore alternative components and materials at the body-scale. At this scale, designers can then refine and interact with their garments as worn on their body. The purpose of this tool is also to understand how might eFashion designers implement their garments and what processes can be supported by a physical prototyping tool. By using the sleeve, designers can quickly explore interactive components on wearable body-scale prototyping sleeves with physical materials on their bodies.

TortillaBoard builds on the design guidelines from chapter 3: explore, reduce, and build. The sleeve enables designers to *explore* different interactive components and their locations on their body. Since the sleeve is prebuilt, a designer can transform small-scale experiments into a wearable device. Thus, *reducing* implementation details such as sewing the sleeve and wiring the electronic components. Finally, the sleeve enables designers to *build* interactive sleeves that they can demonstrate to other clients and stakeholders.

I discuss a key limitation with a physical prototyping tool: conceptual flexibility is limited when implementing the garment. I then discuss an approach using low-fidelity prototypes to help designers explore interactive behaviour, inspiring the next prototyping tool.

4.1 Design Approach

Here, I outline my approach to developing the physical prototyping tool presented in this chapter.

I build on lessons I learned in background research and the case studies. In chapter 2, I identified several physical prototyping systems that help implement interactivity on garments, but these tools cannot yet facilitate access to custom research prototypes which require engineering specialists. In chapter 3, I then set out to understand eFashion design and developed three guidelines for interactive garment prototyping systems: explore, reduce and build. The physical prototyping tools in chapter 2 help eFashion designers anticipate, explore, and build to some degree. For example, Arduino LilyPad has a large resource of Instructables to help designers *anticipate* technical difficulties, designers can *explore* physically using a variety of pre-built components and using LilyPad *builds* a demonstratable prototype.

As seen in chapter 2, using tools like LilyPad, makers often built projects involving visual output (e.g., LEDs) but many projects were also interested in exploring other kinds of input sensors on their projects.

From chapter 3's case studies on eFashion designers, working with physical materials is important since it helped designers find the best material to realize their vision. Using physical materials is important because it helps designers find the best physical approximation of their vision. Designers ultimately need to implement a garment that accurately represents their vision on the runway.

Thus, I set out to develop TortillaBoard to enable eFashion designers to explore components and find the best physical approximation for their vision.

4.2 TortillaBoard: Developing Wearable-scale Prototypes

In this section, I introduce the design of TortillaBoard and how eFashion designers use it to implement their garments.

TortillaBoard is a wearable technology prototyping sleeve intended to help eFashion designers explore interactive components and their functions on their bodies without permanently sewing components. Designers can attach functional electronic widgets called 'badges' (Figure 16b) onto the sleeve and interact with their components using their body. Using Velcro, interactive badges attach to the sleeve temporarily. By attaching the badges temporarily, designers can explore how their bodies affect the interactivity of the electronic components. When connecting components, a removable conduit keeps wires neat while still allowing the designer to add and remove their badges easily.

By prototyping on TortillaBoard, designers can start prototyping interactive components faster. While the current sleeve design is meant for the arms, the intent is to provide sleeves for other parts of the body to make it easier to start prototyping electronics on any part of one's body.

4.2.1 Design

The design of TortillaBoard was inspired by electronics prototyping using breadboards. A breadboard enables electronics engineers and makers alike to prototype circuits testing their functionality without needing to solder wires or components. Extending the solder-free idea of a breadboard to enable designers to attach components easily on their bodies requires a flexible board. Using fabrics and Velcro, TortillaBoard aims to be an eFashion prototyping platform for solderless attachment of electronic components, hence its name. Note: not to be confused with the Tortilla-Board (Ross, 1998) which also inspired this tool's ideas.

TortillaBoard aims to help designers by helping them *explore* interactive components at body-scale, *reduce* implementation details by helping them add relocatable badges, and helps them *build* demonstrable functioning garments. Designers build electronics on badges to explore their placement on their body and how their body affects the sensors readings or the output's effect. By attaching the badges temporarily, TortillaBoard reduces low-level implementation details like having to wire components. Finally, because the sleeve is easily removable, designers can test and demonstrate their TortillaBoard designs to other designers or clients.

A demonstration video for TortillaBoard has been included in this thesis' accompanying materials.

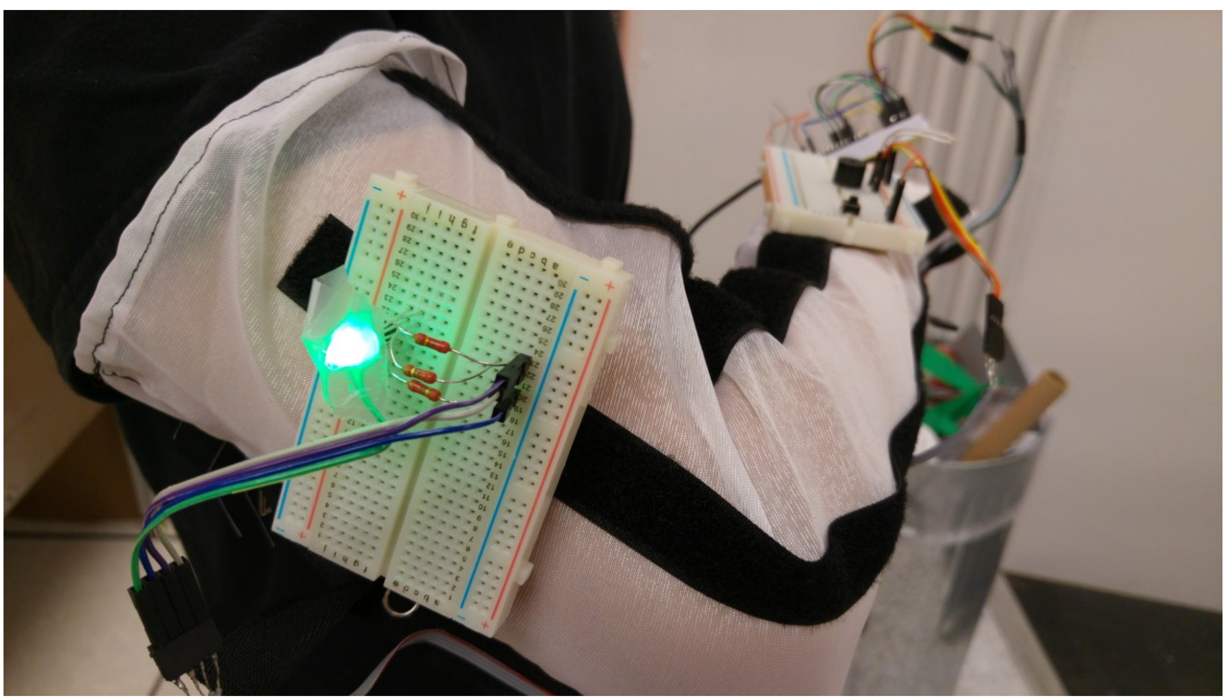

Figure 13 A designer testing their internet connected LED badge with the TortillaBoard.

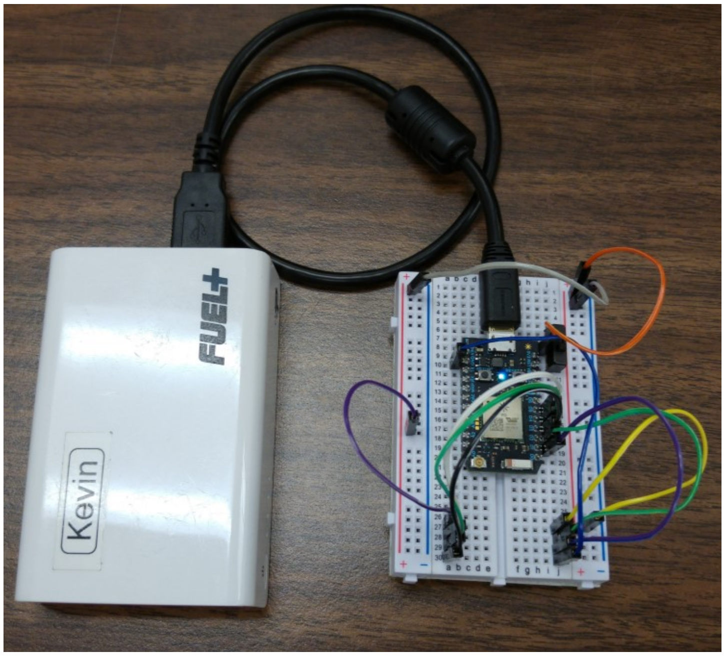

Figure 14 A Photon[33] microcontroller connected to a portable USB battery

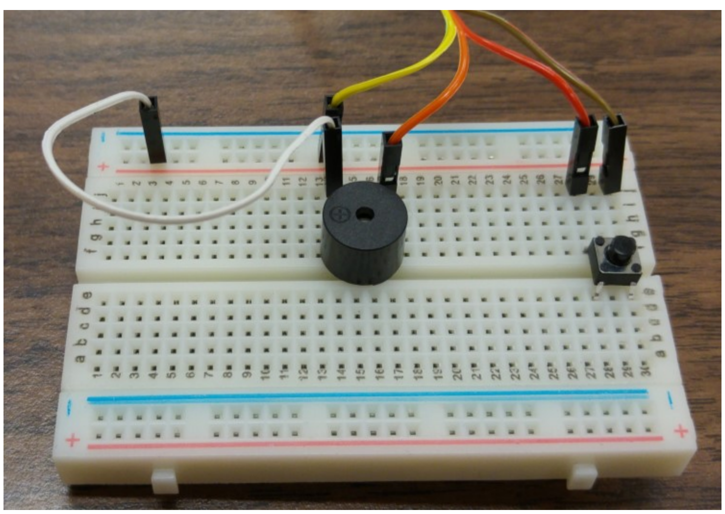

Figure 15 A piezo speaker that plays a musical sequence when the button is pressed.

[33] https://www.particle.io/products/hardware/photon-wifi

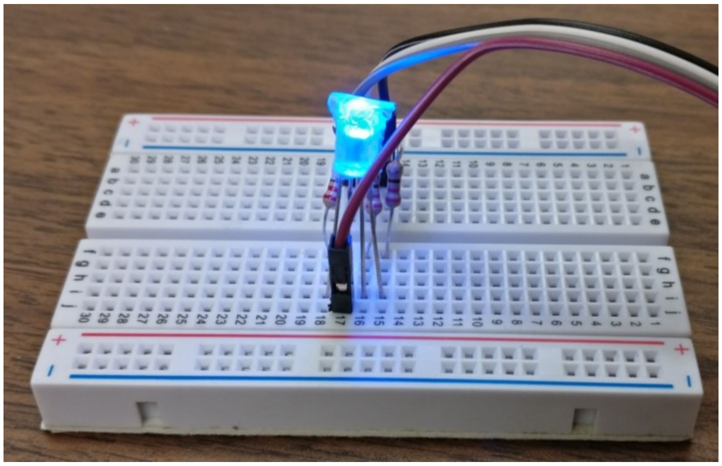

Figure 16 An RGB LED badge

Figure 17 The bottom of an empty badge which includes a velcro piece for attachment.

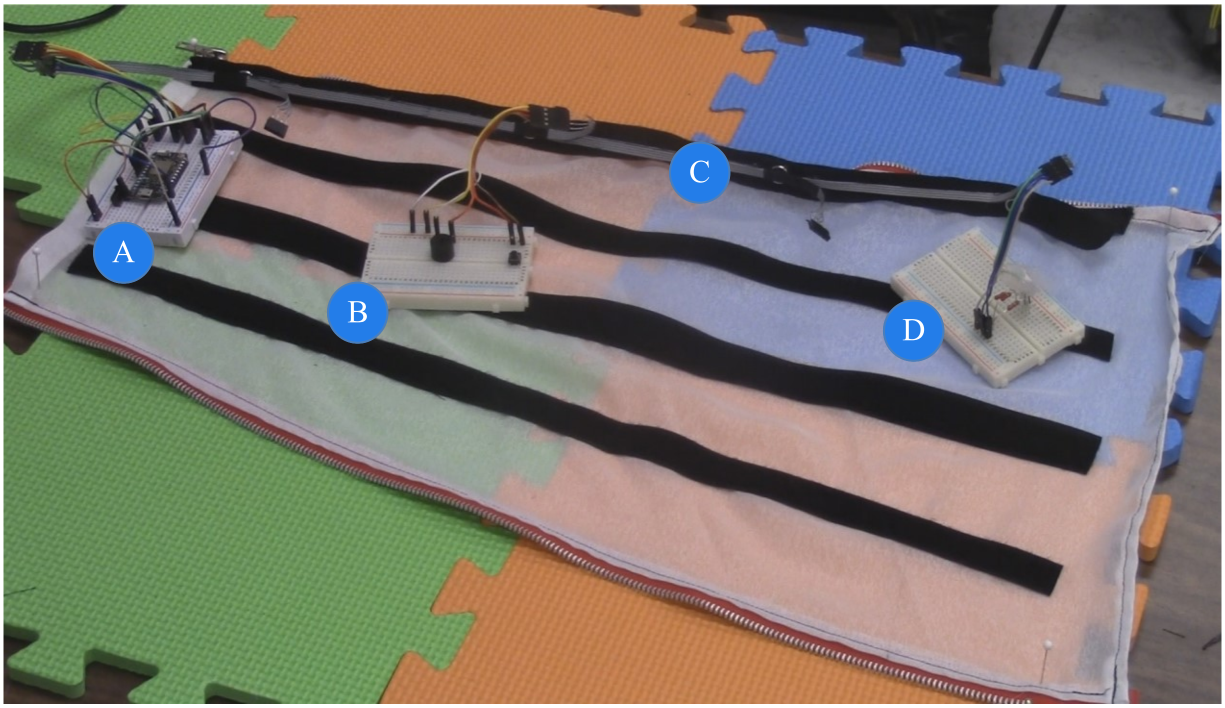

Figure 18 TortillaBoard is laid flat to plan the to layout of various badges. (a) Photon microcontroller controls the various badges, (b) A piezo speaker configured to play a sound on a physical button input, (c) A removable data conduit attached via snaps connects widgets, and (d) a diffused RGB LED widget.

4.2.2 Usage Scenario

Here, I describe how to use TortillaBoard in a usage scenario for exploring different material effects on the sleeve:

Susan, an eFashion designer, wants to explore different light placement locations on the of the sleeves of her dress. She puts together a quick prototype that sequences colors through a color LED on a small breadboard (Figure 18d). Once she has a small sequence written, she tests the LED to make sure it works.

Then she takes out a template TortillaBoard sleeve made for her arms. She unzips the TortillaBoard, laying it flat on the table. She attaches a conduit to the sleeve (Figure 18c). She then detaches her LED light system from her microcontroller and places her LED breadboard on the top shoulder of the sleeve (Figure 18d). The microcontroller and battery are then hidden in a back pocket through the wrist of the sleeve. She then attaches the LED badge through the conduit which attaches to her microcontroller (Figure 18a), carefully reviewing her original wiring diagram. Susan then zips up the sleeve and wears it.

In a mirror, she notices that the LED protrudes too far out the side of her shoulder. She takes the sleeve off, disconnects the widget, and moves the component onto her bicep, making the led face forward. Satisfied with the placement, she tries pinning a purple piece of fabric on top of the LED to see how the fabric diffuses the light. She looks in the mirror again and thinks about trying different materials and color sequences.

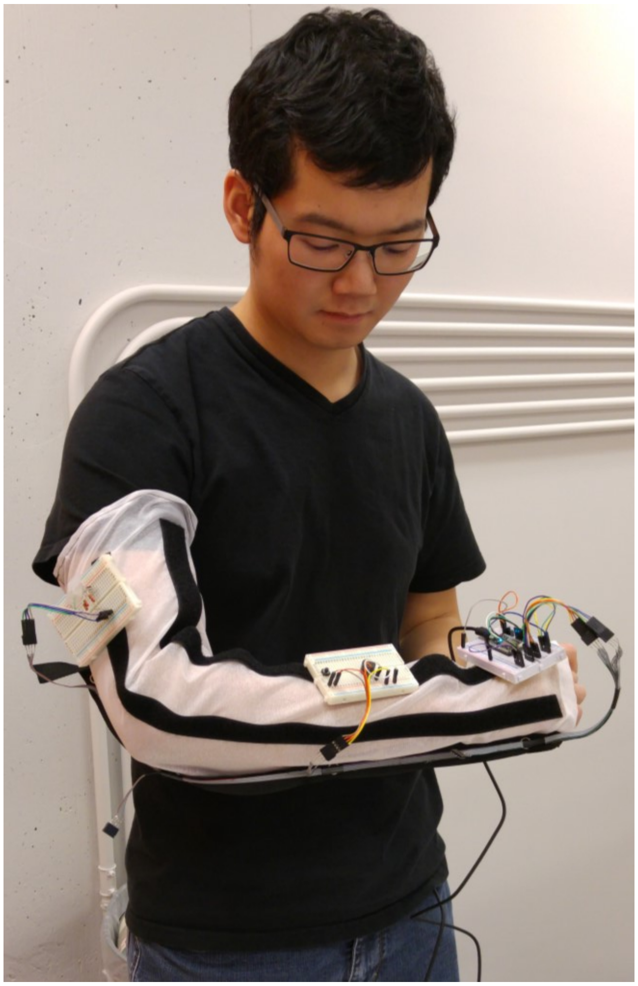

Figure 19 Wearing the Tortillaboard prototype. At this point, the user can relocate their widgets as they see fit. The battery is hidden in pant pockets.

4.2.3 Implementation Overview

TortillaBoard was made using a white semi-transparent fabric, three rows of Velcro, and a zipper. The sleeve features a snap button cable conduit that houses four rows of ribbon cable with 4 individual wires each (Figure 18c). Each badge is a half-sized breadboard with a piece of Velcro attached on the back. The designer can build any badge they want provided that they have the necessary electronic components. Each badge can utilize up to 4 channels on the conduit to communicate with a micro-controller of the designer's choice. In this iteration, TortillaBoard was built using a particle.io[34] Photon (Figure 14) because it had built-in WiFi to access online data services, be programmed remotely, and be powered by a portable USB battery. Currently, the designer must either attach the microcontroller and battery like a badge on the sleeve or hide it elsewhere on their body.

4.2.4 Reducing Implementation Details

ToritillaBoard allows designers to relocate components at low-cost on the sleeve. The sleeve's conduit allows designers to relocate components physically and reattach them to a microcontroller quickly. Using the conduit, designers have a prebuilt means to wire their electronics neatly and temporarily. When designers need to sew their components permanently, they can remove the conduit and sew directly on the sleeve.

By using the sleeve, itself allows designers to interact with interactive technologies on their body quickly. The eFashion designers of chapter 3 often used small-scale experimentation to explore material effects. Using the sleeve, designers can start attaching electronics onto the premade sleeve either by sewing or pinning and observe how introducing body movement affects their interactive behaviour.

4.3 Discussion and Limitations

Here I discuss TortillaBoard's prototyping limitations and compare the approach to low-fidelity prototyping approaches.

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[34] https://www.particle.io/products/hardware/photon-wifi

One use for TortillaBoard is that it provides an underlayer to house electronics. When designers finish experimenting on TortillaBoard, they can directly sew their components onto the sleeve to use as an underlayer for electronics. Thus, helping them transfer their prototyping into the final implementation of their garment.

While TortillaBoard does not make accessing eFashion technologies easier, designers can still experiment by relocating them throughout the sleeve. In chapter 2, I discussed LilyPad with the goal of enabling designers to explore eFashion research technologies. In the current iteration, TortillaBoard does not yet make exploring eFashion research technologies easier. Designers will need to somehow engineer those technologies themselves on a badge compatible with TortillaBoard. Sydney would still need to engineer the proximity sensor to create a badge for the system. If these badges did exist, TortillaBoard does, however, make experimenting with how those technologies work by allowing designers to relocate badges throughout the sleeve. Furthermore, power, weight, wiring, and concealing electronics are physical constraints that the system does not yet assist with which the designer needs to solve before using TortillaBoard.

In the current iteration, however, TortillaBoard can only support two independent devices running simultaneously on the sleeve. Additionally, the bus only allows one widget per upper and lower section of the arm. Badges cannot be placed near the zipper since there is no Velcro in that region of the sleeve.

When exploring alternative interactive components on TortillaBoard, low-level implementation details burden designers by limiting them to realizing similar behaviours that align with their vision. Currently, to explore an alternative interactive component, a designer needs to implement that interactive component as a badge physically. Building a badge requires designers to wire, program, and test them before attaching them to TortillaBoard. Implementing new badges to explore new components and behaviours makes them costly to produce.

TortillaBoard supports physical high-fidelity experimentation towards producing a runway-ready garment. When the eFashion designers of chapter 3 implemented their garments, they explored and tested different materials towards realizing an existing garment vision. TortillaBoard supports physical experimentation on a body-scale wearable platform, allowing designers to make wearable prototypes and test alternative materials. However, to explore the garment conceptually, there are low-fidelity strategies in interaction design that support exploring interactive components and behaviour.

To summarize, TortillaBoard currently:

1. Enables designers to relocate components easily, but accessing custom eFashion technology prototypes still requires engineering specialists
2. Enables designers to explore different materials and placements of interactive components, but it is not meant to explore alternative interactive behaviours.

In the next section, I discuss low-fidelity prototyping techniques like Paper Prototyping and Junk Prototyping as methods for exploring alternative interactive behaviours on garments before physically implementing them using a tool like TortillaBoard.

4.4 Alternatives to Physical Prototyping

To support exploring more expressions of interactivity on clothing, designers can use lower fidelity techniques that avoid low-level implementation. In this section, I discuss lower fidelity techniques like sketching, paper prototyping, junk prototyping, and Fashion CAD as ways conceptually explore interactive behaviours on garments.

By supporting more expressions of interactivity on clothing, fashion designers can produce and pursue more varieties of interactive garments on the runway. TortillaBoard currently only supports physical prototyping. Here I discuss sketching and paper prototyping to determine design considerations when building a conceptual prototyping tool to explore alternative interactive behaviours. These considerations will help inform the creation of a virtual prototyping tool in the next chapter.

One approach is to use sketches to explore interactive behaviours on garments, but sketches are difficult to use for communicating interactive behaviour. As part of the design proposal for their garments, the two eFashion designers of chapter 3 already utilize sketching to develop their interactive garments. However, sketches can be challenging to use to convey interactive behaviours. As Myers et al. (2008) mentions, even interaction designers annotated and used many text descriptions to describe their desired behaviours through sketches. The advantage of using TortillaBoard over sketching is that it allows designers to author interactive and demonstratable artifacts that express interactive behaviour. While sketching is used by eFashion designers to imagine the visual appearance of their garments, they are not suitable tools to express interactive behaviours.

An alternative to sketching interactive behaviours is to use paper prototyping to demonstrate interactive behaviours on an existing garment. Paper prototyping is a technique to help user interface designers imagine and demonstrate the behaviour to other designers by using demonstratable paper cut-out versions of their interface (Greenberg, Carpendale, Marquardt, & Buxton, 2011). Paper prototyping for garments could start designers with an existing garment where they attach paper prototypes on top of the garment to create interactive demonstrations. Garments can then be easily modified and altered with different materials. Designers are then free to develop with any component they wish, even to imagine a technology that does not yet exist. Designers can then use these paper prototypes to convince collaborators to pursue production of non-existent components rather than finding existing technologies that already exist.

As an extension to paper prototyping, Junk prototyping can add extra materials to explore 3D physical interfaces like garments. Junk prototyping is a means of prototyping 3D physical interfaces with ordinary scrap materials like inexpensive toys, loose office supplies, and modeling clay (Frishberg, 2006). Using materials that have interactive features like toys and fabric, designers can use these features to inspire their designs. These interactive features already exist in the real world and can help designers communicate similar interactive behaviours. Potential study materials to examine with junk prototyping through eFashion is included in Appendix B of this thesis.

However, there are a few prototyping limitations when using the paper prototyping approach compared to physically implementing a garment: it may be difficult to transfer towards a high-fidelity garment, it is more difficult to anticipate technical challenges, and require multiple people to operate a demonstration. Paper prototypes have little value for an eFashion designer over physically implementing a garment to realize their vision. They require designers to build non-interactive garments and paper components do not necessarily have physical electronic equivalents. A paper prototype also cannot help designers anticipate technical challenges because paper components do not have technical requirements to implement. Finally, demonstrating with a paper prototype requires multiple people to act out the garment behaviours; making demonstrations involving the human body's abilities (e.g., dancing) challenging to act in real-time.

An alternative to paper prototyping is virtual prototyping tools like Fashion CAD. Using Fashion CAD software, designers can preview and alter garment patterns and interactive behaviours quickly using computer rendering without physically implementing the garment. These tools behave like low-fidelity prototypes because they use computer rendering to preview the garment allowing the designer to quickly iterate on their garment without implementing them, saving designers time. Currently, these tools do not support interactive components but can be extended to add a set of building blocks for interactive behaviours.

A limitation of the Fashion CAD approach is that it cannot test interactions on the human body. In a Fashion CAD tool, patterns can instantly update the 3D render of a garment. However, it may be difficult for interactive behaviours that involve the body, since a designer may need to test their garment against their bodies. For example, designer is testing the accelerometer values for a dancer's high kick to trigger a light pattern. To determine how often the dancer is comfortable with making a high kick may require having the dancer report on how they feel with the garment on. Thus, a virtual prototyping tool should consider having the body of the designer or the intended wearer to test the design of the interactive behaviours.

4.5 Chapter Summary

In this chapter, I explored an initial prototype system for physically implementing interactive garments. Tortillaboard is a system that attempts to enable designers to explore alternative interactive behaviours by making components easier to relocate and exchange.

TortillaBoard supports exploring body-scale wearable prototype implementation by allowing designers to interact with interactive components on their body, relocate components easily, experiment with material effects, and support transferring to higher implementation fidelities. Using TortillaBoard enables designers to turn existing small-scale experiments into wearable devices that can be placed on-the-body and interact with other fabric materials. Using the sleeve, designers can wear their electronic prototypes, explore how their bodies interact with the electronics, test different material effects on components, and easily reposition components when needed. The sleeve also supports transferring prototypes into a garment's final implementation, allowing designers to sew electronic components onto the sleeve permanently.

However, TortillaBoard is limited to finding and exploring physical materials and not to explore interactive behaviours conceptually. If designers are to explore interactive behaviours on their garment, the tool needs to enable them to explore alternatives before they consider implementing the garment. While tools like sketching, paper prototyping, and junk prototyping exist to help designers envision interactive garments, they are difficult to use to communicate interactive behaviours (Myers et al., 2008).

One approach to developing low-fidelity prototyping tools for interactive garments is through a Fashion CAD-like approach to developing virtual interactive garments. Fashion CAD software already helps designers preview their garments in a 3D simulation and allow them to make changes to their garment's visual aesthetic rapidly. Extending this approach, a prototyping tool that authors virtual garments could allow designers to both embed interactive components and test interactive behaviours using their bodies.

This chapter began as an exploration in developing a physical prototyping tool to support the exploration and implementation of interactive garments. The goal for TorillaBoard was to help designers explore alternative interactions and materials on the body. The tool would then help designers in chapter 3 overcome physical barriers such as finding the right materials for their implementation and refining the visual aesthetic on a body-scale prototype. However, TortillaBoard cannot support exploration of alternative garment behaviours because it is intended to help implement a garment from an existing vision. What is promising, however, is to enable designers to explore and refine their visions through a lower fidelity version of their garment in preparation for physical implementation. A possible approach can be to author virtual garments such as those created by Fashion CAD tools. In the next chapter, I build on these lessons by developing and investigating a prototyping tool that authors virtual interactive garment prototypes.

Chapter 5 Envisioning Interactive Garments with Augmented Reality

In this chapter, I address research question 2B: *How might a virtual prototyping tool support eFashion designers in envisioning their interactive garment designs and knowing what is possible before physically implementing such designs?* I built and evaluated a virtual prototyping tool to find opportunities for exploring interactive garments.

In the previous chapter, I found that exploring behaviours during physical implementation is limited because designers were implementing their garments from their vision. Using virtual components can enable designers to use stand-in virtual components (e.g., Polymorphic cubes (Somanath et al., 2017)) that they do not have and enable quick refinement of the design that can be interact with it in real time (Fashion CAD). In this chapter, I respond to those limitations by developing a virtual reality prototyping tool that enables designers to envision interactive components before physically implementing their designs. Using a virtual version of their garment, designers can freely manipulate their garment and its behaviour without needing to consider electronic implementation details.

I present Bod-IDE, an augmented reality (AR) 'mirror' that allows eFashion designers to experiment with virtual interactive wearables. The goal of Bod-IDE is to *make eFashion prototyping easier by allowing designers to explore interactive garment technologies and iterate on their designs before garment production*. I envision Bod-IDE as a compliment to conceptual sketching, where designers can prototype embodied interactivity using an AR representation of their garment. Using relocatable AR tags frees eFashion designers from the need to solder or sew physical materials and instead focus on experimenting with wearable interactivity – exploring alternate behaviors that arise from on-the-body prototyping. This work was presented as a poster in the Designing Interactive Systems 2018 conference (Ta et al., 2018). See Appendix D for the poster.

Bod-IDE builds on the design guidelines from chapter 3: explore, reduce, and build. The mirror enables designers to *explore* different interactive components and behaviours in front of the mirror using low-cost AR tags. By using AR tags, the mirror *reduces* electronic implementation details such as deciding what component model to use, how to wire the component, and how to communicate to the component. Furthermore, these tags can be relocated freely without needing to reconfigure wires or programming. Finally, designers can *build* demonstratable artifacts by wearing their tag augmented physical garments in front of the mirror which can then be worn by other clients or stakeholders.

To evaluate this iteration of Bod-IDE I employed *demonstration*, *usage*, and *heuristic* type feedback (Ledo et al., 2018). I developed a "'how-to' scenario" to demonstrate what the system can do and what problems it intends to solve. I then showcased the system to laypeople using a "walkthrough demonstration" to determine the value and initial feedback of the system. Finally, I applied heuristic evaluations using guidelines from Olsen Jr. (2007) to find Bod-IDE's current strengths and limitations for future work.

Figure 20 Bod-IDE with a designer standing in front of the 'mirror' display with some tags fastened to their body and a prop.

5.1 Design Approach

I build on a similar approach found in Fashion CAD software, by allowing designers to quickly preview rendered interactive behaviours and allow them to test those behaviours on their bodies. I build on a lesson learned in TortillaBoard in chapter 4, namely by helping designers consider alternative interactive behaviours before implementing their garments.

Using AR to create virtual low-fidelity interactive garments, eFashion designers can conceptually *explore* the design and interact with an interactive garment using their own bodies. A designer can start by using sketches of their interactive garment to explore different garment aesthetics before using the system to bring it to life. Then by exploring different interactive components through a modified version of if-this-then-that (IFTTT) programming pattern (Ur et al., 2016), designers can explore alternative garment behaviours without physically implementing their garment. Thus, *reducing* the low-level implementation details required to implement a functioning garment. The simplification of programmed behaviour through the connection of an input to an output makes changing the behaviour of the garment quick and without the need to program. Finally, I support *building* demonstratable artifacts by enabling designers to create wearable virtual garments, where interactive components can be worn, interacted with, and altered by the designer or their client.

5.2 Bod-IDE: Virtual Interactive Garments in Augmented Reality

In this section, I describe the design of Bod-IDE, how designers use the system, an implementation overview, how to author interactivity, and how a designer uses the system to demonstrate virtual garments.

5.2.1 Design

Bod-IDE is an augmented reality 'mirror' that allows designers to author virtual interactive prototypes that they can interact with virtually using their bodies. Using AR tags, designers build interactive garments by using attaching paper tags on an existing garment and wears the garment front of a camera-enabled mirror. The mirror then renders real-time 3D previews of the paper tags as virtual interactive components allowing designers to freely interact with and relocate the tags at little engineering cost. Interactive behaviours are programmed using three tags (input-connector-output) that form modified-IFTTT program to be registered. A designer can easily alter their programs by changing the connector (behaviour) and reregistering the tags. Then, like a virtual personal 'runway', a designer can showcase the garment's interactive behaviour in a mock social scenario to demonstrate to themselves and other people. Using Bod-IDE, designers can explore virtual interactive garments, at low implementation cost, with their bodies in real-time before physically implementing their garments.

A demonstration video for Bod-IDE has been included in this thesis' accompanying materials.

5.2.2 How-to Scenario

Here I describe a usage scenario exploring interactions and getting design feedback using the mirror:

Katie, an eFashion designer, wants to create a steampunk styled jacket that represents her client Sasha's Twitter feed activity. Katie creates concept sketches that capture the aesthetic and basic behavior of the jacket. With her vision in mind, she uses her augmented reality mirror (Bod-IDE) starting with the Twitter feed module. She creates one of her jacket's envisioned behaviors – animating the jacket on a retweet – using the program board (Figure 25) to link the

Twitter tag to various output components that could communicate ‘aliveness’, settling on LEDs and fans. She physically attaches the tags on top of an existing jacket (Figure 21) that she plans to modify for the project using safety pins with the LED tags placed on the side of her shoulders and fans along the inside of her forearms.

To test this implementation, she wears the jacket and sits on a chair in front of a coffee table to simulate a café space. The mirror animates the tags with virtual components by blinking the LED on every retweet. She notices that the LEDs flickers too often because Sasha’s Twitter feed is popular and that it would draw too much public attention. She taps alternative Connector Tags on the program board to explore different mappings between the Twitter tag and the LED’s, settling on a Connector Tag that blinks the LED after a certain threshold and tries again in front of the mirror. After some refinement, she invites her client Sasha to try on the jacket in the mirror. Sasha mentions that she would like the fans to the side of her arms since it had a clockwork automaton aesthetic. Katie quickly swaps the locations of the LED’s and fans. Katie eagerly asks Sasha to try on her jacket again and they continue exploring interactive behaviors together.

Figure 21 Tags attached to an existing garment before being detected by the mirror. The colored tags are attached using safety pins. A designer can quickly reposition the tags without rewiring the components or reprogramming the garment.

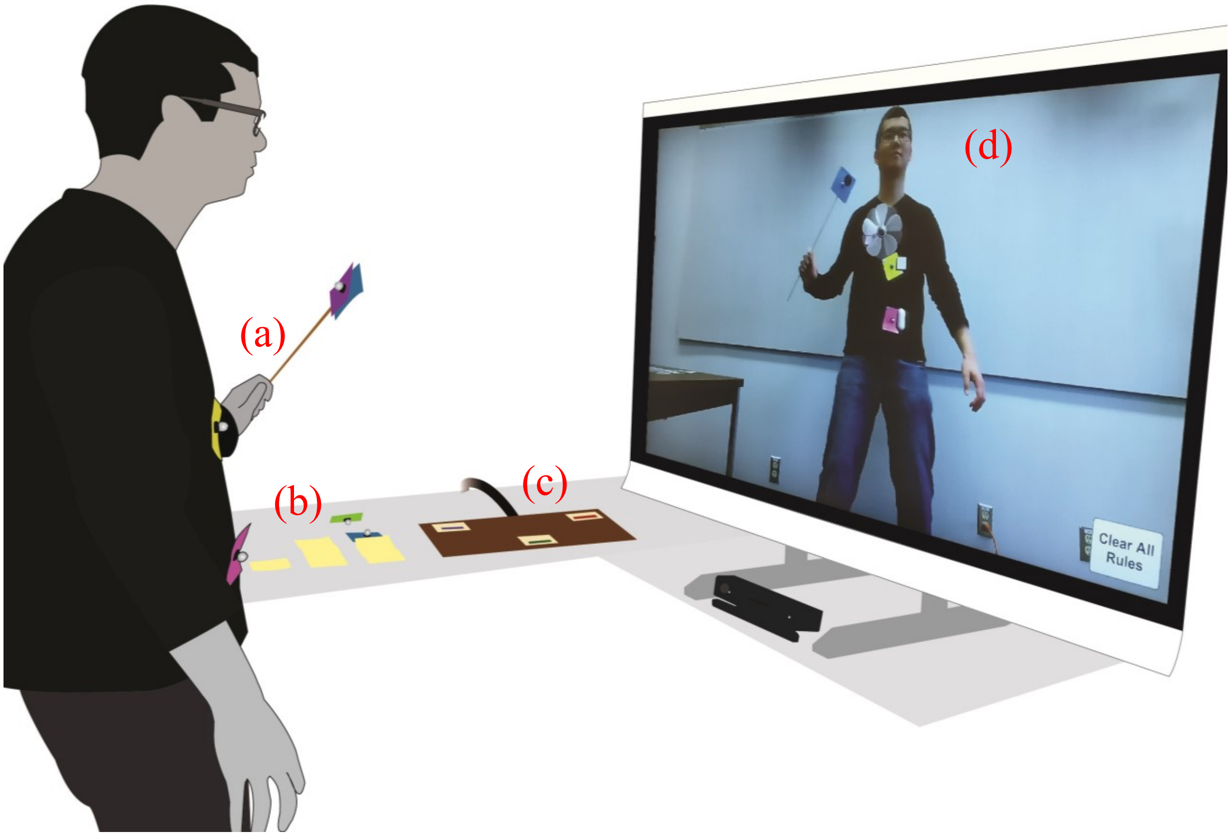


Figure 22 Using Bod-IDE (photo traced for clarity), (a) designer holding a marker augmented prop and wearing tags, (b) programmable tags, (c) programming board, and (d) 'mirror' with component renderings and behaviors.

5.2.3 Implementation Overview

Bod-IDE allows designers to physically place, program, and test virtual interactive components (tags) on their body. The system uses simple paper tags (Figure 23) with reflective markers and RFID tags. These tags can be temporarily attached and repositioned on the wearer's body with tape or a safety pin. The mirror then renders a 3D model of each wearable tag on top of the designer's body or a mannequin.

The initial implementation uses Unity, Kinect v2, and Phidget RFIDs. Using OpenCV, a computer vision library, a Kinect V2's IR camera can detect and track retroreflective markers in the scene (Figure 23b). Using the marker's IR position, the system searches for the tag's background color using CIELAB 76 version of delta-e. The system then renders the identified tag's model on top of the tag.

The initial component tag set includes a button, accelerometer, simulated tweet events, LEDs, motors (fan), sound effects, and virtual cloth (Figure 26a). We also included connectors for toggling on/off components, 1-to-1 analog control, and a threshold-activated toggle. See Table 3 for the types of interactive tags.

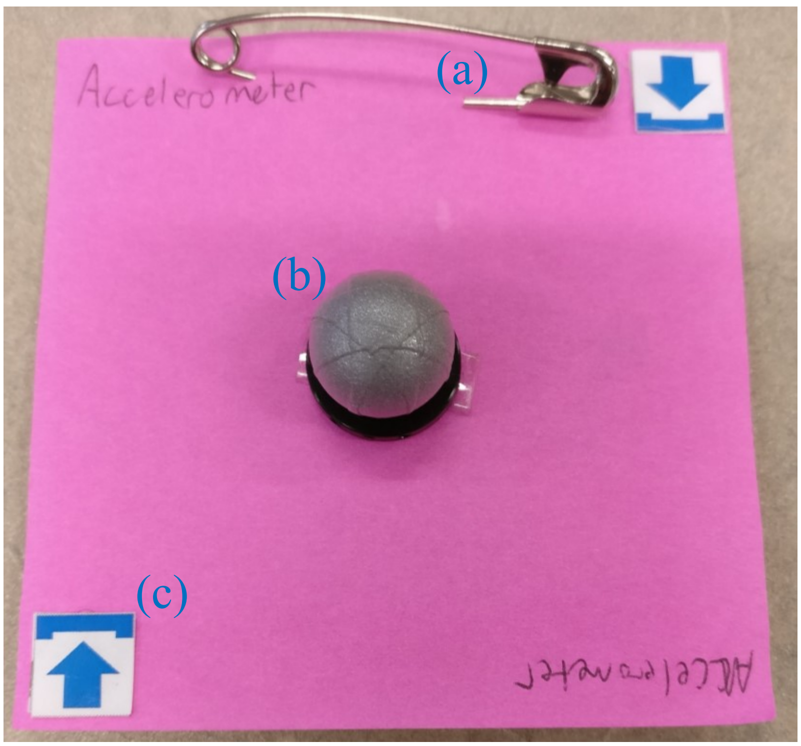


Figure 23 An example wearable accelerometer tag. The tag has (a) a safety pin, (b) reflective marker, and (c) tag type icon. When a designer views the tag in front of the mirror it has a virtual representation and the wearer can interact with it (see Figure 24).

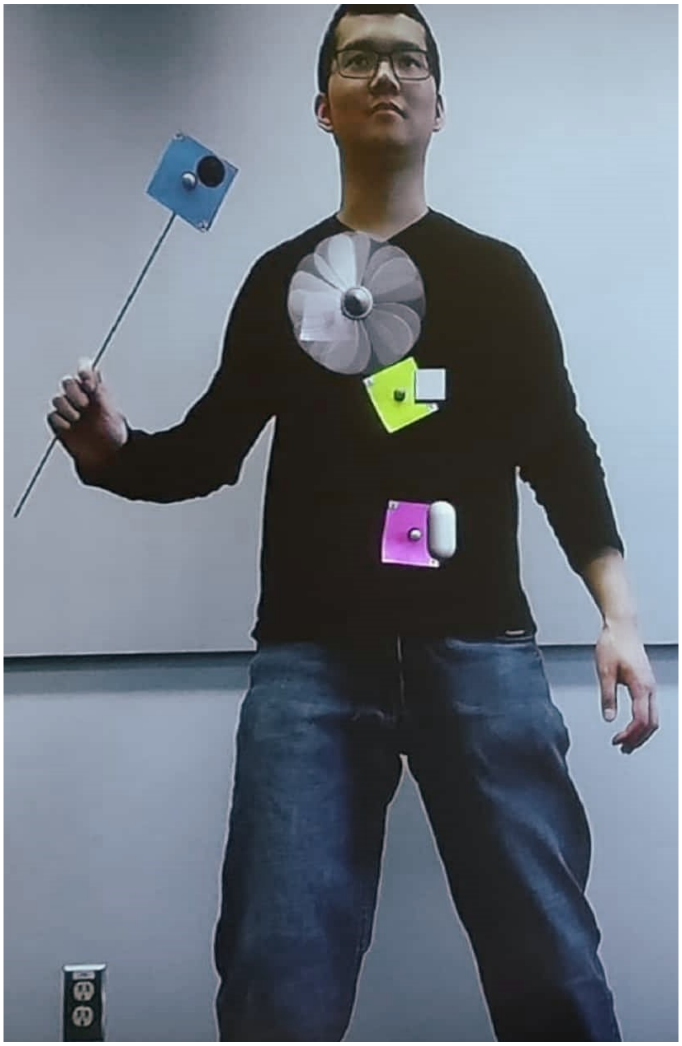


Figure 24 The mirror display (zoomed for clarity) with a designer wearing multiple tags and an augmented prop. The virtual components are rendered in real-time.

5.2.4 Authoring Interactivity

Programming uses a modified if-this-then-that programming pattern similar to IFTTT (Ur et al., 2016). Designers must combine three types of tags to form an if-this (input) then do-this (connector) on that (output) statement. Each statement is registered by physically placing the tags in each bin on the program board (Figure 25). For example, an accelerometer's velocity can be mapped 1-to-1 to the speed of a motor (accelerometer + analog + motor) or toggle the motor on when it has been shaken hard enough (accelerometer + toggle + motor). A designer can go between former and latter examples by changing the connector tag from the analog tag to the toggle tag.

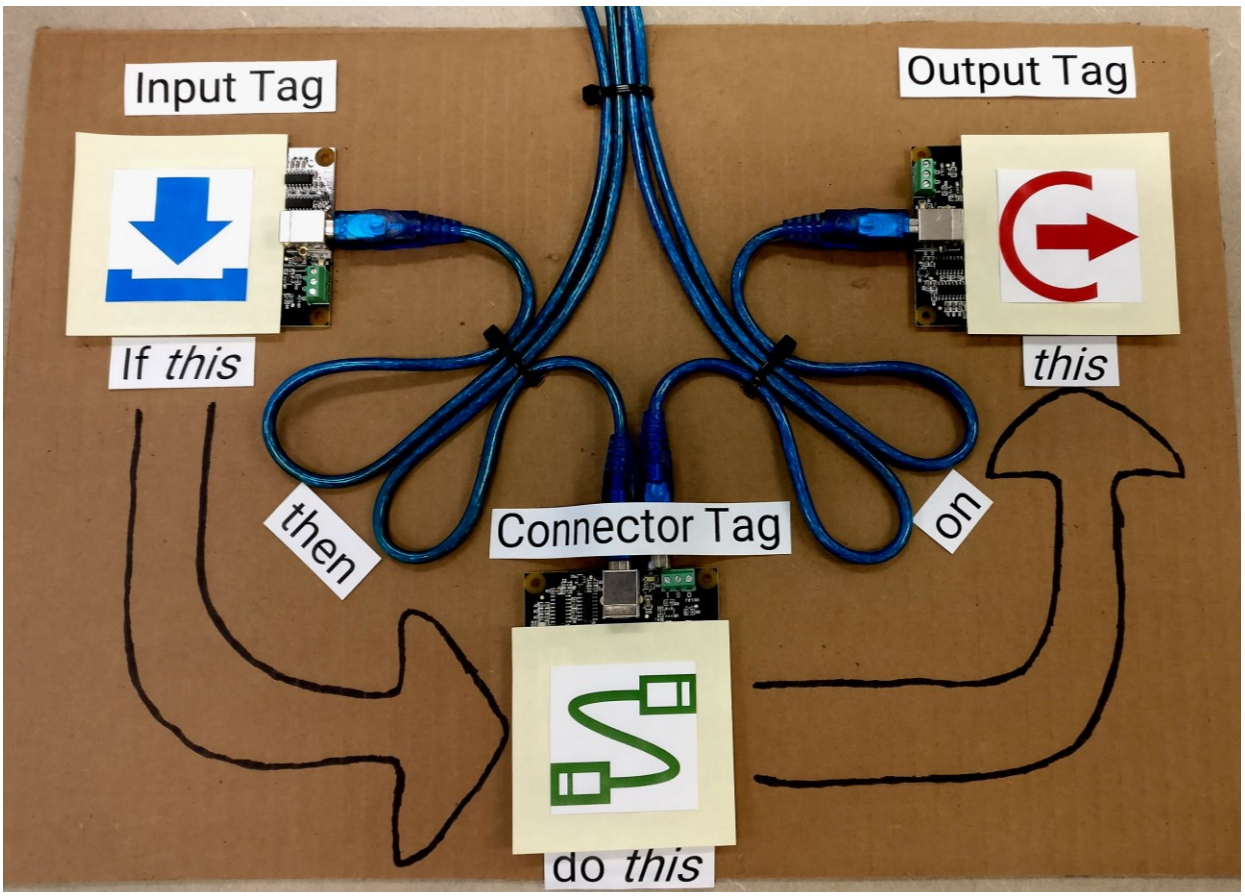
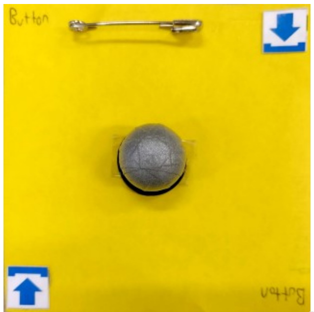


Figure 25 The program board using Phidget RFID readers to register program behaviors. Designers place tags on top of the bins (icons).

Once the designer has defined a set of rules, they can fasten the wearable tags to their body using tape or safety pins. The designer can also attach tags to props (Figure 22a) to create accessories or build larger structures (e.g., wings).

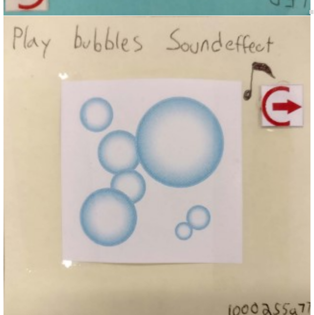
Table 3 Interactive Tags Types



Button
Wearable
Input

New Tweet
Wearable
Input

LED
Wearable
Input



Sound Effect
Wearable
Input

Toggle on/off
Wearable
Input

5.2.5 Demonstrating Virtual Garments

Designers can demonstrate the function of their garments by wearing them in front of the mirror. Once a designer attaches all the wearable tags on their garment, they can interact with the garment in front of the mirror. They can also setup environments in front of the mirror to simulate social scenarios like coffee shops or public spaces to see their garment in. Since tags are attached to existing garments, a designer can transfer their garments to other collaborators to wear, interact, and modify.

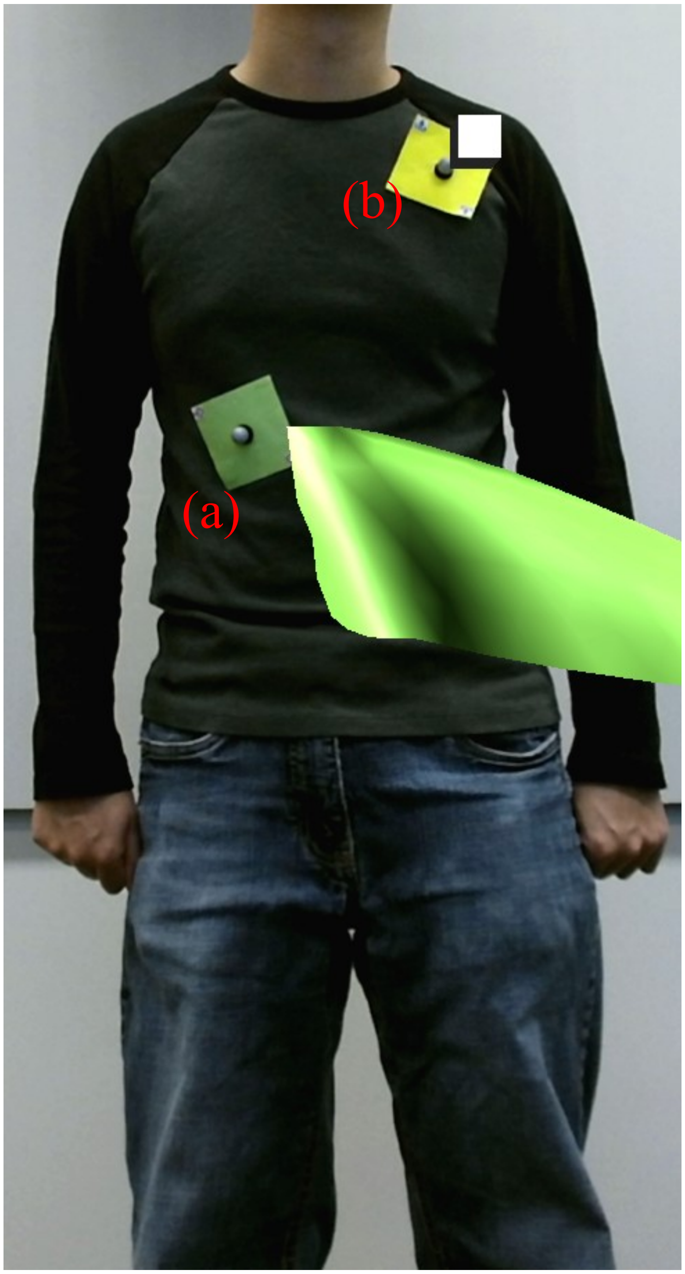


Figure 26 (a) Virtual cloth tag fluttering in the wind when activated by (b) a button.

5.3 Evaluation and Discussion

In this section, I present the initial evaluation for Bod-IDE and considerations for improving the system in the next iteration. I present demonstrations by explaining the usage scenario, initial feedback from laypeople, a heuristic evaluation using Olsen Jr's (2007) guidelines, and discuss the limitations of the system.

5.3.1 Usage Scenario

The how-to scenario (5.2.2 How-to Scenario) for Bod-IDE illustrates five examples of building an interactive garment:

1. relocating components without rewiring
2. simulating data input
3. exploring alternative interactive behaviours
4. building demonstratable virtual interactive garments
5. evaluating a mock social situation

From the usage scenario in section 5.3.1, Bod-IDE solves several problems developing interactive garments. In (1.) when Katie switches the location of the fans and LEDs, she can move the components without rewiring her entire project. She takes the components off the garment moves them directly to the desired locations without reprogramming them. In (2.) Katie also is unburdened by using social media programming interfaces by using the simulated input tag and does not need to make an alternative account to simulate activity. (3.) The trigger-action programming allows Katie to explore alternative behaviours quickly. By switching the connector component, Katie can quickly alter the behaviour of her LEDs without needing to test and devise a new algorithm. In (4.) Katie can also build demonstratable garments by transferring the components to her friend Sasha. Sasha can then alter the design of her garment and give feedback directly on the design. A complete garment would be challenging to implement and be difficult to alter significantly. Finally, in (5.) Katie can evaluate the function of her garment in a mock social situation of a coffee shop. By acting in mock scenarios, enables her to refine the behaviour of her garment according to different social situations that she finds important and find solutions through (3.).

5.3.2 Initial Feedback

I presented Bod-IDE at a computer science departmental showcase, demonstrating it for approximately 30 laypeople. I explained how Bod-IDE works and provided visitors with pre-programmed tags to wear and test the interactions in AR. Our demo included a fan (motor) whose speed varies based on the shaking of an accelerometer and a button that triggers a sound effect.

Visitors often tried to place tags on different parts of their bodies, unaware that the tags needed to face the mirror's camera to be active. Visitors would be place tags on the side of their shoulders facing away from the camera which is not detectable by the current system. Improvements to the AR tracking algorithm or hardware may solve these problems.

Visitors felt that the initial set of components was very focused on electronics. Visitors were not convinced that what they were prototyping was fashion due to the low-fidelity models of the components and lack of decorative components. One visitor commented that the system should leverage fashion designers' existing experimentation practices like draping materials on a mannequin.

5.3.3 Heuristic evaluation

Using Olsen Jr's heuristics for evaluating toolkits, I evaluate Bod-IDE on the following factors: flexibility, expressive leverage, and expressive match. The goal of Bod-IDE is to make it easier to explore interactive garment technologies and iterate on their designs before garment production. Thus, I show how Bod-IDE *reduces solution viscosity* (Olsen Jr., 2007) when designers prototype virtual interactive garments in augmented reality. By aiming for this metric, allows designers to explore alternative garment behaviours and refine their garments rapidly. I also show how Bod-IDE enables the maker community to participate in eFashion. These metrics will also inform the ways the system can be improved.

I posit that Bod-IDE *reduces solution viscosity* because: it is flexible, it has high expressive leverage, and it has a close expressive match. I additionally argue that Bod-IDE has the potential to enable the maker community to participate eFashion.

Bod-IDE is *flexible*, reducing effort to iterate on different component behaviours. When an eFashion designer needs to try different behaviours, inputs, and output, Bod-IDE makes it easy to exchange components and relocate them. To modify the behaviour of a paired input and output component, a designer takes the component off their garment, choose a new connector tag, enter the new program on the program board, and places the tags back on the garment. To experiment in the same way physically, designers would have to purchase new components, ensure components are compatible with each other, wire all the components together, and program the component logic. Bod-IDE avoids low-level electronic requirements altogether in favour of making garment designs easy to alter for exploring different components and behaviours.

Bod-IDE has high *expressive leverage* by reducing the number of electronic choices needed to make an interactive conceptual prototype. Electronic components come in many different models and physical capabilities. For example, motors come in many different shapes, sizes, torque ratings, voltage ratings, etc. However, when a designer needs to rotate an object at a specific rate on the shoulder of a jacket, the physical properties of torque and voltage for the motor are irrelevant for exploring different components. Bod-IDE makes it easy to express a spinning motor without the need to work with low-level electronic implementation details.

When designers place components on their bodies, they create interactive prototype garments that are close *expressive matches* to the completed physical garment. When a designer places a component on their bodies, they are effectively expressing their intent to add a physical component at the location they intend to on their garment. Because Bod-IDE's virtual designs and virtual electronic components mimic the real world, sensors like accelerometers can take advantage of the wearer's movement flexibility based on body location. Designers can effectively replace the tracked markers later with real components in their place.

Lastly, Bod-IDE has the potential to empower makers as new participants in designing interactive garments. Typically, high eFashion designers get funding to build garments for the runway. Makers may not have access to funding like eFashion designers and may not have the luxury to experiment with varieties of materials that eFashion designers do. Bod-IDE can empower makers to explore different kinds of components, behaviours, and materials. When makers have virtual designs, they can share designs in online communities and potentially open new venues for maker eFashion. As Bod-IDE improves as a demonstration tool, this may allow makers to participate in high eFashion by allowing them new tools to demonstrate their capabilities and their ideas to collaborators and potential funders.

5.3.4 Limitations

In the current iteration, Bod-IDE can be improved in the following heuristics: power in combination, simplifying interconnections, enabling designers to scale up to large complex garments, and allow designers to automate the transfer of designs to higher fidelities.

Bod-IDE currently has very few electronic building blocks lacking in *power in combination*. Currently, the number of distinct colors recognized by the system limits the number of different components. By improving the AR tracking system, the system's component set can be extended to include more virtual components. From the analysis on makers in chapter 3, more visual output components beyond the LED like screens, strips, and shapes, and more diverse input components can help appeal to makers.

Currently, Bod-IDE has no means for developing custom user-defined components, but by enabling them would help *simplify interconnections* allowing components to utilize the entire ecosystem of connectors and output. For example, with access to the internet through the mirror, it should be easy to develop components that simplify the connection to internet services and social media (e.g., Twitter). Since Bod-IDE treats internet connections as input sources, they will immediately be compatible with all existing output and connector components given the proper input tag standardization.

To build a complex behaving garment on Bod-IDE is currently labour some, time-consuming, and requires programming expertise. When building a garment, programming is inevitable for fashion designers. However, programming on the mirror can be very tedious when scaling up garment complexity. For example, if a designer needed hundreds of LEDs in a specific pattern, the designer would need to connect every LED to an input source physically on the program board. Physically registering each tag currently makes building complex and large garments tedious to program using the mirror. One alternative to attaching AR tags is to 'paint' or 'stamp' the components on the garment mannequin using a physical wand like in DressUp (Wibowo et al., 2012). A wand can easily extrude many multiples of a component.

Finally, Bod-IDE currently has no means to automate some of the processes to transfer into a physical garment. In future iterations, the system should support transferring the virtual garment to printable designs, sewable patterns, or generate a bill of physical electronic components.

5.4 Chapter Summary

In this chapter, I discussed Bod-IDE, an augmented reality mirror that enables eFashion designers to experiment with garment interactivity on existing garments. Bod-IDE attempts to make eFashion prototyping easier by allowing designers to explore interactive garment technologies and iterate on their designs before garment production (RQ 2B). From an existing sketch or garment, the system supports virtual interactive components that can be programmed and interacted with in an AR mirror. Through the mirror, the designer can rapidly test and refine their garment's behaviour using their own body.

Through augmented reality, Bod-IDE combines the limitless capabilities of the virtual world to design real-world objects. AR allows designers to ignore physical constraints such as wiring electronics, finding compatible components, and aesthetic cost of mounting interactive prototype hardware. Thus, allowing designers to test or experiment with different garment behaviours. While designers will eventually need to implement their garments, the virtual approach helps designers envision what behaviours may be worth pursuing with real materials.

Designers can then wear their designs and can be used as a demonstratable artifact to show other collaborators for design feedback or implementation assistance.

Bod-IDE itself does not create eFashion garments, but rather virtual prototypes of them. Bod-Ide creates virtual prototypes that can be used to imagine how the garment may behave in the real world. The mirror is like a personal virtual runway for an eFashion designer allowing them to quickly test the interactive behaviours of their garments before physical implementation.

With Bod-IDE, this concludes this thesis' exploration into prototyping tools to support eFashion design. The initial goal of developing prototyping tools began with an attempt to develop prototyping tools to support interactive garment design. This gap in the current tools that support eFashion design led to a study to understand how eFashion designers currently develop their garments. In this study lead to design guidelines and an initial prototype TortillaBoard, a tool that supports physical implementation and exploration of eFashion garments. The lessons learned from this tool lead to the development of Bod-IDE to explore how might a virtual garment support the design of an interactive garment before physical implementation. With this initial implementation of a virtual interactive prototyping tool, there are some limitations and room for improvement. In the next chapter, I recap the contributions in this thesis and discuss limitations and future work.

Chapter 6 Conclusion

In this thesis, I set out to *explore physical and virtual prototyping tools to enable electronic high fashion designers in envisioning the behaviour of interactive components in an electronic fashion garment before physically implementing their designs.* To address this thesis, I addressed two research goals through the following research questions:

Research Goal 1: develop design guidelines for prototyping tools in eFashion design practice

Research Question 1. **What are the challenges and opportunities in an eFashion designer's practice that an interactive garment prototyping tool can support?**

To develop a prototyping tool, I developed case studies with makers and eFashion designers to understand the challenges and opportunities in their practice for an interactive prototyping tool. I discovered that when makers used Arduino LilyPad, they often used LEDs as output devices and a wide variety of input devices on a diverse set of garment use cases. Through the eFashion designer case studies, I also discovered how they conceptually developed their garment visions and the implementation challenges they faced in building their interactive garments for the MakeFashion runway.

I then synthesize the findings from all case studies into design guidelines inform the creation of interactive garment prototyping tools. These guidelines are: explore alternative physical and interactive realizations on garments, reduce low-level implementation details, and build demonstratable and alterable artifacts. Although these guidelines are not absolute rules, nor do they represent all eFashion designers, they help inform the design of the prototyping tools that I create to address research goal 2.

Research Goal 2: develop prototyping tools that create interactive garment prototypes

In this goal, I set out to build prototyping tools based on the design guidelines developed in research question 1. By addressing these guidelines will help ensure that the resulting prototyping tool addresses some of the challenges and opportunities that the eFashion designers in chapter 3 faced. There are two approaches to authoring interactive garments that I explore through prototyping tools: physical and virtual.

Research Question 2A. **How might a prototyping tool support the exploration of physical implementation and behaviours on an interactive garment?**

In this research question, I set out to explore a physical prototyping tool to support the physical implementation of interactive garments. By building a physical prototyping tool, I aimed to gain an understanding of how eFashion designers currently implement their garments and what processes can be addressed by a prototyping tool. With TortillaBoard I aimed to reduce low-level implementation details so that designers can refine their garments at body-scale wearable prototypes, have more time to refine their garments, and explore more novel interactive eFashion technologies.

However, I discovered that when exploring the physical implementation of interactive components on the body, designers wanted to realize behaviours and aesthetics that aligned with their vision. When the eFashion designers were implementing their garments, they looked for materials and components that aligned with their vision and not to drastically alter the behaviour or underlying electronic components of their garment. While sketching and paper prototyping offer low-fidelity prototyping, there are trade-offs such as being difficult to communicate interactive behaviours (Myers et al., 2008) and that they are difficult to transfer to a higher fidelity prototype with little benefit for the designer. With a promising low-fidelity approach like Fashion CAD, I based my next prototyping tool on developing virtual interactive garments.

Research Question 2B. **How might a virtual prototyping tool support eFashion designers in envisioning their interactive garment designs and knowing what is possible before physically implementing such designs?**

From research question 2A, I developed a virtual garment prototyping tool to help designers envision the interactive behaviours of their garments before physical implementation. It is an augmented reality mirror that enables eFashion designers to build interactive garments using existing garments. As a complement to sketching, Bod-IDE designs can enable designers to explore interactive components without needing to sew or solder their garments. Designers can then wear their garments in front of the mirror and interact with their garments in real time. This allows designers to author demonstratable artifacts to communicate their ideas to other collaborators and stakeholders. Using Bod-IDE, designers can anticipate and explore what implementations are possible before physically implementing their interactive garment designs.

I evaluated Bod-IDE using demonstration, usage, and heuristic type evaluation (Ledo et al., 2018). Namely, I used a "'how-to' scenario" to show what the system is capable of and gathered initial feedback on the system. I then used a "walkthrough demonstration" on laypeople to elicit initial feedback and find the value of the system. I finally evaluated the system using heuristics based on guidelines from Olsen Jr. (2007). Through my evaluation, Bod-IDE *reduces solution viscosity* by enabling designers to prototype and refine interactive garments without physical implementation rapidly. However, as an initial prototype, the system could be improved by developing more interactive components and support transfer to higher fidelities by exporting virtual garments to fabrication machines.

6.1 Contributions

This research made the following contributions: (1a) a detailed examination into two eFashion designer's practice building interactive garments for the fashion runway; (1b) a set of design guidelines for building prototyping tools to support said eFashion designers; (2a) a physical prototyping tool that allows designers to quickly start experimentation at garment-wearable scales; and (2b) a virtual prototyping tool that allows designers to explore and envision the behaviour of interactive components.

In the following sections, I discuss this thesis' limitations and opportunities for future work for the prototyping systems I have presented.

6.2 Limitations and Future work

In this section, I discuss the limitations of this thesis and future work for the two prototyping tools developed. I examine the limitations of investigating the field of eFashion as it is developing and the two high eFashion designers. I then discuss potential opportunities for future work in the two prototyping tools I developed in this thesis.

The original vision for this thesis was to create tools to bring eFashion design into everyday life. One possible future for eFashion is one where the utility of technology on clothing can be a form of communication. Interaction can bring about new communicative utilities beyond the ones described by Sproles (1979) as the field of eFashion evolves. Thus, bringing about a new means to communicate through the medium of interactive clothing. In order to create this vision, however, eFashion designers need to have the tools to explore and communicate compelling visions without limitation to existing technologies. With the right tools, eFashion designers can build not only interactive garments but also propose new technological problems to solve and bring about these innovations into everyday clothing. This thesis is a step towards this vision, but not without several limitations.

Currently, there are very few designers with the expertise the complete set for sewing, electronics, and programming. Because of the technical skills required to create an eFashion garment, this limited the case study's access to a tiny set of designers. Despite the two designers I had access to, they are not experts in all the skills needed to create an interactive garment. As the field of eFashion develops, an eFashion designer may have a different set of skills required to build an interactive garment. It may be that a designer works in a team of other experts like engineers and seamstresses. Or it may be that the tools to create eFashion mature enough such that a designer may not need other experts. In any case, the findings in this thesis may diminish as the assumed eFashion designer's skills and knowledge may change as the field of eFashion matures.

Furthermore, eFashion is not yet widely adopted by consumers. It is not yet known if eFashion garments will appear in retail markets or whether the existing channels for distribution (i.e., fashion runways) will be the means for creating consumer demand and initiating the production of eFashion. It is possible that eFashion will remain a niche clothing style due to a variety of reasons such as cost, difficulty in mass production, or challenging to wear on an everyday basis.

Currently, this thesis only considers high eFashion designers that have developed interactive garments. The interviews I present in chapter 3 only present two eFashion designers. These designers both happen to be familiar with the technology, participated in the same designer group, presented at identical venues, and have little prior fashion design background when they developed their garments for MakeFashion. Thus, the design guidelines cannot be generalized to the eFashion designers. However, the two prototyping tools and their limitations can help inform the design of future eFashion prototyping tools.

While limited to high eFashion designers, there are implications for this work to extend to include makers in eFashion. Currently, high eFashion runways are exclusive to a select few eFashion designers requiring competition for funding and support. By extending the design of the prototyping tools to include makers would enable them to build more eFashion garments and thus enable them to participate in the development of the eFashion field. By authoring virtual prototypes that can be transferred on the internet easily, alternative fashion distribution channels can allow eFashion ideas from makers to “bubble-up” (Jones, 2011) to consumer demand.

In the next section, I discuss future work for TortillaBoard and Bod-IDE.

6.2.1 Extending TortillaBoard

I intend to extend TortillaBoard to multiple sizes for different body parts, additional 3D structures to interface with fabric, and integrate essential components like a microcontroller directly into the sleeve to help the designer get started with full body prototyping faster.

TortillaBoard can be extended to come integrated with common components. Currently, the TortillaBoard comes in an arm-sized sleeve and require an external battery and microcontroller. In future work, there will be other sleeves made for the torso, legs, and other body parts. There can also be rigid 'sleeves' of 3D structures like wings or shoulder pads that the designer can use to build off. Sleeves would have integrated low profile batteries, microcontrollers, and basic input sensors to help designers begin prototyping quicker on the sleeve.

TortillaBoard's toolset can be extended to include parts that enable designers to electronic interface components with different fabrics and materials. Currently, there are no other support tools outside the sleeve to help designers integrate badges to fabrics. Designers may want ways to interface with the fabrics directly. For example, suppose a designer wants to have LEDs shine through the fabric material to a 3D printed diffusion structure, they can potentially use a pin-enabled plastic piece that allows LEDs to shine directly through the fabric while providing a retaining piece to hold their diffusion structure.

To evaluate TortillaBoard in future work, I would employ *demonstration* and *usage* type evaluations (Ledo et al., 2018). Demonstration should show what the features of the tool are and how the features support the current practice of eFashion designers. Observing how designers or makers use TortillaBoard can help reveal usage patterns and what garments the tool typically produces much in the same regard as chapter 3's analysis on makers using LilyPad. Observation is especially useful when evaluating the impact of new toolsets and building blocks like the future plastic-fabric interfacing material mentioned.

6.2.2 Extending Bod-IDE

The next step for Bod-IDE is to use it as a design probe to interview with eFashion designers. As a design probe, Bod-IDE can initiate discussion of how eFashion designers might use technology to: (1) encourage exploration, (2) support discussion, and (3) bridge physical and virtual materiality in prototyping.

Encouraging Exploration. Bod-IDE can be extended to include additional interactive wearable components and environmental simulations.

Additional wearable components can explore physical effects without constraints of the physical world. Some work has been done to create actuating dynamic clothing using pneumatic origami (Perovich et al., 2013) and memory shape alloys (von Radziewsky et al., 2015). These operations may include scaling, actuating, stiffening, or multiplying forms on-the-body. In augmented reality, the mirror can easily allow designers to prototype components that are physically challenging to implement without real-world constraints. Designers are then free to explore materials and components that express different variations of interactivity in the basic elements of clothing design.

From chapter 3's makers, Bod-IDE's component set should be extended to include more kinds of visual output like different shaped LEDs and lighting along with more varieties of input sources. Currently, Bod-IDE has a single type of LED in the system. Having more varities of LEDs in different shapes, multiple lighting sources, and decorative elements would improve the system's component set. In LilyPad Arduino, designers often used the Lilypad patch as a decorative element (Buechley et al., 2008). More components that are decorative could help designers also focus on the aesthetic of the interactions. Furthermore, as suggested by the maker analysis and the heuristics, having more input sources would enable designers to explore more diversity and use cases in their interactive garments. Input sources like simulating internet social services and body posture can easily be simulated, captured, and manually adjusted in virtual reality. Thus, allowing designers to explore and finetune their interactions on their virtual garments quickly.

Without the limitation of real-world physics, new interactive materials that do not yet exist can be prototyped and demonstrated. For example, Figure 27 shows unlimited explosive scales that drip off the elbows of its wearer. The scales would explode like a firework and emit a comic book graphic. Although this material would be impractical, it is meant to help the designer realize the idea and see whether it is worth pursuing the engineering challenges of such a material. Thus, enabling designers to present the need to engineer a technology rather than find an existing material or technology.

Figure 27 A designer exploring the value of a non-existent material in virtual reality. This material can then be demonstrated to other collaborators to help eFashion designers discuss new technologies. These scales would make a loud pop sound after falling a certain distance and emit a comic book like "pop!" effect.

Furthermore, designers could test their garments in various virtual environments – such as train stations, funeral processions, or weddings – to communicate how the garment's visual and behavioral aesthetic might address social expectations. A designer can stage an environment and add virtual actors to the scene. The mirror could be set up to create simulated actors and environments. These scenarios can simulate different input sensors that are hard to control such pollution levels or the weather. These designs and other explorations could be video recorded and revisited for further refinement.

Supporting Discussion. Bod-IDE designs can act as boundary objects (Star, 1989) facilitating interdisciplinary communication across eFashion designers, engineers, or clients. For example, designers may want to work more directly with models or clients (e.g., dancers, actors) to tailor interaction to the wearer's unique physical abilities, while simultaneously supporting design input from all stakeholders (participatory design). Designers can save designs and ask collaborators to make suggestions directly on the virtual garment. The designer can also use recordings or demo their designs to convey exactly how they imagined the garment is supposed to behave.

Designs authored through Bod-IDE can be used as a remote collaboration tool – exporting designs to send to remote engineers or clients for feedback, before the designer has committed to physical prototyping (Figure 28). Designers can send their virtual garments to other stakeholders or their clients for design feedback. Other collaborators can then make suggestions directly on their garment and demonstrate their changes through the mirror.

Prototyping in virtual and augmented reality can empower makers to participate in eFashion. To access eFashion runways, designers need to compete for funding to build their garments. Makers who do not have access to these runways are then left few communication channels. Using Bod-IDE, makers can author interactive garments at little cost and send designs for other people to try. By digitally authoring designs, opens possibilities for virtual fashion runways on the internet allowing maker communities to distribute their fashion ideas.

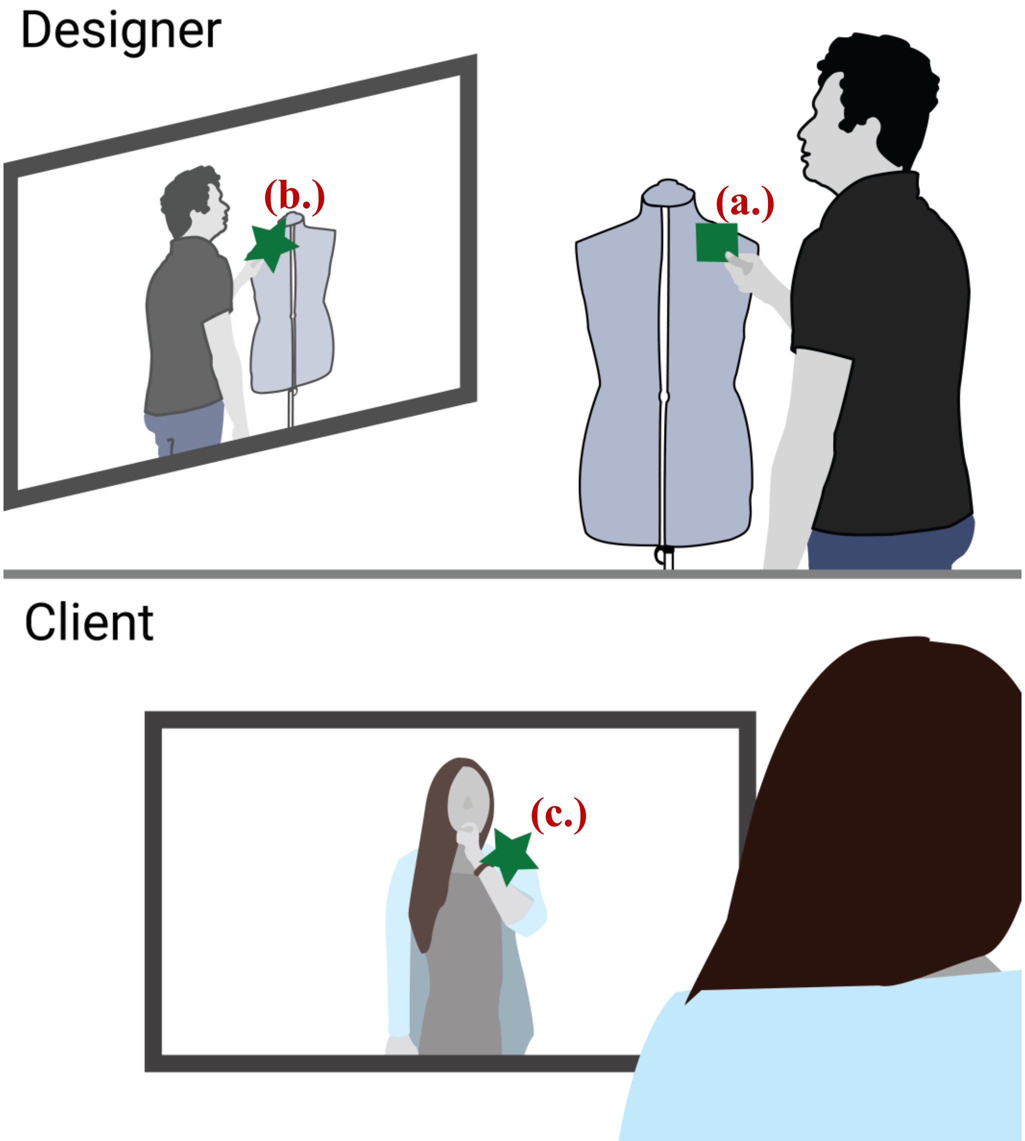


Figure 28 A designer and their client sharing feedback to one another. The designer (a.) holds up a Bod-IDE tag on a mannequin which renders on the mirror in (b.) as a virtual component. The designer then sends their design to the client where (c.) they can see and interact with the same component.

Bridging Physical and Virtual Materiality. In future iterations, Bod-IDE can enable designers to build garments that cross virtual-physical boundaries, having components that exist both virtually and physically. For example, many eFashion designers examine how different materials or fabrics will diffuse light. A future version of Bod-IDE could potentially communicate across physical and virtual representations of materiality. This duality can be used in tandem with existing fashion design practices – such as draping textiles on a mannequin or using a swatchbook (Gilliland, Komor, Starner, & Zeagler, 2010) library of both virtual and physical interactive textiles (Figure 29). GetToyIn (Ozaki, Matoba, & Siio, 2018) is a device that allows toys to cross between virtual and physical materiality. Bod-IDE can also author virtual garments that have components that exist in the virtual world that interacts with the physical world. Designers can explore garments that exist between the boundary of virtual and physical materialities.

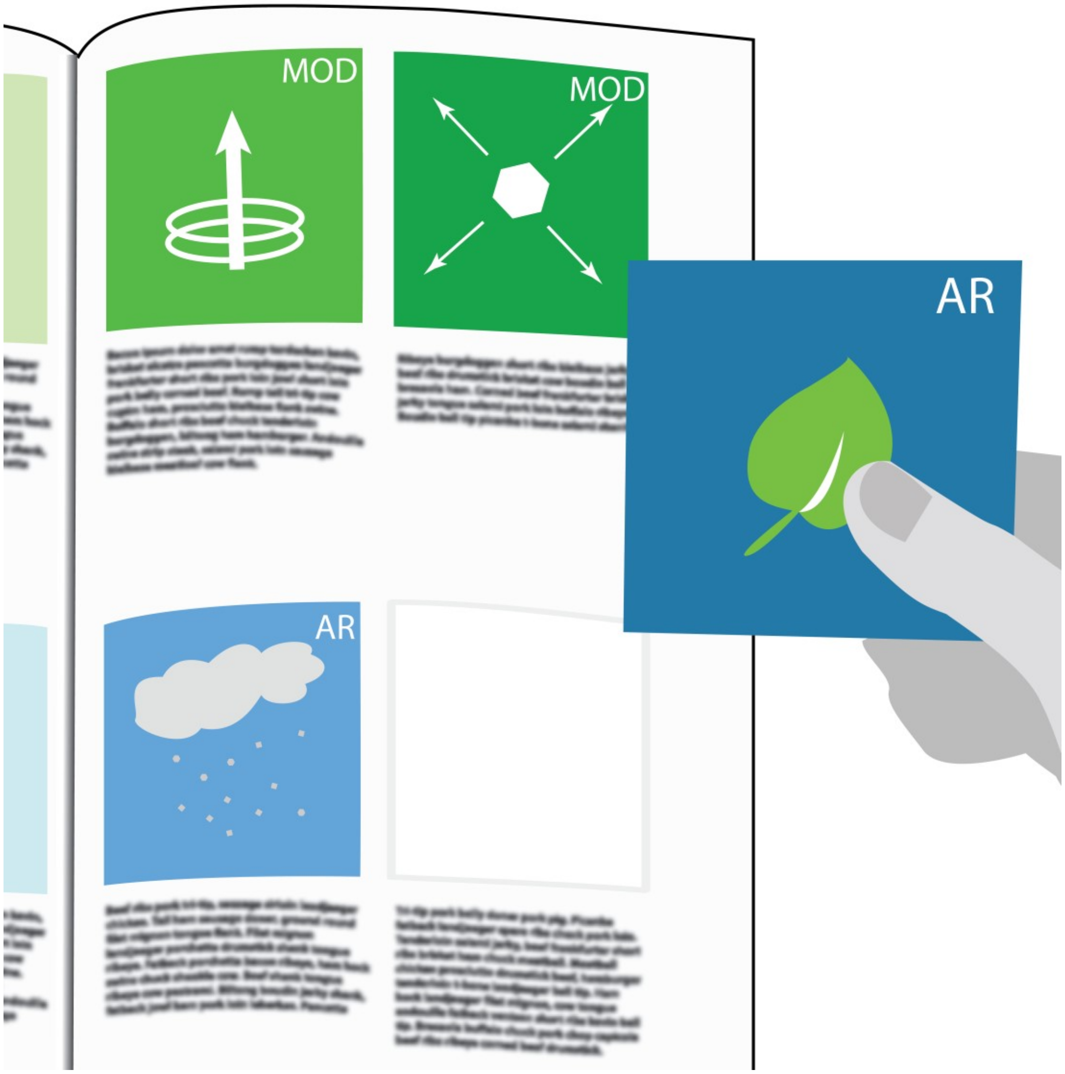


Figure 29 A swatchbook of augmented reality textiles. Designers would be able to look up different interactive behaviours, preview their effect, and use them in their designs.

Outside of fashion, Bod-IDE can be used to design non-fashion interactive objects. In the 3D fabrication community, it is often challenging to design interactive components into real-world objects. Maker's Marks (Savage et al., 2015) is a system that uses augmented reality that allows a 3D scanner to embed interactive component features onto the object's virtual model.

Using Bod-IDE's AR technique, interaction designs can add interactive components to larger 3D (e.g., a large outdoor monument) objects without integrating physical interactive components where it may be expensive to modify.

6.3 Closing Thoughts

In this thesis, I explored two prototyping tools for eFashion design that author interactive garments. To build these tools, I examined what makers already make with LilyPad and how two eFashion designers conceptually developed and implemented their interactive garments. From this, I developed design guidelines that inform the creation of a physical and a virtual prototyping tool for interactive garments.

What this thesis attempts to do is explore ways prototyping tools can help eFashion designers envision and explore more expressions of interactivity on clothing. The prototyping tools I developed attempt to enable designers to explore more eFashion technologies that are otherwise difficult to access. By enabling this exploration, designers can author demonstratable artifacts that can help them communicate with other experts to help them realize their ideas.

It is with hope that with more prototyping tools to support eFashion design, fashion designers will have more ways to express interactivity on garments. Thus, allowing them to envision more ways to express interactive garments, showcase their ideas on the fashion runway, and therefore bringing new interactive garments to market.

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Appendix

Appendix A: eFashion Design Interviews: Semi-Structured Interview Questions

- In your *most recent* project, how did you go about:
  - Conceptualizing the idea?
  - Exploring possible designs (sketches, drafts, etc)
  - Realizing your designs with the tools you have available
  - Addressing the challenges you faced in implementing the final version?
- Who do you design for?
  - How do you go about finding out what they need or want?
- How do you go about designing your work?
  - What are your sources of inspiration?
  - What techniques are involved?
  - How do you transform your thoughts on paper to a working prototype or final product?
- How do you test your design?
  - How do you know you got the right design?
  - How do you refine your ideas?
- Who works with you and who are your collaborators?
  - How do they help you in your projects?
  - How do you communicate your needs with them?
  - What do your collaborators rely on you for?
- What are some constraints/limitations/requirements that you face when making any of your creations?
- If you had a perfect assistant that could do any task, what would you ask that person to do the most? Why?
- What do you enjoy about your craft?
- What is the current state of the field?
  - What is the state of the art?
  - What is currently trending?
  - What future directions do you envision your field going in?

Appendix B: Study materials for Junk Prototyping Study

B.1 Tasks

Task A

Design an interface that helps people model with virtual Lego pieces.

Think of one novelty feature and describe that with your prototype.

Choose any device or invent your own to use to accomplish this design.

Task B

Design an interface that helps people design their own playgrounds for children.

Think of one novelty feature and describe that with your prototype.

Choose any device or invent your own to use to accomplish this design.

Task C

Design an interface that helps users assemble their own humanoid robot from various parts.

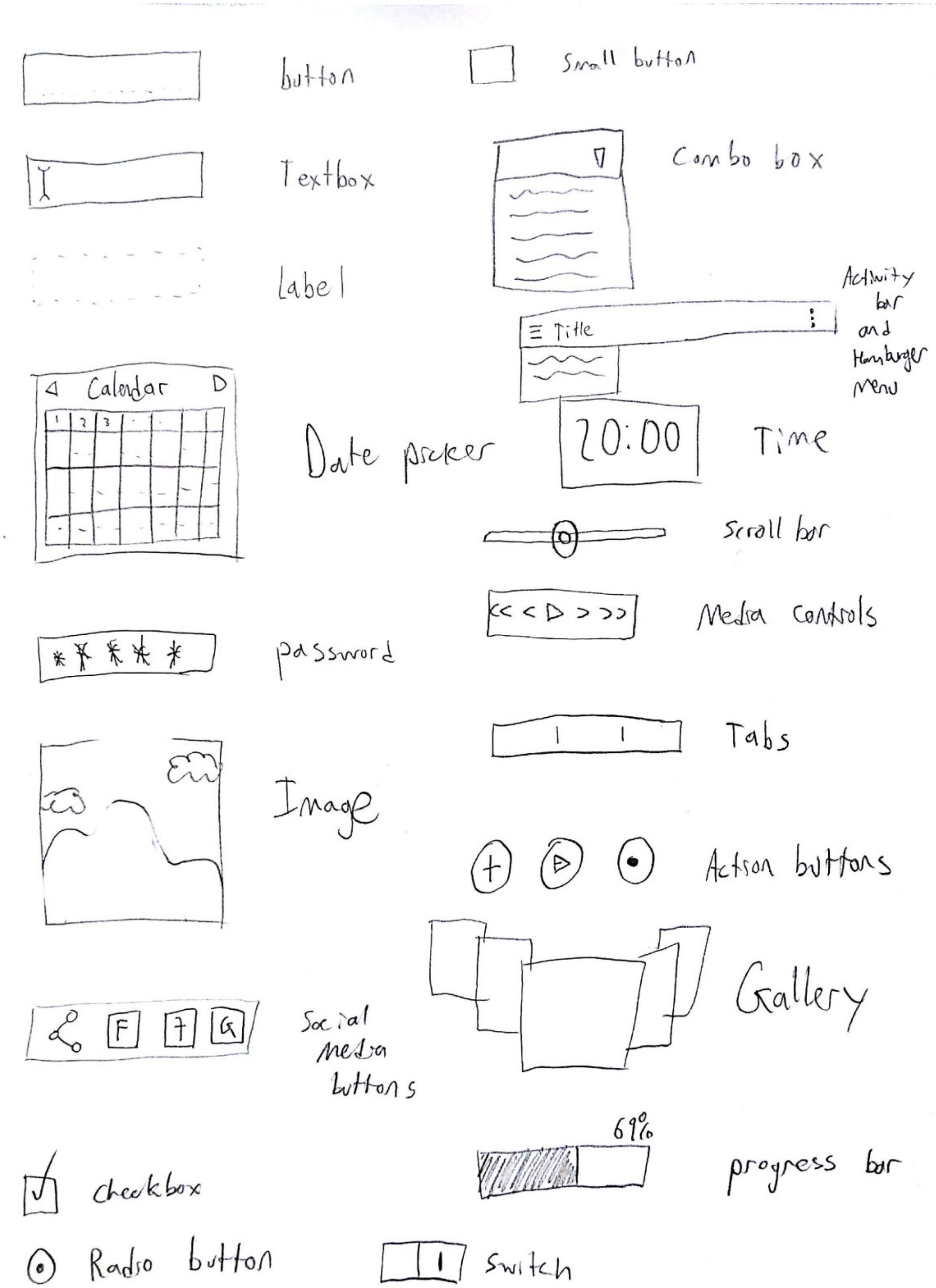
Think of one novelty feature and describe that with your prototype.

Choose any device or invent your own to use to accomplish this design.

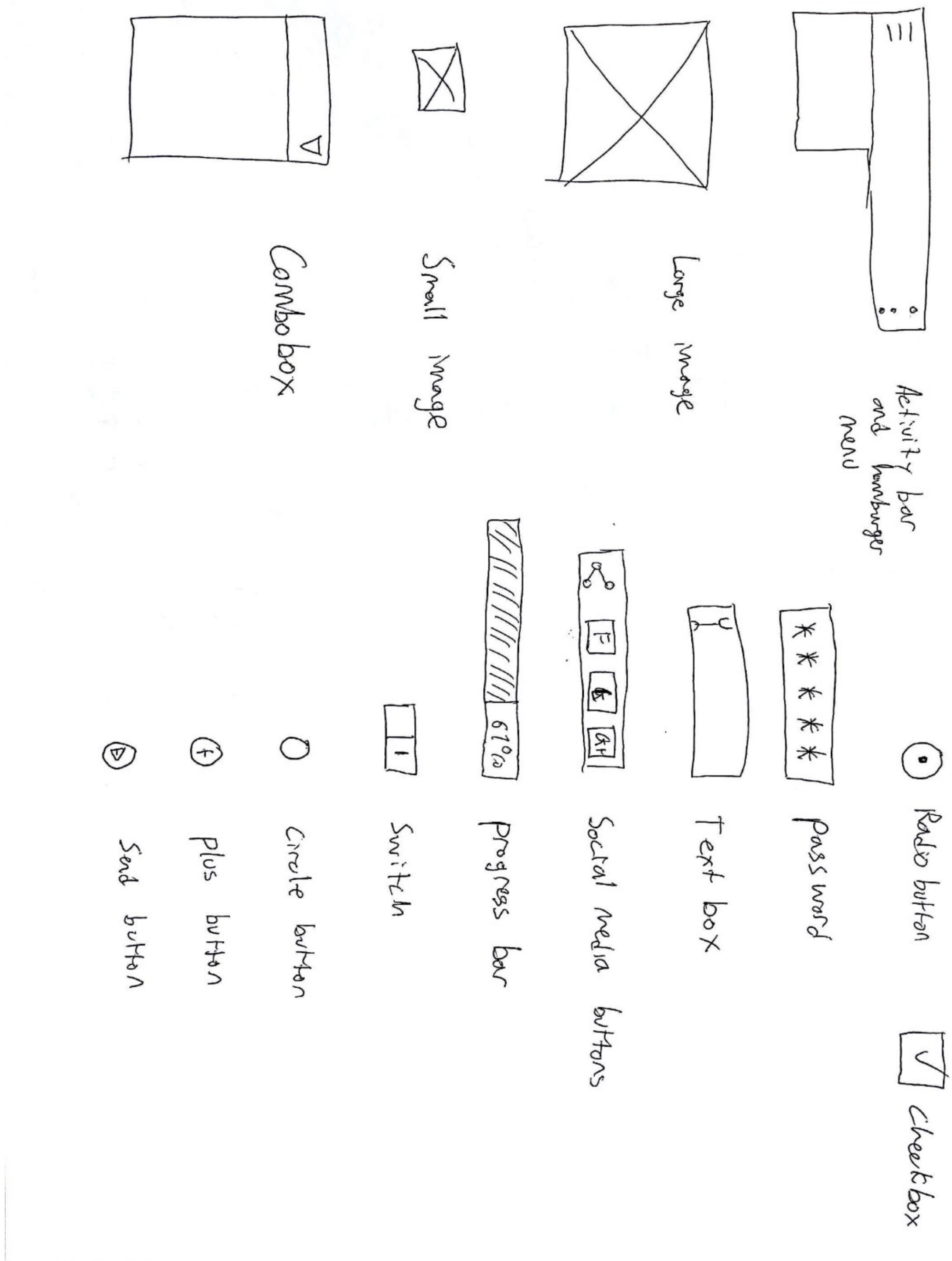
Templates

In the templated case, participants will be exposed to several piles of a variety of user interface controls that they can use. The following is a sample of the potential templates that the participants may be using in their prototypes.

Magnetic templates version 1



Magnetic templates version 2



B.2 Questionaire

Understanding Prototype Output of Design Templates

Age:

- ☐ 18-25
- ☐ 26-32
- ☐ 33-40
- ☐ 41-55
- ☐ 55+

Gender:

- ☐ Male
- ☐ Female
- ☐ Prefer not to say

Please indicate your highest level (or current) education:

- ☐ High school or Equivalent
- ☐ University Degree
- ☐ Master's Degree
- ☐ Doctorate Degree
- ☐ Professional Degree
- ☐ Other: ______________________________

Major or specialization (if applicable): ____________________________________

Please rate your level of familiarity with the following topics (circle your choice):

	Not Familiar	**Elementary**	**Average**	**Proficient**	**Expert**
Prototyping (e.g., interfaces, design work)	**1**	**2**	**3**	**4**	**5**
Paper prototyping	**1**	**2**	**3**	**4**	**5**
Mobile Smartphone design (e.g., interfaces, hardware, etc)	**1**	**2**	**3**	**4**	**5**
Design (e.g., industrial, software, etc)	**1**	**2**	**3**	**4**	**5**
Interface building software (e.g., WYSIWYG editors, drag and drop editors, GUI libraries, etc)	**1**	**2**	**3**	**4**	**5**
Fashion Design	**1**	**2**	**3**	**4**	**5**

B.3 Semi-structured Interview Questions

The following are a sample of the interview questions that we may use during the study. The exact wording is subject to change but the style will remain consistent. If there are substantial changes, we will issue an amendment.

Between-task questions

- Can you please explain to me how your prototype works?
- Do you think your application is novel? In what way?
- Did you base your prototype on a prior experience?
- Were there any factors outside the interface that you considered? E.g.,
    - Who might be using the interface?
    - Feasibility?
    - Practicality? Cost?
    - Goals in mind?
    - Prior experience?

Post-session questions

- Which condition (e.g., template, no template, freeform) did you felt like you had the most success in?
    - What about this prototype made you feel it was successful?
- Did you experience any difficulties with the tools?
    - What was the most difficult aspect of designing/communicating your prototypes?
- If there was one tool you could have had to help you, what would that be and why?

Appendix C: LilyPad Projects on Instructables Samples

Search conducted December 12, 2016 at https://www.instructables.com/

Project number	Name	URL	Intended Utility	LED?	Input?	Internet Enabled?	Components used
1	Arduino LilyPad Duck Dynasty Hoodie with sound and LED lights	http://www.instructables.com/id/Arduino-LilyPad-Duck-Dynasty-Hoodie-with-sound-and/	Garment	Decorative	Yes	No	LED, Zipper switch, Buzzer, Conductive thread, RGB LED, LilyPad, Li-po Battery
2	Open Heart Hoodie	http://www.instructables.com/id/Open-Heart-Hoodie/	Garment	Decorative	Yes	No	LilyPad, LED array, Open Heart Kit, LEDs, Conductive Thread, magnetic snaps, AAA battery, Zipper Switch
3	How to make a LilyPad Arduino LED skirt	http://www.instructables.com/id/How-to-make-a-LilyPad-Arduino-LED-skirt/	Garment	Decorative	Yes	No	LED, Conductive thread, Light sensor, AAA Battery, Lilypad, Light sensor
4	LED Matrix Shirt	http://www.instructables.com/id/LED-Matrix-Shirt/	Garment	Decorative	Yes	No	LilyPad, LiPo Battery, LEDs, Conductive Thread, Fabric glue, Joystick
5	Lilypad Arduino Christmas Sweater	http://www.instructables.com/id/Lilypad-Arduino-	Garment	Decorative	Yes	No	LED, Lilypad, Speakers, Conductive Thread, Li-Po Battery,

	with Blinking Lights and Music	Christmas-Sweater-with-Blinking-Li/					Switch
6	Wireless Dance Costume	http://www.instructables.com/id/Wireless-Dance-Costume/	Performance	Decorative	Yes	Yes	LilyPad, LEDs, XBee, XBee Breakout board, LiPo Battery, Resistor, Flex sensor, Pressure sensor, Conductive Thread
7	Lilypad Arduino Spider Costume	http://www.instructables.com/id/Lilypad-Arduino-Spider-Costume/	Costume	Decorative	Yes	No	LED, LilyPad, Conductive Thread, Li-Po battery, Switch
8	Bats Have Feelings Too	http://www.instructables.com/id/Bats-Have-Feelings-Too/	Accessiblity Aid	No	Yes	No	LilyPad, Vibration, Conductive Thread, Magic Marker, Iron-on Adhesive, Ultrasonic Sonar Range finder, Li-Po Battery
9	Lilypad and Pulse Sensors: The Other Body Experience	http://www.instructables.com/id/Lilypad-and-Pulse-Sensors-the-Other-Body-Experienc/	Empathy Tool	Utility	Yes	No	Lilypad, LED, Pulse sensor, Processing, Conductive Thread, Coin battery

10	Posture Awareness Sensor	http://www.instructables.com/id/Posture-Awareness-Sensor/	Health	No	Yes	No	LilyPad, Vibration, LilyPad battery, snaps, Lilypad Vibeboard, Lilypad button, Flex sensor, Resistor, Conductive thread, LiPo battery
11	Musical Exercise: Workout Shirt MP3 Player Powered by Exercise	http://www.instructables.com/id/Musical-Exercise-Workout-Shirt-MP3-Player-Powered-/	Physical Game	Utility	Yes	No	LilyPad, Shirt, LilyPad MP3Player, Accelerometer, RGB Rotary Encoder, LiPo Battery, Micro SD card, Headphones, Speakers, Conductive Thread, Vibration, RGB LEDs, LEDs
12	Smallsword Choreography Shirt	http://www.instructables.com/id/Smallsword-Choreography-Shirt/	Performance	Utility	Yes	No	LED, Lilypad, Coin Battery, Plain Wire, lilypad buzzer, lilypad switch, glove, shirt
13	Soundie: a musical touch-sensitive light-up hoodie	http://www.instructables.com/id/musical-conductivity-detecting-light-up-hoodie/	Performance	Decorative	Yes	No	LilyPad, Hoodie, LEDs, Speaker, Nail polish, Iron-on Conductive fabric, Conductive Thread, AAA Battery

14	How to make a Heating and Cooling Jacket	http://www.instructables.com/id/How-to-make-a-Heating-and-Cooling-Jacket/	Personal Protection	Decorative	Yes	No	LilyPad, Jacket, LilyPad Mainboard, LilyPad Power Supply, Conductive thread, LEDs, RGB LEDs, Solar panel,LiPo Battery, battery charger, ping-pong balls, Computer Fans, Model Airplane battery, Solid state relay, Mesh fabrics, Glue, Teflon Wire, Temperature sensor
15	Turn signal biking jacket	http://www.instructables.com/id/turn-signal-biking-jacket/	Personal Protection	Utility	Yes	No	LilyPad, button, Conductive Thread, fabric glue, LEDs, AAA Battery
16	The Motivational Moody Workout T-Shirt	http://www.instructables.com/id/The-Motivational-Moody-Workout-T-Shirt/	Physical Game	Decorative	Yes	No	LilyPad, Solar Panel, Conductive Thread, LEDs, Ball tilt Sensor, T-Shirt,

17	Flashlight Tag with Lilypad	http://www.instructables.com/id/Flashlight-Tag-with-Lilypad/	Physical Game	Utility	Yes	No	LilyPad, LED, Vibration motor, Light sensor, conductive thread, Wood board, LiPo Battery

Appendix D: Bod-IDE Poster

This poster was presented in the Designing Interactive Systems 2018 Conference in Hong Kong.

Appendix E: Copyright Permissions

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September 19, 2018

University of Calgary
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Sincerely, [redacted]

Ehud Sharlin

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September 19, 2018

University of Calgary
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Canada

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Sincerely,

[redacted]

Lora Oehlberg