A MODULAR FRAMEWORK FOR SMART GARMENT DESIGN

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by

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ABSTRACT

The challenges associated with designing smart garments can result in a burden that negatively impacts designers’ creativity and motivation. To address technical difficulties and encourage a holistic approach to design, this study proposed a modular framework for smart garment design. This modular framework also reduced barriers to entry and allowed creators to prioritize aesthetic and function, rather than technology. Interviewing nine design and engineering students who expressed interest in smart garment creation led to the identification of key technical challenges surrounding electrical hardware integration, electrical connection creation, and component selection. The modular framework proposed addressed these technical challenges by outlining a central module-peripheral module structure, establishing a substrate-based hardware attachment system, and organizing an adaptable wire connection protocol. A prototype toolkit implementing the framework was created and given to seven teams of design and engineering students for evaluation. Key evaluation metrics such as electrical connections and secure placement showed statistically significant improvements with the prototype toolkit. Further study could address limitations with customization, durability, and deeper participant involvement.
Albert Lin is currently a graduate student at Cornell University. His career objective in fashion is to find meaningful ways to integrate fashion design and technology, with a focus on the design process. His background in both electrical engineering and apparel design gives him a unique perspective and skillset that empowers him to explore smarter methods of apparel design and manufacturing through computing and technology. Prior to graduate school, Lin collaborated on a machine learning project as part of his undergraduate senior design project. This project involved hand gesture detection using radar in a popular machine learning platform. His current research relates to wearable technology and design. In the future, Lin plans to research ways in which artificial intelligence can enrich the apparel design process and enhance designers’ creativity. Ultimately, as a researcher, Lin strives to find ways to enhance human well-being through design and technology.
Dedicated to Leif, who brought me
to so many fun restaurants.
ACKNOWLEDGMENTS

I would like to express my deepest appreciation to my committee, Dr. Heeju Park and Dr. Cindy Hsin-Liu Kao, who have guided and supported my master’s thesis research. I would also like to express my gratitude to all professors I have interacted and worked with in the last two years. Furthermore, I would like to thank the Department of Human Centered Design for financially supporting portions of my research. I would also like to thank every participant in my research for without them this research would not be possible. Finally, I would like to thank the Digital Design and Fabrication Studio team for their expedient 3D printing support.
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LIST OF SYMBOLS

\[ G \quad \text{flexural rigidity} \]
\[ w \quad \text{fabric mass per unit area} \]
\[ l \quad \text{overhang length in } \text{mm} \]
\[ \theta \quad \text{overhang angle in degrees} \]
\[ p \quad \text{p-value} \]
\[ \Delta \quad \text{mean difference} \]
Chapter 1
Introduction

Designing and developing smart garments involves technical, functional, and aesthetic challenges that can create a burden for designers and developers. A modular framework for smart garment design allows designers and developers to focus less on technical aspects and more on aesthetic and functional aspects. The multi-disciplinary nature of smart garments also requires simplified technical content that can reduce barriers to entry. A modular framework can also improve education and knowledge by encouraging a holistic view of design. This research’s goal is to develop a modular framework for smart garment design. The research begins with the identification of technical burdens and perceived challenges. Then, these burdens and challenges are addressed by the development of a modular framework. Finally, the extent to which these burdens and challenges are addressed is assessed.

1.1 Purpose of the Study

The overarching goal of this research is to develop a modular framework for smart garment design. This process begins with the identification of technical burdens and perceived challenges in designing and developing smart garments. Then, these burdens and challenges are addressed through the development of a modular framework. Finally, the extent to which these burdens and challenges are mitigated is assessed.

Therefore, the research objectives are to:

1) Identify technical burdens and perceived challenges with smart garment design and development.
2) Address technical burdens in smart garment design and development through the proposal of a modular framework.

3) Address consumer needs by establishing a common user interface for the modular framework’s usage.

4) Evaluate the effectiveness of the framework.

1.2 Specific Hypotheses or Objectives

The first objective is to identify technical burdens and perceived challenges to smart garment design and development. The modular framework must address specific burdens and perceived challenges in smart garments. Therefore, these must be identified and given priority rankings that reflect the importance of resolving each burden or challenge.

The second objective is to address technical burdens in smart garment design and development. Doing so can simplify the process of developing smart garments. Some technical burdens include technical framework development, electronic component selection, securing soft and hard components, and managing component connections in the garment.

The third objective is to address consumer needs by establishing a common interface. By establishing a common interface, consumer concerns regarding ease of use may be mitigated. Designers and developers would also have a common standard to build upon.

Finally, the last objective is to evaluate the framework. Evaluation is key to ensuring the framework does simplify the design and development process without disrupting manufacturing. Another key factor to balance is creativity versus control, where the tradeoff between customizability and simplicity must be assessed. In the
evaluation process, a prototype toolkit that demonstrates the features of the framework is constructed and analyzed.
CHAPTER 2
LITERATURE REVIEW

To inform this research on a modular framework for smart garments, understanding technical burdens and consumer needs, as well as prior research in adjacent fields such as human computer interaction is needed. Therefore, this chapter summarizes existing knowledge and serves as a literature review on areas relevant to this study.

2.1 Addressing Technical Burdens of Smart Garments

Developing a modular system for smart garment design will allow designers and developers to focus less on technical aspects and more on aesthetic and functional aspects. According to Perry and Malinin and Sanders and Li and Leigh (2017), many designers and developers view “solving technical problems” as a major challenge. Perry et al. reveal that since designers and developers view current technologies as “not robust enough”, they must spend disproportional effort on solving technical problems. Perry et al. also argue that since designers and developers focus on solving technical problems, fewer efforts are dedicated to other important design considerations such as aesthetics and integration. This leads to smart garments that may not fully satisfy consumers’ demands (2017). One way to mitigate this imbalance in development efforts is to simplify the technical content necessary to design smart garments. A modular framework can abstract some technical challenges. Therefore, establishing a modular framework can remove the technical burden from designers and developers. Designers and developers will then be able to fully address non-technical aspects of smart garment design and fully satisfy consumer demands.
The multi-disciplinary nature of smart garment design also calls for simplified technical content that can reduce barriers to entry into smart garment design. According to Dunne (2010), there is little motivation for companies to overcome technical obstacles when there is no “high-potential application”. Dunne also notes that oftentimes, companies with the resources to solve technical obstacles are either apparel companies or tech companies, with little intersection in both industries. On the other hand, Dunne notes, companies with expertise in both, which is necessary for smart garment design, often do not have the money to fund their smart garment development (2010). Here, the development of a modular smart garment framework can mitigate this incentive problem. For example, large apparel companies with little experience in tech will now have a modular system that will allow them to step into the world of tech without much investment or risk. Smaller companies would also benefit from a modular system because they can offset some development costs. The simplified technical content from a modular system thus can create a platform that bridges the divide between apparel and tech and allow for lower barriers to entry.

2.2 Addressing Consumer Needs from Smart Garments

A modular smart garment framework can create a unified standard for both smart garment consumers and smart garment designers and developers, thereby allowing consumers to easily understand and use all their smart garments. Perry et al. (2017) and Salahuddin and Romeo (2020) note that there is a significant divergence between what consumers want from smart garments and what smart garments currently offer. According to Salahuddin and Romeo (2020), some aspects that consumers had significant interest in include product safety, data privacy, and battery longevity. Having a modular smart garment framework can standardize how these aspects are addressed by smart garment designers and developers. For example, a
modular smart garment framework can implement a uniform information security protocol. When each smart garment designer and developer creates a product using the framework, both the consumer and the designer-developer can be assured that a set standard is being followed. This would not only address the consumers’ needs but also create guidance for designers and developers.

Furthermore, a modular smart garment framework can establish certain user interface standards and give the consumer a simpler method to integrate different smart garment products from different designers and developers. Many technical standards, such as USB-C (USB-IF, 2014), have established user interface standards that simplify consumer understanding. By establishing a single USB connector, the USB-IF simplified what the consumer needs to know about USB devices (2014). A similar user interface standard for smart garments would also simplify the consumer’s learning and therefore lead to increased smart garment adoption.

2.3 Building on Prior Work from Human Computer Interaction

Prior works in the field of Human Computer Interaction present novel solutions but demonstrate limitations in functionality or end-use. Buechley (2006) describes an e-textile “construction kit” that serves as an introductory educational and prototyping tool for e-textiles. Buechley’s kit focuses on basic electric components such as LEDs, switches, sensors, and actuators. Notably, each individual component in Buechley’s kit is attached using fabric PCBs and “sewn in” using conductive thread or iron-on circuits. However, Buechley’s kit is limited in terms of the functionality of smart garments constructed, as the kit’s primary intent is education and STEM interest development. Similarly, Kazemitabaar et al. (2017) describes “MakerWear”, another educational construction kit designed to introduce electronics to elementary school students. This kit uses rigid magnetic “modules” with a standard size to house
electronic components and connections. Once again, this kit is limited in functionality due to its intended audience. Furthermore, this kit is constrained by its requirement that modules physically contact to allow for electrical current flow, which also affects the flexural rigidity of the fabric substrate. Jones et al. (2020) presents a prototyping toolkit, “Wearable Bits,” that uses square, interconnectable fabric “bits” to achieve wearable technology function. However, since this toolkit’s primary purpose is prototyping, the aesthetic of the constructed garment is greatly hampered. Finally, while Buechley, Kazemitabaar, and Jones tackled specific problems in smart garments, none present a holistic solution to smart garments. Other adjacent Human Computer Interaction fields, such as on-skin electronics, have also tackled modularity. For example, Ku et al. (2021) present a modular prototyping toolkit for on-skin electronics. Notably, this toolkit emphasizes “skin conformability” and presents various wire modules. Like the wearables prior, Ku et al.’s platform is targeted to individual beginners, not manufacturers.

2.4 Landscape of Wearables and Smart Garments in Higher Education

A modular smart garment system could also improve the education and knowledge of smart garment designers by encouraging a holistic view of design. According to Perry (2018), few smart garment creators have “knowledge related to all fields of smart clothing”. Perry concludes that this lack of knowledge leads to frequent overlooking of important issues such as sustainability (2018). Currently, the education of wearable technology leans closer to electrical engineering and computer science. Buechley and Eisenberg (2008), for example, describe an e-textile workshop that they hope can “serve as an introduction to computing”. Lau and Ngai and Chan and Cheung (2009) also describe a wearable course for students that hopes to inspire computer science talent. On the other hand, there is little literature on wearable
technology education in fashion design curricula. This bias not only reflects the tech-heavy reality of smart garment design mentioned prior, but also exposes the lack of design education in smart garment designers. Having a modular smart garment system could encourage a holistic view of design by de-emphasizing technical aspects of smart garments. This would encourage smart garment designers, especially those with more technical backgrounds, to solve other design problems.

2.5 Prior Work on Qualitative Evaluation Methods

Various prior modular systems from adjacent fields have tackled qualitative and holistic evaluation with a focus on open-ended making. Buechley (2006) and Kazemitabaar et al. (2017) introduce STEM education-focused modular wearable systems that were evaluated through workshops with children where observations are analyzed qualitatively. Jones et al. (2020) and Ku et al. (2021) introduce prototyping kits that were qualitatively evaluated through workshops with adults with mixed backgrounds.

Buechley (2006) describes an e-textile “construction kit” that serves as an introductory educational and prototyping tool for e-textiles. Buechley’s kit focuses on basic electric components such as LEDs, switches, sensors, and actuators. However, Buechley’s kit is limited in terms of functionality, as its primary intent is STEM education. Here, Buechley evaluates their “kit” in two ways: demonstrating potential use cases, and workshops with children and teens. In their application demonstration, Buechley constructs three samples, including “[a] Communicating Shirt”, “a Temperature-Sensing Hat”, and “[a] Wearable LED Display”. Notably, outside participants who have no experience with the kit are not involved in this demonstration. Therefore, this demonstration only showcases the functional applications of the kit, but not how end-users interact with the kit. In Buechley’s
workshops, children and teens used their kits to learn electronics and circuit design. Here, Buechley uses “complete working designs” as a metric to evaluate the kits. Few details are given on the specifics of Buechley’s workshops.

Similar to Buechley, Kazemitabaar et al. (2017) describe “MakerWear”, another educational construction kit designed to introduce electronics to elementary school students. This kit uses rigid magnetic “modules” of a standard size to house electronic components and connections. Once again, this kit is limited in functionality due to its intended audience. Furthermore, this kit is constrained by its requirement that modules physically contact. Kazemitabaar et al. first held pilot studies that seek “[to] gain [a] preliminary understanding of how and what children could build”. Here, Kazemitabaar et al. recorded qualitative “common challenges” and verbal feedback from participants. Kazemitabaar et al. then held formal workshops where students experimented and constructed open-ended designs. They collected data on “video, design challenge performance, artifact-based interviews, and the pre- and post-study questionnaires” (2017). Notably, they use video to analyze “facial expressions, physical movement, and social interactions” with thematic coding. In their analysis, Kazemitabaar heavily relies on quotes combined with other qualitative and quantitative data.

Jones et al. (2020) present a prototyping toolkit, “Wearable Bits,” that uses square, interconnectable fabric “bits” to achieve wearable technology function. However, since this toolkit’s primary purpose is prototyping, the aesthetic of the constructed garment is greatly hampered. Jones et al. held workshops with a wider participant age range but still retained an open-ended design prompt. Here, their workshops consisted of ideation sessions followed by prototype development (2020). The workshops were video recorded and then thematically coded (2020). Combined
with observation notes and pre- and post-workshop questionnaires, Jones et al. analyzed data qualitatively for themes with an emphasis on social dynamics.

Ku et al. (2021) present a modular prototyping toolkit for on-skin electronics. Notably, this toolkit emphasizes “skin conformability” and presents various wire modules. Ku et al. conducted both single- and multi-session workshops to evaluate their kit. Both workshops recruited student participants from both design and engineering fields. In their single-session workshops, participants trialed the kit by completing two simple tasks. Their experiences were qualitatively captured in audio recordings and post-workshop interviews. This data was then coded iteratively for themes (2021). In their multi-session workshop, Ku et al. asked participants to complete two sessions, with one introductory session similar to the single-session workshop, and one “final project” session with more open-ended experimentation. Once again, their experiences were qualitatively captured in audio recordings and post-workshop interviews. This data was then coded iteratively for themes (2021).
Perceived challenges in smart garment design and development the modular framework must address are first identified through focus groups and interview sessions. Then, these technical burdens are addressed through framework development, component selection, secure attachment, and intra-garment connections. Consumer needs are also addressed through the establishment of certain user interface standards. Finally, the framework is evaluated through prototype development and prototyping trials. This process is illustrated below in Figure 1.

**Figure 1**

*Overall Methodology*

<table>
<thead>
<tr>
<th>Identifying Specific Needs and Perceived Challenges</th>
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<td>1. Focus Group Interviews</td>
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<td>1. Framework</td>
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<td>2. Components</td>
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<td>3. Secure Attachment</td>
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<td>4. Intra-garment Connections</td>
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<table>
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<th>Evaluating the Framework</th>
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<tbody>
<tr>
<td>1. Prototype Toolkit Development</td>
</tr>
<tr>
<td>2. Prototyping Trials</td>
</tr>
</tbody>
</table>
3.1 Identifying Specific Needs and Perceived Challenges

The first action item is to understand smart garment designers and developers, and their perceived barriers to entry into smart garment design. This data is collected through focus group interviews. Questions guiding the focus group interviews gauge the proficiency level of technical skills associated with smart garments, such as basic electrical skills, programming skills, materials familiarity, and other related aspects. The focus group interviews also attempt to gauge more qualitative aspects, such as designers’ and developers’ fears, and what makes designers and developers uncomfortable. The focus group interviews involve students who are interested in or have participated in smart garment design. Data synthesized from the focus group interviews is used to prioritize certain outcome objectives for the modular framework.

The purpose of the focus group interviews is to understand students’ familiarity and fears when it comes to smart garment design in terms of aspects related to three categories: functional, technical, and aesthetic components of smart garments. The population of interest is comprised of students (undergraduate and graduate) who are interested in smart garment design and development, since the modular framework should specifically satisfy the needs of this population. Data gathered through the focus groups informs aspects of the framework and is used to evaluate the framework.

The focus group interviews are guided by questions from the three aforementioned categories. The three categories represent general aspects of smart garment design and development. The ‘functional’ category represents the end-use functionality of smart garments. Specifically, how, and where smart garments are used, whether smart garments available on market are actually useful, and other issues related to the function of smart garments. The ‘technical’ category relates to the design and construction of smart garments from electrical components to programming to garment design. For example, integrating components, component selection, and other
technical issues. The ‘aesthetic’ category relates to how or whether smart garments are integrated with clothing in a seamless manner. This subjective category deals with how electronic components affect how a garment looks and feels, how or whether a garment ‘hides’ electronics, and other ‘look-and-feel’ issues.

In terms of logistics, the focus group interviews involve a total of nine participants. Participants are provided an incentive of twenty-five dollars of cash following the completion of their focus group session. Prior to the focus group, a short presentation is given on the definition of smart garments and some current market offerings. The session itself consists of five minutes to confirm consent, a five-minute introduction and educational segment, followed by sixty minutes for discussion. The focus group interviews are conducted via Zoom. An interview guide for the focus group is available in Appendix 1. An Institutional Review Board has reviewed and approved the focus group protocol. The IRB Exemption Letter is available in Appendix 7.

A total of nine students are interviewed for their views and opinions on smart garment design and development. These participants all expressed interest in smart garment design prior to the interview or have previously taken a course on smart garments and wearable technology. Of the nine participants, two are undergraduate students and seven are graduate students. Six students report being in a design-related field, such as apparel design or studio art. Three students report being in an engineering-related field, such as electrical engineering or computer science. A detailed breakdown of the participants’ backgrounds is tabulated in Table 1 below. These interviews are used to gauge areas and priorities for the modular smart garment framework to address. Each participant’s interview transcript was coded and analyzed thematically in Atlas.ti.
Table 1

<table>
<thead>
<tr>
<th>Field/Level</th>
<th>Undergraduate</th>
<th>Graduate</th>
<th>Totals</th>
</tr>
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</tr>
<tr>
<td>Engineering</td>
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<td>3</td>
</tr>
<tr>
<td>Totals</td>
<td>2</td>
<td>7</td>
<td>9</td>
</tr>
</tbody>
</table>

3.2 Addressing Technical Burdens of Smart Garments

Addressing technical burdens in smart garment design and development can eliminate some technical burdens and simplify smart garment design and development. The primary technical challenge is the development of the framework, including its centralized computing module and use-case specific peripheral modules. Additional important high-level technical burdens include electronic component selection, securing components, and managing connections in the garment.

3.2.1 Central Module-Peripheral Module Framework and Components

The primary challenge in addressing technical burdens is the development of the framework’s technical foundation. Broadly, the framework consists of a centralized computing module and various use-case specific peripheral modules. The centralized computing modules incorporate all ‘active’ components while peripheral modules incorporate ‘basic’ components. The centralized computing module contains all core electronic components essential to all smart garments. Thus, this module is the largest module and should be placed in a relatively large and stable part of the garment. Electronic components necessary in this central module include a microcontroller board with wireless communications, a battery, and electrical contacts to connect the central module to peripheral modules. To complete the centralized module, suitable off-the-shelf components are identified. Then, enclosure options are
considered, evaluated, and finalized. The peripheral modules are use-case specific and contain basic components such as sensors and actuators. Excluding ‘active’ components such as batteries simplifies the implementation of peripheral modules. Once again, suitable off-the-shelf components are identified and selected for peripheral modules.

3.2.2 Securely Attaching Components with Component Substrates

After components are selected, the components must be securely attached to the garment. The primary objective for securely attaching components is to develop an attachment system that not only utilizes established practices in garment construction but also interfaces with existing electrical components without the need for additional unnecessary construction steps.

To facilitate integration with existing garment construction practices, a sew-on component substrate is used to facilitate electrical component attachment. A component substrate consists of a sheet of flexible plastic backing with cutouts to facilitate sewing, and an electrical component secured using epoxy or another glue. Figure 2 below illustrates the basic set of component substrates, each with hole cutouts to facilitate sewing. The basic set consists of substrates that are one-inch by one-inch, two-inch by two-inch, one-inch by two-inch, and 2.5-inch by 2.5-inch. Sewing attachment methods for the basic component substrate are illustrated in Figure 3 where bar tacks or hand stitching is possible in various orientations. The direction or orientation of the bar tacks can facilitate slight amounts of movement if such is necessary based on the requirements of the garment.
For component attachments that require a smooth hand, the streamlined component substrates, illustrated in Figure 4 below, allow for a buttonhole or zig-zag stitch to eliminate any contact with the substrate’s plastic edges. Otherwise, this set is identical to the basic set dimensionally. Sewing attachment methods for the streamlined component substrate are illustrated in Figure 5. For streamlined component substrates, substrate attachment to fabric results in less movement potential due to the large number of stitches required, which may be desirable depending on the type of garment.
Figure 4
Streamlined Component Substrates

Figure 5
Streamlined Component Substrate Attachment

Slitted substrates that allow for more flexibility allow large substrates to feel less rigid. The larger substrates, which are two-inch by two-inch and 2.5-inch by 2.5-inch, can feel rigid due to their large sizes. Therefore, slitted substrates are made to allow for additional flexibility. Figure 6 below illustrates slitted versions of both the basic and streamlined substrates. As the figure shows, slits for the basic substrates are larger, since the streamlined substrates have more flexibility inherently. The center for each slitted substrate remains solid to allow for solid component affixing. Attachment of these substrates follows either the basic or streamlined versions they are based on.
3.2.3 *Managing Intra-garment Connections*

The secured components need to be connected in an electrically reliable and mechanically durable manner. Cable management options include utilizing seam allowances to securely attach electrical wires. Various conductive wires are evaluated, including off-the-shelf electrical wires commonly used in prototyping with breadboards and conductive thread products. Here, the regular wire represents an approach closer to electronics development while the conductive thread represents an approach closer to apparel design. Once again, the goal is to use products that are off-
the-shelf to reduce costs related to custom components. Cable endpoint options range from metallic magnetic snaps to wireless electrical contacts. As in the ‘Securely Attaching Components’ section, samples of each potential cable management system are constructed and evaluated qualitatively and given a best use-case. Once again, the framework would provide recommendations for attachments but not dictate the use of any specific method.

Managing intra-garment connections poses a significant technical challenge. Prior modular designs have incorporated connection modules of the same size as other device modules (Ku et al., 2021) (Jones et al., 2020) (Kazemitabaar et al., 2017), with a typical longer connection resembling modules configured in Figure 7. Generally, each wire ‘module’ is identical in size. To achieve a longer connection, multiple modules are connected side-by-side. This approach, while consistent and simple, may not be practical for smart garments or any scenario where longer connections are required. Furthermore, some of these utilize square modules that, when chained together, blanket a large surface area. To mitigate these issues while retaining some modular commonality, this framework divides the intra-garment connection system into the endpoint, exit, midpoint, enclosure, and wire. This paradigm is illustrated in Figure 8. Here, the wire that facilitates electrical signals is covered by the enclosure. Each midpoint connects different wires together. The exit allows for the transfer of wiring between the inside and outside of the garment. Finally, the endpoint interfaces the in-garment electronics with the central computation module. Although this system introduces some complexity, it brings the ability to create connections of varying lengths and interfaces between different connection methods.
**Figure 7**

Conventional Solution for Modular Connections

**Figure 8**

Intra-garment Connection System Overview

**Connection Midpoints.** Intra-garment connection midpoints represent junctions between connections. Conductive thread and electrical wires have differing midpoint mechanisms due to their material properties. For conductive thread, there are no thread-thread midpoints since thread can be sewn in an overlapping manner to form a contact. However, a wire-thread midpoint is necessary to interface conductive thread and electrical wire since the conductive thread is not receptive to solder. This midpoint mechanism is illustrated in Figure 9, where the wire is terminated with a metal ring. Here, mechanical crimp (shaded, dark) is combined with heat-bonded permanent glue (shaded, light) on the wire side, while conductive thread is knotted onto the metal ring.
For electrical wires, two types of midpoints exist, as illustrated in Figure 10. The first type is a heat-shrink wire connection, where two wires are permanently bonded with glue (shaded, light) and their stripped electrical cores are soldered (shaded, dark). This bonding is done with a heat gun. The second type of midpoint is a mechanically crimped connection. This represents a conventional port-style connection where each wire is mechanically attached to a plug or receptacle connector via crimping (shaded). Although this port-style connection can be disconnected and reconnected, in practice, a considerable amount of force is required to disconnect the ends. Midpoint selection is almost completely dependent on the specific intended usage of the midpoint and will be summarized in the Results and Analysis section.

**Figure 9**
*Thread Connection Midpoints*

**Figure 10**
*Wire Connection Midpoints*

1. Heat-shrink Wire-wire Midpoint

2. Crimp Wire-wire Midpoint
**Connection Endpoints.** Intra-garment connection endpoints represent the interface between the intra-garment connections and the central computation module. This interface consists of one module-facing end comprised of magnetic pogo pins and another garment-facing end with either the knotted endpoint or wire endpoint. The knotted endpoint is used for conductive thread and has pad-holes for thread knotting. The wire endpoint is used for electrical wires and has pre-attached wires that can be spliced with wires from the garment using a midpoint. The magnetic connectors are positioned such that the endpoint forms an “L” shape that can connect with the central module in a flat and flush manner. A through-hole is included to facilitate fastening to the garment. Figure 11 below illustrates the two endpoints. Endpoint selection entirely depends on the type of connection wire and will be summarized in the Results and Discussion section.
To facilitate easier magnetic connection to the central computation module, an additional substrate, the central module interface, is created. This substrate serves a similar purpose as the aforementioned connection endpoints. Figure 12 below illustrates the substrate, whose cut holes match the placement of magnetic pogo pins on the central computation module. Note that a large central cutout is present to allow for better flexibility.
**Connection Exits.** Intra-garment connection exits facilitate wire transport between the inside and outside of the garment. There are two exit types, the buttonhole exit, which can be placed on any part of the garment, and the in-seam exit, which can be placed through seams such as in pockets or other places where seams already exist. The two exits are illustrated in Figure 13. Exit selection depends on placement in the garment and will be summarized in the Results and Analysis section.
**Connection Wires.** A key part of intra-garment connections is the connection wire itself. The two primary means of connection are the conductive thread and the electrical wire. Here, the conductive thread is analogous to regular thread in terms of application, while the electrical wire requires an external attachment. To determine the best use case for each, the electrical and thermal characteristics of each option are tested at relevant wire lengths.

The two primary means to connect electrical components inside smart garments are conductive thread and electrical wires. Conductive thread typically contains silver fibers or stainless steel, with many generic options available on retailers such as Amazon and Alibaba. The primary advantage of conductive thread is its application method. Like any regular thread, most thin conductive thread can be sewn on with a sewing machine. This reduces the complexity of manufacturing as it conforms with typical garment construction processes, although most conductive thread resembles heavier thread. Since different conductive threads behave differently, four types of conductive thread with varying thickness and conductive fiber composition are selected and examined. On the other hand, flexible electrical wires can also be used. Stranded electrical wires with silicone insulation and 18 AWG and 22 AWG gauge are used in this study. Table 2 below summarizes the different connection types examined.

<table>
<thead>
<tr>
<th>Connection Type</th>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thread A</td>
<td>Conductive Thread</td>
<td>With silver fibers</td>
</tr>
<tr>
<td>Thread B</td>
<td>Conductive Thread</td>
<td>With stainless steel fibers, 2-ply</td>
</tr>
<tr>
<td>Thread C</td>
<td>Conductive Thread</td>
<td>With stainless steel fibers, 3-ply</td>
</tr>
<tr>
<td>Thread D</td>
<td>Conductive Thread</td>
<td>With stainless steel fibers, “Yarn”</td>
</tr>
<tr>
<td>Electrical Wire</td>
<td>Electrical Wire</td>
<td>18 AWG gauge</td>
</tr>
</tbody>
</table>
The length of the connection should be increased to account for fabric movement and stretch. For woven fabrics or fabrics that do not stretch, a half inch should be added at each end of the connection to account for fabric movement. For knit fabrics or stretch fabrics, an additional inch should be added between the connection endpoints to account for stretch. Even more length should also be added based on the stretch of the fabric.

Fundamentally, the conductive thread and the electrical wire must be attached differently to smart garments. The conductive thread is sewn onto fabric just like any other regular thread. Typically, conductive thread is sold on a bobbin, since the bottom thread of a straight stitch does not loop to the top of the fabric, which keeps the shape of the conductive thread relatively straight. On the other hand, the electrical wire must be attached externally. The next section, Intra-garment Connection Enclosures, details different attachment methods and their effects on fabric.

**Resistance Characteristics.** To highlight the electrical differences between these two connection types, the resistance of each connection type (see Table 2 above) is measured at various lengths. Resistance measurements were taken with a multimeter at five-inch increments ranging from five inches to sixty inches. This is to ensure a wide range of connection lengths are observed. Each length is also given an example application that highlights the relevance of the length. For example, the five-inch length is approximately the length of the inseam on running shorts. Prior to measurement, each connection is straightened to reduce the effects of induction.

**Thermal Characteristics.** Conductive thread and electrical wires may also exhibit different thermal attributes that can influence comfort and safety. To
characterize this thermal performance, a 0.5 Ampere current, supplied by a DC power source, is run through a six-inch-long segment of each conductive thread type and a six-inch-long electrical wire. The 0.5 Ampere current represents the typical maximum amount of current that can be driven by a microcontroller. The heat emitted from each is recorded using a FLIR One Pro infrared camera with a temperature readout for sixty seconds. The ambient room temperature is set to 24 degrees Celsius. A video of each’s temperature gradient is recorded along with wire temperature to capture how heat radiates. Temperature measurements are recorded at the initial condition, five seconds, ten seconds, fifteen seconds, thirty seconds, forty-five seconds, and one minute. This data is then compared.

**Connection Enclosures.** Intra-garment connections need to be placed in stable locations in the garment with minimal impact on the look and feel of the garment. Therefore, enclosures for the connections are crucial. Placing wires on seam allowances seems to be a natural choice because seam allowances are typically hidden from the outside of garments and provide access to all parts of a garment. Four connection enclosure options are proposed and each’s effect on a fabric’s flexural rigidity is assessed.

Four enclosure options are proposed based on the type of connection enclosed and seam type. For open seams, connections can simply be placed on the seam allowance. Conductive thread can be directly sewn-on, and electrical wires can be attached underneath a zigzag stitch. If necessary, the seam allowance can be increased to add more room at the cost of more fabric consumption. A fourth option is the encased electrical wire, where the wire is encased in a French seam. These four options are illustrated in Figure 14 For knitted fabrics, a ‘pouch’ fabricated using a
lightweight knit can be overlocked on top of the body fabric to create a casing similar to the fourth option, as illustrated in Figure 15.

**Figure 14**

*Connection Enclosure Types*

| 1. Conductive Thread | 2. Conductive Thread (Folded) | 3. Electrical Wire (Zigzag) | 4. Electrical Wire (Encased) |

![Figure 14](image)

**Figure 15**

*Overlock Pouch*
The stiffness of the connection enclosures influences the overall stiffness of the garment. Fabric stiffness is an important factor in garment design and can impact the look and feel of the garment. Cho, Kim, and Casali (2002) found that psychophysical touch sensations are influenced by pliability and stiffness. Furthermore, Hu, Chung, and Lo (1997) found that varying seam properties such as seam allowances influence drapability of a fabric. Therefore, the stiffness of each connection enclosure type must be assessed to gauge its influence on the fabric’s stiffness and by extension the garment’s stiffness. Here, stiffness is tested and quantified as flexural rigidity.

A flexural rigidity test is used to determine the effects of each connection enclosure type. This test is based on ASTM D 1388-18, “Standard Test Method for Stiffness of Fabrics”, with a few variations (ASTM, 2018). Here, five 160-millimeter-by-50-millimeter samples are constructed, four corresponding to each connection enclosure type and one control with just fabric. The fabric base used is a muslin fabric. The samples are illustrated, not to scale, in Figure 16. Then, the sample is secured such that 60 ± 1 millimeters are hanging. The angle at which the sample hangs, \( \theta \) is then measured using a protractor. Fabric mass per unit area \( w \) is calculated by first measuring the sample mass with a digital scale and sample area, followed by calculations using conversion factors. Propagation of uncertainty is used to calculate the percentage error, which is then converted to absolute error. The mechanism of this test is illustrated in Figure 17. Finally, the flexural rigidity \( G \) is calculated using Equation 1.
Figure 16

*Connection Enclosure Test Samples*

![Connection Enclosure Test Samples](image)

Figure 17

*ASTM D 1388-18 Based Test*

![ASTM D 1388-18 Based Test](image)

Equation 1

*ASTM D 1388-18 Equation for Flexural Rigidity*

\[
G = 1.421 \times 10^{-5} \times w \times l^3 \times \frac{\cos(\frac{\theta}{2})}{8 \times \tan(\theta)}
\]

Where \(G\) is flexural rigidity in units of \(\frac{\mu m}{m}\), \(w\) is fabric mass per unit area in \(\frac{g}{m^2}\), \(l\) is overhang length in mm, and \(\theta\) is overhang angle in degrees.
3.3 Evaluating the Framework

Evaluation is key to ensuring the framework simplifies the design and development process. To evaluate the framework, a prototype toolkit is developed to demonstrate the features of the modular framework. This prototype is also used to evaluate the effectiveness of the framework through rapid prototyping trials. Trials are conducted to assess the usefulness of the framework prototype quantitatively and qualitatively.

3.3.1 Framework Prototype Toolkit Development

A prototype toolkit is developed to demonstrate the framework’s modular components, including the centralized computing module and peripheral modules. The prototype toolkit also demonstrates intra-garment cable management and cable endpoints.

Prototype Toolkit Modules and Components. Components of the framework’s prototype toolkit are selected from a variety of retailers. These components consist of off-the-shelf components that are easily obtained and do not require further assembly. These components also represent a range of functionalities useful in smart garments. Table 3 below lists some components and the vendor each is obtained from. These components are then attached to substrates according to the method outlined in the securely attaching components section prior. Two of these components are digital while two are analog. This variation in digital and analog components ensures that both digital and analog components can be incorporated as part of the framework, and are evaluated in the rapid prototyping trials.
Table 3

List of Components for the Prototype Toolkit

<table>
<thead>
<tr>
<th>Name</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSM6DS3TR-C 6-DoF Accel + Gyro IMU</td>
<td>Adafruit Industries, New York, USA</td>
</tr>
<tr>
<td>Conductive Rubber Cord Stretch Sensor</td>
<td>Adafruit Industries, New York, USA</td>
</tr>
<tr>
<td>HTU31 Temperature &amp; Humidity Sensor Breakout Board</td>
<td>Adafruit Industries, New York, USA</td>
</tr>
<tr>
<td>10K Precision Epoxy Thermistor</td>
<td>Adafruit Industries, New York, USA</td>
</tr>
</tbody>
</table>

Prototype Toolkit Central Computation Module and Enclosure. The central computation module consists of a variety of electrical components encased in a 3D-printed enclosure. Table 4 below lists the electrical components in the central computation module. This includes an Arduino microcontroller, a rechargeable lithium-ion battery, a solderable breadboard, a Qi wireless charging pad, and magnetic pogo pin connectors. The solderable breadboard allows for some custom circuitry required to support certain analog modules.

Table 4

List of Components for the Central Computation Module

<table>
<thead>
<tr>
<th>Name</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arduino</td>
<td>Adafruit Industries, New York, USA</td>
</tr>
<tr>
<td>Battery</td>
<td>Adafruit Industries, New York, USA</td>
</tr>
<tr>
<td>Solderable Breadboard</td>
<td>ElectroCookie, USA</td>
</tr>
<tr>
<td>Wireless Charging Pad</td>
<td>Adafruit Industries, New York, USA</td>
</tr>
<tr>
<td>Magnetic Pogo Pins</td>
<td>Alibaba, Singapore, Singapore</td>
</tr>
</tbody>
</table>

3D-printed enclosures are constructed for the central module. Figure 19 illustrates a rough sketch of the 3D-printed enclosure for the central module. The cutouts, illustrated in Figure 18 indicate where the magnetic connections are placed, and are arranged in an orthogonal orientation where no misaligned or incorrect connections can occur.
Figure 18

Central Computation Module Cutouts

Figure 19

Central Computation Module Mockup
3.3.2 Holistic Rapid Prototype Trials

The evaluation of the modular framework toolkit consists of both quantitative and qualitative measurements. Here, rapid prototyping trials conduct a holistic assessment of all subcomponents in the framework. Specifically, these trials seek to identify the strengths and weaknesses of the framework in a real-world environment. The trials also recognize any potential usability oversights in the modular framework. The trials then discern the framework’s influence on the smart garment designers’ design process or approach and probe the framework’s balance between creativity and simplicity. Finally, the trials solicit feedback from smart garment designers.

Rapid Prototyping Trial Objectives. The rapid prototyping trials seek to identify the strengths and weaknesses of the modular framework in a limited real-world environment. The rapid prototyping trials would also recognize any potential usability oversights in the modular framework design. The rapid prototyping trials would then discern the framework’s influence on the smart garment designers’ teamwork dynamics and probe the framework’s balancing of creativity. Finally, the rapid prototyping trials would solicit feedback through exit interviews. The following list specifies detailed objectives for evaluation:

1. **Overall Framework Issues**: The primary objective of the rapid prototyping trials is to evaluate the usefulness and mechanics of the framework as a whole. This includes any usability issues, any component issues, and any overlooked or missing modular components.

2. **Baseline Comparison**: Related to the primary objective, the rapid prototyping trials rate the additional value the framework brings when
compared to basic or traditional smart garment design methods or components that do not involve the framework.

3. **Influence on Teamwork:** The next objective of the rapid prototyping trials is to observe the framework’s impact on teamwork dynamics. Specifically, this refers to whether the framework can equalize the technical abilities of apparel designers and engineers. Ideally, the framework would enable more input from apparel designers and allow engineers to tackle issues beyond technical challenges.

4. **Influence on Creativity:** Another objective of the rapid prototyping trials is to judge the tradeoff between creativity and simplicity. Due to the nature of the modular framework, some creativity is sacrificed for simplified technical content. The trial gauges, subjectively, whether users believe creativity sacrifices are worthy of the simplified technical content.

5. **Input from Participants:** The final objective of the rapid prototyping trials is to gather miscellaneous feedback from the participants. This feedback is gathered after the trial.

**Rapid Prototyping Trial Procedure.** Each rapid prototyping trial consists of a pre-trial warm-up, a trial prompt selection, the observed trial, and exit interviews. Participants are recruited from the student body population and put into teams of two. Each team then participates in one trial. The pre-trial warm-up introduces the participants to components in the modular framework and additional provided resources. The trial prompt selection assigns each team a specific smart garment functionality to implement. The observed trial consists of teams attempting to complete the assigned trial prompt. Finally, exits interviews gather feedback from participants. The estimated total time required for each trial is two hours, and each
team completes its trial separately. Figure 20 below illustrates the four sequential components of each trial. Prior to the trials, an IRB review is completed and approval is obtained. The IRB Approval Letter is available in Appendix 8.

**Figure 20**

*Rapid Prototyping Trial Procedure*

| Pre-trial Warm-up | Trial Prompt | Observed Trial | Exit Interviews |

**Trial Participant Recruitment and Exclusion Criteria.** Participants for the trials are recruited from the population of students who are interested in or experienced with smart garment design and development. Particularly, students who have completed a wearable technology course, FSAD 3990. Students from this class consist of both apparel designers and engineers, and thus make a good population to recruit participants from. Other students, such as graduate students from apparel design and engineering are also good fits for this study depending on their research interests. Following recruitment, participants are paired into teams of two with one designer and one engineer. A total of seven teams are recruited. Each team is given a different time slot for their trial to ensure independence. Note that participants are not asked to wear the garments they create.

**Pre-trial Warm-up (10 Minutes).** The pre-trial warm-up stage is the first segment in the rapid prototyping trial. In this stage, each team is introduced to the components of the modular framework. Then, each team is presented with additional apparel design supplies and additional electrical supplies that may be used during the
trial. Each team is given exactly the same physical resources to ensure material equality. This segment takes approximately 10 minutes.

The education segment introduces each team to the components and principles of the modular framework. First, components of the framework are outlined, including the core computing module, intra-garment connection methods, and peripheral devices. Then, teams are introduced to the framework's user interface guidelines. Finally, teams are shown sample swatches that demonstrate how some of the components work. Table 5 details the sample swatches and briefly describes each swatch.

Table 5

<table>
<thead>
<tr>
<th>Swatch</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Intra-garment Connection Wires and Enclosures</td>
<td>Four samples of different wire attachment methods.</td>
</tr>
<tr>
<td>2 Intra-garment Connection Endpoints</td>
<td>Three samples of different wire endpoint methods.</td>
</tr>
<tr>
<td>3 Intra-garment Connection Wire Midpoints</td>
<td>Two samples of different wire midpoint methods.</td>
</tr>
<tr>
<td>4 Module Attachments</td>
<td>Three samples of different module attachment samples.</td>
</tr>
</tbody>
</table>

Then, teams are introduced and familiarized with additional provided apparel design resources and supplies. As listed in Table 6, these resources and supplies reflect typically what is found in an apparel design studio. These supplies are given to ensure that design decisions do not depend on the lack of any specific apparel design resource and that teams are not constrained by factors outside of the modular framework. This segment is also an opportunity for any engineer on the team to form some
understanding of apparel design. For expediency, teams are provided with pre-cut fabric as well.

Table 6

Additional Provided Apparel Design Resources and Supplies

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Buttons</td>
<td>Plastic buttons.</td>
</tr>
<tr>
<td>2 Elastic</td>
<td>Various width elastic.</td>
</tr>
<tr>
<td>3 Fabric Shears</td>
<td>Fabric scissors.</td>
</tr>
<tr>
<td>4 Fusible Interfacing</td>
<td>Various weight fusible (iron-on) interfacing.</td>
</tr>
<tr>
<td>5 Iron</td>
<td>Iron with steam.</td>
</tr>
<tr>
<td>6 Knit Fabric</td>
<td>Various weight knit fabric.</td>
</tr>
<tr>
<td>7 Metal Snaps</td>
<td>Metal snap closures.</td>
</tr>
<tr>
<td>8 Needles</td>
<td>Various sized needles.</td>
</tr>
<tr>
<td>9 Overlocker/Serger</td>
<td>Industrial overlocker for knits.</td>
</tr>
<tr>
<td>10 Pattern Paper</td>
<td>Translucent dotted tracing paper.</td>
</tr>
<tr>
<td>11 Pre-cut Fabric</td>
<td>Pre-cut fabric for pants, shorts, and t-shirt.</td>
</tr>
<tr>
<td>12 Rib Knit</td>
<td>Various sized rib knit for hems and cuffs.</td>
</tr>
<tr>
<td>13 Rulers</td>
<td>Various rulers.</td>
</tr>
<tr>
<td>14 Sewing Machine</td>
<td>Industrial sewing machine with lockstitch and zig-zag stitch.</td>
</tr>
<tr>
<td>15 Slopers</td>
<td>Basic pattern blocks for tops and bottoms.</td>
</tr>
<tr>
<td>16 Thread</td>
<td>Black multipurpose thread.</td>
</tr>
<tr>
<td>17 Woven Fabric</td>
<td>Various weight woven fabric.</td>
</tr>
<tr>
<td>18 Zippers</td>
<td>Various centered, separating, and invisible zippers.</td>
</tr>
</tbody>
</table>

Finally, teams are introduced to additional provided electrical resources and supplies. As listed in Table 7, these supplies include typical electrical work necessities. Once again, these supplies are given to ensure that design decisions do not depend on the lack of any resources and that teams are not constrained by external factors. This segment is also an opportunity for any apparel designer to gain some familiarity with the electrical tools.
Table 7

Additional Provided Electrical Resources and Supplies

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Crimping Tool</td>
<td>Crimping tool with three built-in AWG’s.</td>
</tr>
<tr>
<td>2 Electrical Tape</td>
<td>Black insulating tape.</td>
</tr>
<tr>
<td>3 Glue</td>
<td>Superglue.</td>
</tr>
<tr>
<td>4 Heat Gun</td>
<td>Handheld heat gun.</td>
</tr>
<tr>
<td>5 Multimeter</td>
<td>Multimeter for resistance, voltage, and current measurement.</td>
</tr>
<tr>
<td>6 Soldering Iron</td>
<td>Soldering iron with solder.</td>
</tr>
<tr>
<td>7 Wire Stripper</td>
<td>Wire stripper with various built-in AWG’s.</td>
</tr>
</tbody>
</table>

**Trial Prompt (1 Minute).** Then, each team is given a specific functional prompt for implementation in their trials and some required implementation components. The functional prompt for the framework trial is randomly selected from a range of social, health, and comfort related smart garment functionalities. Unlike prior modular system evaluations, the function of the smart system is not open-ended. Eliminating the open-ended functionality gives each team a specific task to solve and removes any biases participants may have from their personal interests or abilities in smart garment design. Table 8 below lists the pool from which a function is randomly selected, a garment style, and its corresponding materials. Functionalities are non-replaceable to ensure that each team receives a different functionality to implement. Additionally, each trial prompt has a corresponding reference design. These reference designs are outlined in the Appendix. This segment takes approximately one minute.

Table 8

Rapid Prototyping Trial Prompts

<table>
<thead>
<tr>
<th>Trial</th>
<th>Function</th>
<th>Style</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motion Capture Through Gyroscope (Digital)</td>
<td>Top</td>
<td>2x 6-DoF Accel + Gyro IMU</td>
</tr>
<tr>
<td></td>
<td>Mobility Measurement Through Stretch Sensor (Analog)</td>
<td>Top</td>
<td>2x Conductive Rubber Cord Stretch Sensor</td>
</tr>
<tr>
<td>---</td>
<td>-----------------------------------------------------</td>
<td>-----</td>
<td>-----------------------------------------</td>
</tr>
<tr>
<td>3</td>
<td>Garment Microclimate Measurement (Digital)</td>
<td>Top</td>
<td>2x Temperature &amp; Humidity Sensor Breakout Board</td>
</tr>
<tr>
<td>4</td>
<td>Garment Temperature Measurement (Analog)</td>
<td>Top</td>
<td>2x Thermistor</td>
</tr>
<tr>
<td>5</td>
<td>Motion Capture Through Gyroscope (Digital)</td>
<td>Bottom</td>
<td>2x 6-DoF Accel + Gyro IMU</td>
</tr>
<tr>
<td>6</td>
<td>Mobility Measurement Through Stretch Sensor (Analog)</td>
<td>Bottom</td>
<td>2x Conductive Rubber Cord Stretch Sensor</td>
</tr>
<tr>
<td>7</td>
<td>Garment Microclimate Measurement (Digital)</td>
<td>Bottom</td>
<td>2x Temperature &amp; Humidity Sensor Breakout Board</td>
</tr>
<tr>
<td>8</td>
<td>Garment Temperature Measurement (Analog)</td>
<td>Bottom</td>
<td>2x Thermistor</td>
</tr>
</tbody>
</table>

**Observed Framework Trial (99 Minutes).** Following trial prompt selection, each team is given 99 minutes to implement the trial prompt functionality. Here, each team is allowed to utilize the framework and the provided additional resources to freely create a smart garment that fulfills the functionality specified in the trial prompt.

In terms of qualitative evaluation, this segment consists of non-participant observation. Non-participant observation is most appropriate in order to avoid any bias brought by the researcher, who has knowledge of how the framework operates. Specifically, this segment assesses whether Objectives 1 and 3, “Overall Framework Issues” and “Influence on Teamwork” are met. In particular, observation focuses on emotional responses, including facial expressions, body language, and other behaviors. The emotional responses are then linked to the task they are conducting to pinpoint potential usability issues in the framework. Furthermore, observation of teamwork dynamics, including the level of participation of each team member can provide insight into whether the framework appropriately enables both the apparel designer and the engineer to engage fully and equally. Moreover, observation of any
workarounds or flawed mechanisms the team is forced to utilize can illuminate fundamental shortcomings in the framework. Finally, observation of verbal comments, both positive and negative, can provide real-time insight into both the usability of the framework and how intuitive the framework is to the team. Notably, any differences in observed responses from the apparel designer and engineer can uncover the framework’s bias towards design or engineering.

In addition to fulfilling the trial prompt, some implementation components are required for quantitative comparison and analysis purposes. These requirements would allow for insight and differentiation on what value the framework brings beyond basic or traditional methods, as outlined in Objective 2, “Baseline Comparison.” Table 9 below lists the required implementation components. Furthermore, teams are asked to implement one side of the garment, such as the left side, with modular framework components, and the other side, such as the right side, with basic components. The left-right split would facilitate easier and more meaningful comparisons.

### Table 9

**Required Implementation Components**

<table>
<thead>
<tr>
<th>Implementation Component</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 electrical connection using basic components</td>
<td></td>
</tr>
<tr>
<td>2 electrical connection using framework components</td>
<td></td>
</tr>
<tr>
<td>3 sensor/actuator placement using basic components</td>
<td></td>
</tr>
<tr>
<td>4 sensor/actuator placement using framework components</td>
<td></td>
</tr>
<tr>
<td>5 connection midpoint using basic components</td>
<td></td>
</tr>
<tr>
<td>6 connection midpoint using framework components</td>
<td></td>
</tr>
</tbody>
</table>

This segment is timed to stop at exactly 99 minutes to ensure each team is given the same amount of time. Field notes from the observed framework trial are then analyzed for common themes, issues, and ideas. The analyzed notes should present
some conclusions on the framework’s performance in terms of usability and teamwork.

**Post-trial Exit Interview (20 Minutes).** Following the observed framework trial, each team is interviewed together to gather any user insights. The first portion of each exit interview consists of a rating and comparison activity. Here, each team member is asked to rate and compare their experience with basic and modular components when completing the required implementation components. Each team member is asked to mark, on a visual analog scale of 0 centimeters to 10 centimeters, the ease and functionality of electrical connections, component placements, and connection midpoints. Here, a zero would represent very poor performance, while a 10 would represent perfect performance. Ease is defined as “how easy or difficult component installation is” while functionality is defined as “how technically competent and aesthetically acceptable the component is”. Table 10 below outlines the three metrics in detail. The rating and comparison worksheet used is available in the Appendix.

**Table 10**

*Quantitative Metrics for Evaluation*

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantitative Evaluation Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Electrical connection using basic components</td>
<td>• For digital components, connecting wires to the component using soldering iron, solder without using the plug-and-play port, if that port exists.</td>
</tr>
<tr>
<td></td>
<td>• For analog components, connecting wires to the component by first creating a solder point and then solder using soldering iron.</td>
</tr>
<tr>
<td>2 Electrical connection using framework components</td>
<td>• For digital components, connecting wires to the component using the plug and play port.</td>
</tr>
<tr>
<td></td>
<td>• For analog components, connecting wire to the component using pre-made solder points using</td>
</tr>
</tbody>
</table>
3 Sensor/actuator placement using basic components

- Securing component to the garment using basic components such as glue, tape, thread, without usage of a substrate.
- Securing component to the garment using the substrate.

4 Sensor/actuator placement using framework components

- Connection of two wires using soldering iron, tape, and other basic components without heat shrink connector or crimp connector.
- Connection of two wires using heat shrink connector or crimp connector.

5 Connection midpoint using basic components

6 Connection midpoint using framework components

The second portion of each exit interview consists of an open-ended semi-structured interview. These semi-structured exit interviews consist of questions intended to gauge each participant’s overall impression of the framework. The exit interviews also aim to assess whether the framework satisfies Objectives 4 and 5, “Influence On Creativity” and “Input from Participants”. Questions, guided by the interview guide in the Appendix, consist of subjective questions on the framework’s added value, any perceived compromise between simplicity and creativity, and open-ended questions that elicit any miscellaneous opinions and ideas. Each exit interview is recorded, transcribed, then coded. This is then used to compile any recurring notions on value and creativity as well as thoughts on other aspects of the framework not captured in other segments. This should generate conclusions on the framework’s value and its effect on creativity and any other framework-related issues.
**Participants Recruited.** A total of fourteen students are recruited to participate in rapid prototyping workshops. To ensure that all participants have a basic and equivalent skillset, and that they could safely use tools involved in the workshop, all students are required to have taken a course on wearable technology. Table 11 below breaks down the fields and levels of the participants. Half of the participants self-report as being in a design-related program, such as apparel design. The other half self-report as being in an engineering-related program, such as computer science. From these fourteen participants, seven teams of one designer and one engineer are formed. The breakdown of team makeup is listed in Table 12 below. A total of seven workshops are conducted, with one for each team. As listed in Table 13 below, three workshops involve tops, four workshops involve bottoms. Of the seven workshops, four involve analog components, and three involve digital components.

**Table 11**

*Trial Participants’ Demographics*

<table>
<thead>
<tr>
<th>Field/Level</th>
<th>Undergraduate</th>
<th>Graduate</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>6</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Engineering</td>
<td>7</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>13</strong></td>
<td><strong>1</strong></td>
<td><strong>14</strong></td>
</tr>
</tbody>
</table>

**Table 12**

*Trial Team Makeup*

<table>
<thead>
<tr>
<th>Team Makeup</th>
<th>Number of Teams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teams with 1 Engineer</td>
<td>0</td>
</tr>
<tr>
<td>Teams with 1 Designer</td>
<td>0</td>
</tr>
<tr>
<td>Teams with 1 Engineer and 1 Designer</td>
<td>7</td>
</tr>
<tr>
<td>Teams with 2 Engineers</td>
<td>0</td>
</tr>
<tr>
<td>Teams with 2 Designers</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7</strong></td>
</tr>
</tbody>
</table>
Table 13

Summary of Trials

<table>
<thead>
<tr>
<th>Type/Style</th>
<th>Top</th>
<th>Bottom</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog Components</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Digital Components</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Totals</td>
<td>3</td>
<td>4</td>
<td>7</td>
</tr>
</tbody>
</table>
4.1 Burdens and Perceived Challenges among Designers and Developers

Focus group interviews are analyzed to identify perceived challenges in the smart garment design process and some popular smart garment functionalities among designers and developers. The challenges and functionalities identified informed the modular framework development and prototype toolkit.

4.1.1 Smart Garment Design

The primary concern among interviewed participants is the technical content and challenges involved with smart garments. Figure 21 below lists some smart garment design-related topics discussed by participants and the number of quotations about each topic. In terms of smart garment design, participants were most concerned about technical issues with designing smart garments, the teamwork necessary in the design process, and care issues associated with durability. Notably, important issues such as cost and sustainability were not top priorities to the participants.
Figure 21

Smart Garment Design Topics

<table>
<thead>
<tr>
<th>Smart Garment Design Concerns</th>
<th>Quotations</th>
</tr>
</thead>
<tbody>
<tr>
<td>technical issues with smart garments</td>
<td>40</td>
</tr>
<tr>
<td>teamwork</td>
<td>30</td>
</tr>
<tr>
<td>smart garment care issues</td>
<td>28</td>
</tr>
<tr>
<td>consumer perception of smart garments</td>
<td>25</td>
</tr>
<tr>
<td>difficulty combining hard and soft materials</td>
<td>23</td>
</tr>
<tr>
<td>using modules for smart garment design</td>
<td>21</td>
</tr>
<tr>
<td>privacy and trust issues</td>
<td>14</td>
</tr>
<tr>
<td>smart garment comfort issues</td>
<td>10</td>
</tr>
<tr>
<td>lack of skillset in creating smart garments</td>
<td>8</td>
</tr>
<tr>
<td>smart garment sustainability issues</td>
<td>5</td>
</tr>
<tr>
<td>potential simplification of design</td>
<td>4</td>
</tr>
<tr>
<td>smart garment as a complementary device</td>
<td>3</td>
</tr>
<tr>
<td>advantages of smart garments</td>
<td>2</td>
</tr>
<tr>
<td>cost implications of smart garments</td>
<td>2</td>
</tr>
<tr>
<td>smart garments as a means to facilitate...</td>
<td>2</td>
</tr>
</tbody>
</table>

**Technical Challenges in Smart Garment Design.** The primary concerns among interviewed participants are technical challenges involved with smart garments. Overall, technical issues accounted for 40 quotations, the highest amount among smart garment design topics. Among these technical issues, participants reported apprehension about combining electrical components and textile materials, selecting appropriate electrical components, creating electrical connections, and ensuring durability.

Participants expressed difficulty interfacing hard electrical components with soft textile materials. Difficulty combining hard and soft materials accounted for 23
quotes. One design student, Participant C, reflected that they found it difficult to
“[make] sure that the garment doesn't feel like you're wearing a piece of technology”
and “[minimize] the number of hard pieces”. Participant C’s anecdote highlights how
hard components, when not integrated properly, make smart garments feel less like
clothing. An engineering student, Participant J, also reflected on having to resort to
“non-traditional ways” of integrating hard components with the aid of an “adapter”
they developed. Participant J’s anecdote highlights the lack of a consistent method to
attach electrical components to clothing. This prevalent opinion suggests that the
modular framework should streamline the process of attaching hard electrical
components to soft textiles.

Participants also indicated that they had trouble identifying necessary and
usable electrical components. Participant D, an engineering student, experienced
difficulties just getting started with a smart garment project: “it's almost like you have
to find the proper tool[s] for your project, and then you start building from there.”
Participant D’s experience emphasizes the need for a framework that provides both the
necessary components and guidelines on their usage. Participant J also experienced
difficulties identifying suitable electrical components: “there is no such list of
components, we know for sure, can be used for wearable products.” Furthermore,
participants expressed interest in using electrical modules in smart garment design,
which accounted for 21 quotes. This reflects the need for a framework that provides
appropriate electrical components in an easy-to-use and modular system.

Participants also experienced difficulties with electrical connections in the
garment. Participant D expressed concerns with the viability of interfacing conductive
thread to a microcontroller: “how does conductive thread like, how can you make it
[better] connected to your microcontroller.” On the other hand, Participant T, a design
student, attempted to use electrical wires in a smart garment project: “those red,
yellow, or blue wires, when they were too thin or they bent in a weird way, it gave us some connectivity [issues].” Participant D and Participant T’s anecdotes warrant further investigation into best electrical connection practices, and the development of an easy and reliable electrical connection procedure.

Smart garment care issues are another technical area of concern for some participants. Care issues accounted for 28 quotations. Participant M, a design student, remarked that consumers may have “a fear of getting [smart garments] wet because of electricity”. This highlights the need for some degree of water resistance. Participant J also mentioned difficulty verifying whether a specific component would survive routine maintenance: “they won't say like oh it's washable so it's really up to us to decide whether to use that [component] for the project.” Participant J’s anecdote reflects the need for more consideration for durability in smart garments, especially for laundering. Participant T proposed a workaround involving the removal of certain components prior to laundering: “how can I remove the smart component to make sure that it is easy for the user to launder.” Participant T’s anecdote highlights how system design can mitigate certain durability shortcomings. Durability, therefore, should be tackled from both the individual component level to satisfy maintenance needs and the system level to minimize hazardous encounters.

**Teamwork in Smart Garment Design.** Participants with a background in design and participants with a background in engineering all recognize the importance of having a balanced design process informed by both areas of expertise. All participants, when asked about the ideal team, acknowledge that consistent and equitable input from designers and engineers is required for a successful smart garment. Participant V, a computer science student, states that “the dream would be like you have your designer [and] a CS [person]”. However, the level of understanding
of technical content in smart garment design is inconsistent among designers and engineers. Participant V also notes how the current market of smart garments and wearables largely comes from tech companies, and reasons that this is because tech companies are better positioned to solve the technical challenges at the cost of design. Participant V’s anecdote highlights how the difference in understanding shifts the technical burden to the engineer. Two other participants, Participant J (engineer) and Participant W (designer) previously collaborated on graduate-level research on smart garments. In separate interviews, Participant W remarked that “it's easy to figure out [the] hardware part always,” reflecting their belief that technical difficulties with smart garment hardware are easy to overcome. On the other hand, Participant J remarked that they encountered many difficulties with finding electrical components and integrating electrical components into the garment. This incongruent experience highlights the imbalance of the technical burden, which is disproportionately on the engineer. Solving this teamwork problem, then, requires equalizing the technical burden and enabling more input from the designer. The framework therefore must lower technical burdens to a point where both engineers and designers can effectively communicate and solve problems proportionally.

4.1.2 Smart Garment Functionality

Participants reported more interest in smart garments with a social function, health monitoring function, or aesthetic function. Other functionalities, including tactile functions, comfort functions, and safety functions received less interest. Social functions include functions related to social media and gaming, such as motion tracking, augmented reality, and Metaverse. Health monitoring functions relate to health data collection. Aesthetic functions relate to visual and artistic interest enhanced by technology. Tactile functions include tactile interactions facilitated by the
garment. Comfort functions involve garment microclimate augmentation. Finally, safety-related functions relate to wearer protection. These function-related inputs from interview participants inform the functionality required from the modular smart garment framework. Figure 22 below lists some smart garment functionality-related topics participants discussed and their corresponding number of quotations, which indicates participant interest.

**Figure 22**

*Smart Garment Functional Interest*

<table>
<thead>
<tr>
<th>Smart Garment Functional Interest</th>
<th>Quotations</th>
</tr>
</thead>
<tbody>
<tr>
<td>social function</td>
<td>27</td>
</tr>
<tr>
<td>health monitoring function</td>
<td>23</td>
</tr>
<tr>
<td>aesthetic and visual interest function</td>
<td>20</td>
</tr>
<tr>
<td>tactile function</td>
<td>12</td>
</tr>
<tr>
<td>comfort function</td>
<td>9</td>
</tr>
<tr>
<td>safety related function</td>
<td>4</td>
</tr>
</tbody>
</table>

Social functions represented most of the smart garment functions participants were interested in, with 27 quotations. In general, social functions facilitate some sort of social media interaction. Some social functions mentioned by participants include smart garments that facilitate more intimate ways of connecting people. Participant C envisions a smart garment where “you can tap and like communicate with your partner.” Social functions related to motion tracking were also popular among participants. Participant D notes that “[they] could definitely work for motion tracking and [something] like those Oculus [and] remotes that you hold on like the Xbox.” Related to motion tracking, virtual reality-related social functions also interested
participants. Participant K imagines smart garments in the metaverse: “if [a smart garment] had sensors and then you could like move your little character in the in virtual reality.” Some participants brought up augmented reality-related social functions. Participant W sees smart garments that connect people: “garments that [when] they're close in proximity to each other when [your] elbows to touch, you can like trade social media handles.” Smart garments can provide an intimate social media experience while still giving the wearer control: on the body, smart garments facilitate a sensing platform that the wearer can take off when desired.

Health monitoring functions for smart garments were also popular among interviewed participants, with 23 quotations. Participant V mentioned that a smart garment that “monitored elderly health” would be useful. Another participant, Participant C, suggested exercise-related health monitoring of “how much oxygen is pumping through your blood during a workout.” Here, Participant C notes how a smart garment, when compared to other wearables, would have an “intimate connection with the body” that allows for better data collection. Participant M also envisioned location-specific smart garments that “[collect] data on biometrics or working out or during say a geriatrics or the patients were in hospital”. Like with social functions, health monitoring functions on smart garments give access to on- or near-body sensing that can be easily removed when desired.

Finally, aesthetic and visual interest functions were popular among participants, with 20 quotations. Participant C, a design student, mentioned: “exciting garments that maybe don't necessarily have a function, like [for] music videos.” An engineering student, Participant A, imagines smart garments that can facilitate “sensory interactions” including “lighting and everything that's visible.” While aesthetic and visual interest functions add little functional value to a smart garment,
aesthetic and visual interest still represent the easiest entry into smart garments, with some added novelty factor.

4.2 Addressing Technical Burdens of Smart Garments

In terms of technical challenges, focus group interviews highlighted the need for easier attachment of hard components to soft textile materials, simpler electrical connection creation, and straightforward component selection. These key technical challenges must also be addressed with durability in mind. Two of these technical challenges, secure attachment, and electrical connections, are addressed in the following sections. The third key challenge, component selection, is addressed with the prototype toolkit creation later.

4.2.1 Securely Attaching Components and Component Substrates

Component substrates act as attachment interfaces between hard electrical components and soft fabrics. Varied sized substrates are cut out of 0.02-inch thick sheets of polystyrene plastic with a CNC machine. Both opaque and transparent polystyrene are used since some electrical components, such as photoresistors, require light transmission. Figure 23 below pictures some of these substrates against a backdrop with 0.5-inch boxes.
To illustrate the usage of these substrates, three sample swatches demonstrate how substrates are attached to fabric. In Figure 24 below, three samples show (a) a Streamlined Substrate with no components attached with a zig-zag stitch, (b) a basic substrate with a component on the visible side of the substrate attached with hand stitches, and (c) a basic substrate with a component on the invisible (sandwiched) side of the substrate attached with hand stitches. These samples also demonstrate how the side with the components can vary based on the needs of a garment. Note that these samples do not depict wires that would be extending out of electrical components. Table 14 below summarizes the various substrate recommendations.
### Figure 24

*Selection of Substrate Sample Swatches*

(a) Streamlined Substrate with No Component, Zig-zag Stitch  
(b) Basic Substrate with Attached Component (Visible), Hand Stitched  
(c) Basic Substrate with Attached Component (Invisible), Hand Stitched

### Table 14

*Summary of Component Substrates*

<table>
<thead>
<tr>
<th></th>
<th>Basic Substrate</th>
<th>Streamlined Substrate</th>
<th>Slitted Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td>Polystyrene</td>
<td>Polystyrene</td>
<td>Polystyrene</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>1” by 1”</td>
<td>1” by 1”</td>
<td>2” by 2”</td>
</tr>
<tr>
<td></td>
<td>1” by 2”</td>
<td>1” by 2”</td>
<td>2.5” by 2.5”</td>
</tr>
<tr>
<td></td>
<td>2” by 2”</td>
<td>2” by 2”</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.5” by 2.5”</td>
<td>2.5” by 2.5”</td>
<td></td>
</tr>
<tr>
<td><strong>Flexibility</strong></td>
<td>Least</td>
<td>Moderate</td>
<td>More</td>
</tr>
<tr>
<td><strong>Movement</strong></td>
<td>More</td>
<td>Less</td>
<td>Dependent on type</td>
</tr>
<tr>
<td><strong>Attachment</strong></td>
<td>Bar tack</td>
<td>Buttonhole or zig-zag</td>
<td>Dependent on type</td>
</tr>
</tbody>
</table>

### 4.2.2 Managing Intra-garment Connections

The creation and management of electrical connections in the smart garment is another key technical challenge. The following sections summarize and compare approaches to connecting and enclosing electrical wires in the smart garment. As described in Chapter 3, the intra-garment connection system is depicted in Figure 8.
**Figure 8**

*Intra-garment Connection System Overview*

**Connection Midpoints.** Midpoint selection depends on the intended usage of the midpoint in addition to the connection wires. Figure 25 displays three physical implementations of the midpoints with a half inch scale for reference. Table 15 summarizes the properties and selection recommendations of each midpoint.

**Figure 25**

*Examples of Midpoints*

<table>
<thead>
<tr>
<th>Wire-thread Midpoint</th>
<th>Heat-shrink Wire-wire Midpoint</th>
<th>Crimp Wire-wire Midpoint</th>
</tr>
</thead>
</table>

*(Scale: 0.5in)*
Table 15

Summary of Midpoint Selection

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire-thread</td>
<td>Wire-thread</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Midpoint</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat-shrink</td>
<td>Wire-wire</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Wire-wire</td>
<td>Wire-wire</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Midpoint</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crimp</td>
<td>Wire-wire</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Wire-wire</td>
<td>Wire-wire</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Midpoint</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Connection Endpoints.** Endpoint selection entirely depends on the type of connection. For practicality and economic reasons, only the wire-magnetic endpoint is physically produced. This example is illustrated in Figure 26 with a half-inch scale for reference. Here, a magnetic pogo-pin is soldered to a small solderable breadboard.

Table 16 summarizes the properties and selection recommendations of each endpoint.

**Figure 26**

Example of Wire-magnetic Endpoint, Front and Side Views
Table 16

Summary of Endpoint Selection

<table>
<thead>
<tr>
<th>Endpoint</th>
<th>Endpoint</th>
<th>Connect to…</th>
<th>Connect using…</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knotted-magnetic</td>
<td>Pad-hole</td>
<td>Conductive thread</td>
<td>Knot</td>
</tr>
<tr>
<td>Wire-magnetic</td>
<td>Wire</td>
<td>Electrical wire</td>
<td>Midpoint</td>
</tr>
</tbody>
</table>

The central module interface substrate can be used in conjunction with the endpoints. Figure 27 below depicts examples of the central module interface substrate with attached magnetic connectors.

Figure 27

Examples of Central Module Interface

Connection Exits. Exit selection depends on placement on the garment. Table 17 summarizes the properties and selection recommendations of each exit.

Table 17

Summary of Exit Selection

<table>
<thead>
<tr>
<th>Exit</th>
<th>Placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buttonhole</td>
<td>Anywhere (with consideration to stability)</td>
</tr>
<tr>
<td>In-seam</td>
<td>Through seams</td>
</tr>
</tbody>
</table>
**Connection Wires.** The electrical wire is recommended unless using the electrical wire is impractical due to the poor resistance and thermal characteristics of the conductive thread.

**Resistance Characteristics.** As observed in Table 18, every conductive thread tested presents substantial resistance values, especially at longer thread lengths. Every conductive thread tested also exhibits linear increases in resistance with thread length, as shown in Figure 28. At longer thread lengths such as sixty inches, the measured resistance of every conductive thread is substantial enough to significantly affect the electrical characteristics of any overall circuit. Thread C seems to have the best performance among the conductive threads tested, while the others performed roughly the same. On the other hand, the stranded electrical wire demonstrates much less resistance at every length. The measured resistance of the stranded wire also never exceeds negligible resistances at any length. Therefore, the resistance performance of the electrical wire is far superior.

**Table 18**

*Resistance vs. Wire Length*

<table>
<thead>
<tr>
<th>Length (in)</th>
<th>Example Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00 ± 0.05</td>
<td>Running Shorts Inseam</td>
</tr>
<tr>
<td>10.00 ± 0.05</td>
<td>Wrist (Around)</td>
</tr>
<tr>
<td>15.00 ± 0.05</td>
<td>Shorts Outseam</td>
</tr>
<tr>
<td>20.00 ± 0.05</td>
<td>Shirt Body Width</td>
</tr>
<tr>
<td>25.00 ± 0.05</td>
<td>Shirt Sleeve Length</td>
</tr>
<tr>
<td>30.00 ± 0.05</td>
<td>Waist (Around)</td>
</tr>
<tr>
<td>35.00 ± 0.05</td>
<td>Shirt Body Length</td>
</tr>
<tr>
<td>40.00 ± 0.05</td>
<td>Chest (Around)</td>
</tr>
<tr>
<td>45.00 ± 0.05</td>
<td>Pant Outseam</td>
</tr>
<tr>
<td>50.00 ± 0.05</td>
<td>Coat Length</td>
</tr>
<tr>
<td>55.00 ± 0.05</td>
<td>Long Coat Length</td>
</tr>
<tr>
<td>60.00 ± 0.05</td>
<td>Full Body Below Neck</td>
</tr>
<tr>
<td>Length (in)</td>
<td>Thread A (Ω)</td>
</tr>
<tr>
<td>------------</td>
<td>--------------</td>
</tr>
<tr>
<td>5.00 ± 0.05</td>
<td>4.1 ± 0.1</td>
</tr>
<tr>
<td>10.00 ± 0.05</td>
<td>7.9 ± 0.1</td>
</tr>
<tr>
<td>15.00 ± 0.05</td>
<td>12.7 ± 0.1</td>
</tr>
<tr>
<td>20.00 ± 0.05</td>
<td>16.6 ± 0.1</td>
</tr>
<tr>
<td>25.00 ± 0.05</td>
<td>21.9 ± 0.1</td>
</tr>
<tr>
<td>30.00 ± 0.05</td>
<td>25.7 ± 0.1</td>
</tr>
<tr>
<td>35.00 ± 0.05</td>
<td>30.4 ± 0.1</td>
</tr>
<tr>
<td>40.00 ± 0.05</td>
<td>35.9 ± 0.1</td>
</tr>
<tr>
<td>45.00 ± 0.05</td>
<td>40.3 ± 0.1</td>
</tr>
<tr>
<td>50.00 ± 0.05</td>
<td>44.1 ± 0.1</td>
</tr>
<tr>
<td>55.00 ± 0.05</td>
<td>49.4 ± 0.1</td>
</tr>
<tr>
<td>60.00 ± 0.05</td>
<td>53.4 ± 0.1</td>
</tr>
</tbody>
</table>

**Figure 28**

*Resistance vs. Wire Length*
Thermal Characteristics. As observed in Table 19, the conductive threads and the electrical wire display drastic differences in thermal behavior when supplied with a 0.5 Ampere current. Each conductive thread heats up from ambient temperature, around 24°C, to hot-to-the-touch, around 40°C within five seconds. Each conductive thread’s temperature then stabilizes until the end of the test. Figure 29 illustrates the logarithmic heat behavior of each conductive thread compared to each other and the electrical wire. On the other hand, the electrical wire does not heat up substantially, remaining at the ambient temperature for the entirety of the test. Each conductive thread’s heat emissions can affect the thermal comfort of a garment as the fabric will absorb some of the heat emitted by the conductive thread. This phenomenon is seen in Table 19 as the bright-colored conductive thread radiates heat onto the dark-colored environment.
<table>
<thead>
<tr>
<th>Thread</th>
<th>0s</th>
<th>5s</th>
<th>10s</th>
<th>15s</th>
<th>30s</th>
<th>45s</th>
<th>60s</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 19**

*Temperature vs. Time Recording*
**Figure 29**

*Thermal Characteristics Comparison*

![Thermal Characteristics Comparison graph](image-url)
The electrical wire is recommended unless using the electrical wire is impossible. Due to the poor resistance characteristics of the conductive thread, especially with longer threads, the conductive thread can only realistically be used in limited circumstances, such as when the fabric is much thinner than the electrical wire, or when used with very basic electronic components, or when the length of the conductive thread can be kept short. Conductive thread C, the 3-ply conductive thread with stainless steel fibers performs best among the conductive threads tested. Furthermore, the conductive thread is observed to radiate heat and sometimes emit smoke and fumes. Table 20 below summarizes connection type recommendations.

**Table 20**

*Summary of Connection Type Recommendations*

<table>
<thead>
<tr>
<th></th>
<th>Conductive Thread</th>
<th>Electrical Wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application Method</td>
<td>Sew-on.</td>
<td>Attached externally.</td>
</tr>
<tr>
<td>Resistance Characteristics</td>
<td>Linear, with high values at longer lengths.</td>
<td>Negligible.</td>
</tr>
<tr>
<td>Thermal Characteristics</td>
<td>Stable, little difference from ambient at 0.5A.</td>
<td>Substantial and rapid temperature increase from ambient followed by stabilization at 45°C.</td>
</tr>
<tr>
<td>Length</td>
<td>At least additional 0.5 inches, more for stretch fabrics.</td>
<td>At least additional 0.5 inches, more for stretch fabrics.</td>
</tr>
<tr>
<td>Recommended Use Cases</td>
<td>Limited: only with shorter lengths, basic components, or when electrical wire is impractical. Thread C, the 3-ply conductive thread performs best.</td>
<td>General purpose.</td>
</tr>
</tbody>
</table>

**Connection Enclosures.** The four connection enclosures present differing masses and flexural rigidities, which affects the enclosure choice for each garment.
type. Figure 30 below depicts samples of the four enclosures outlined in Chapter 3.

The selection of an enclosure type should follow the selection of a connection type.

**Figure 30**

*Samples of Intra-garment Connection Enclosures*

![Samples of Intra-garment Connection Enclosures](image)

Conductive Thread  Conductive Thread (Folded)  Electrical Wire (Zigzag)  Electrical Wire (Encased)

All connection enclosures affected fabric stiffness significantly. A test based on ASTM D 1388-18 is used to calculate the flexural rigidity of each connection enclosure and a control. Table 21 summarizes the results of this test. A detailed table with all calculations, including uncertainty, is provided in the Appendix. The data shows that all connection type-connection enclosure combinations significantly affected the stiffness of the fabrics. This is shown both in the decreases in overhang...
angle and the increases in flexural rigidity. Among the four enclosures, conductive thread alone affected bending the least, while encased electrical wire affected bending the most. This is largely due to the stiffness of the wire itself but is also affected by the increase in fabric required for the encasement. The data also shows how mass per unit area is affected by enclosures, which may implicate enclosure choice based on garment type.

Table 21

Flexural Rigidity of Each Connection with Enclosure

<table>
<thead>
<tr>
<th>Connection and Enclosure</th>
<th>Relative Mass $w$</th>
<th>Overhang $l$</th>
<th>Overhang $\theta$</th>
<th>Rigidity $G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>135 ± 2</td>
<td>60 ± 1</td>
<td>61° ± 1°</td>
<td>76 ± 2</td>
</tr>
<tr>
<td>Conductive Thread</td>
<td>140 ± 2</td>
<td>60 ± 1</td>
<td>47° ± 1°</td>
<td>113 ± 4</td>
</tr>
<tr>
<td>Conductive Thread (Folded)</td>
<td>143 ± 2</td>
<td>60 ± 1</td>
<td>25° ± 1°</td>
<td>241 ± 9</td>
</tr>
<tr>
<td>Electrical Wire (Zigzag)</td>
<td>361 ± 4</td>
<td>60 ± 1</td>
<td>18° ± 1°</td>
<td>860 ± 30</td>
</tr>
<tr>
<td>Electrical Wire (Encased)</td>
<td>500 ± 5</td>
<td>60 ± 1</td>
<td>20° ± 1°</td>
<td>1070 ± 40</td>
</tr>
</tbody>
</table>

Where $G$ is flexural rigidity in units of $\frac{\mu J}{m}$, $w$ is fabric mass per unit area in $\frac{g}{m^2}$, $l$ is overhang length in $mm$, and $\theta$ is overhang angle in degrees.

Practically speaking, the rigidity impacts of enclosures affect comfort and fabric choice. An obvious effect of rigidity is its effect on comfort. With encased wires, for example, the manifold increase in rigidity results from a combination of doubling up of fabric and the electrical wire itself. Here, the wearer would feel the presence of electrical wires in areas of the garment where there is an increased rigidity. In other words, the rigidity is concentrated near wires and is not uniform across the garment. Furthermore, the rigidity impacts necessitate careful fabric choice.
considerations. The increased rigidity would be felt by a wearer when compared to a garment without a wire enclosure, especially with lighter-weight fabrics. Although the tests here utilize a medium-weight muslin, it would be logical to extrapolate larger rigidity increases for lightweight fabrics, such as activewear fabrics.

Table 22 below summarizes each enclosure type, their properties, and recommendations. Note that connection type recommendations should take precedent over enclosure recommendations. In other words, the decision between conductive thread and electrical wire should be made prior to selecting an enclosure type.

### Table 22

**Summary of Connection Enclosure Recommendations**

<table>
<thead>
<tr>
<th></th>
<th>Conductive Thread</th>
<th>Conductive Thread (Folded)</th>
<th>Electrical Wire (Zigzag)</th>
<th>Electrical Wire (Encased)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural Rigidity ( \frac{\mu J}{m} )</td>
<td>113</td>
<td>241</td>
<td>860</td>
<td>1070</td>
</tr>
<tr>
<td>Relative Mass ( \frac{m}{m^2} )</td>
<td>140</td>
<td>143</td>
<td>361</td>
<td>500</td>
</tr>
<tr>
<td>Application Method</td>
<td>Sew-on</td>
<td>Sew-on</td>
<td>Sew-on</td>
<td>Slotted</td>
</tr>
<tr>
<td>Application Notes</td>
<td>Added seam allowance.</td>
<td>Additional added seam allowance.</td>
<td>Added seam allowance, wire attached during sewing.</td>
<td>French seam, wire attached after sewing.</td>
</tr>
</tbody>
</table>

#### 4.3 Evaluating the Framework

To evaluate the modular framework, a prototype toolkit is developed, and seven workshops are conducted.
4.3.1 Prototype Modular Toolkit

A prototype toolkit that implements the modular design framework is constructed for use in rapid prototyping trials. This toolkit consists of various modular components and a central computation module.

Prototype Toolkit Modular Components. Four modular components are constructed for the prototype toolkit. These components cover a range of smart garment functionalities, including mobility measurement and environmental sensing. Two modules, the corded stretch sensor module, and the gyroscope module, represent analog and digital modules that have a mobility measurement functionality. The other two modules, the thermistor module, and the temperature and humidity module, represent analog and digital modules that have an environmental sensing functionality. These four sample modules are then used in rapid prototyping trials. Figure 31 depicts the sample modules.

Figure 31

Prototype Modules

Corded Stretch Sensor  Gyroscope  Temp and Humidity  Thermistor
Prototype Toolkit Central Computation Module and Enclosure. The internals of the central computation module, including all electrical components and their placement, is illustrated in Figure 32. The closed enclosure is illustrated in Figure 33. Note that the lid forms a seal to the base and can be waterproofed with a sealant.

Figure 32

Prototype Central Computation Module Internals
4.3.2 Rapid Prototyping Trials

**Workshop Observation and Outcomes.** Through seven workshops, teams accomplished their smart garment trial prompts to varying degrees of completion. Figure 34 below pictures teams during the workshop, a selection of work-in-progress smart garments, and a selection of smart garments at the completion of the workshop.
During the workshop process, the most common process-related issues teams encountered included order of operation challenges, preparation of action challenges, and communication challenges. Figure 35 below summarizes common issues and their number of occurrences. Order of operation challenges occurred 13 times across the seven workshops. These challenges involve the team sewing on a component too early or too late. For example, Team 2 attached the central module interface after the access pouch was sewn on. This led to an awkward maneuver to attach the interface inside the pouch. Other teams, such as Team 5, tried to complete electrical portions first, and then complete sewing operations. This approach led to some difficulty in stringing wires through parts of the garment that were already sewn together.
Long planning and preparation times were also common, with all seven teams displaying long planning and preparation times. The fact that all teams experienced long planning times suggests that students are not properly prepared to tackle smart garment creation. This also exposes their lack of specific smart garment design education.

Finally, communication challenges occurred five times across the seven workshops. Communication challenges manifested in long periods of silence during a workshop with one teammate idling or waiting for the other teammate to complete a task. Teammates in Team 3, for example, seldom communicated. Other communication challenges, such as distraction, also occurred because of idling. For example, a member of Team 6 was observed to be using their mobile phone while their other teammate was working.

Other common issues included difficulty transporting wires across the inside and outside layers of a garment (5), tool usage challenges (4), and mistakes due to a lack of familiarity or skillset (3). Note that time-related issues, especially regarding completion, were excluded from common issues due to the short duration of the workshop. A longer workshop duration would simply be too impractical from a participant scheduling and commitment perspective.
Prototype Toolkit Evaluation. To assess the performance of the prototype modular toolkit’s technical performance, participants were asked to rate various metrics related to their experience with the toolkit and smart garment creation. Table 23 below summarizes participants’ ratings of electrical connections, secure component placement, and cable midpoint creation. Participants provided ratings in terms of both perceived ease of creation and function. Exact Wilcoxon signed rank tests were performed on these ratings to determine whether the prototype modular toolkit provided statistically significant differences.

Analysis of participants’ ratings shows statistically significant improvements in function across all rated criteria, including electrical connections ($\Delta = 4.78, p = 0.0001221$), secure component placement ($\Delta = 3.75, p = 0.0006104$), and cable midpoints ($\Delta = 3.59, p = 0.0008545$). Analysis also shows statistically significant difference in ease of cable midpoint creation ($\Delta = 2.62, p = 0.0006104$).
Two criteria, ease of creating electrical connections, and ease of secure component placement, show higher mean ratings with the prototype modular toolkit but without a statistically significant difference. When breaking down the ease of creating electrical connections rating, there is a statistically significant difference when isolating digital components ($\Delta = 4.07, p = 0.03125$), but not analog components. For ease of secure component placement rating, there is no statistically significant difference for either digital or analog components.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Mean, Basic</th>
<th>Mean, Modular</th>
<th>Mean, Difference</th>
<th>P-value</th>
<th>Significant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Connections (Ease)</td>
<td>6.28</td>
<td>7.59</td>
<td>1.31</td>
<td>0.1937</td>
<td>No</td>
</tr>
<tr>
<td>(Digital Only)</td>
<td>3.97</td>
<td>8.05</td>
<td>4.07</td>
<td>0.03125</td>
<td>Yes</td>
</tr>
<tr>
<td>(Analog Only)</td>
<td>8.01</td>
<td>7.25</td>
<td>-0.76</td>
<td>0.3828</td>
<td>No</td>
</tr>
<tr>
<td>Electrical Connections (Function)</td>
<td>2.41</td>
<td>7.20</td>
<td>4.78</td>
<td>0.0001221</td>
<td>Yes</td>
</tr>
<tr>
<td>Secure Placement (Ease)</td>
<td>6.97</td>
<td>6.83</td>
<td>-0.14</td>
<td>0.9863</td>
<td>No</td>
</tr>
<tr>
<td>(Digital Only)</td>
<td>7.87</td>
<td>6.72</td>
<td>-1.15</td>
<td>0.6875</td>
<td>No</td>
</tr>
<tr>
<td>(Analog Only)</td>
<td>6.29</td>
<td>6.90</td>
<td>0.61</td>
<td>0.5469</td>
<td>No</td>
</tr>
<tr>
<td>Secure Placement (Function)</td>
<td>2.54</td>
<td>6.28</td>
<td>3.75</td>
<td>0.0006104</td>
<td>Yes</td>
</tr>
<tr>
<td>Cable Midpoint (Ease)</td>
<td>5.92</td>
<td>8.55</td>
<td>2.62</td>
<td>0.0006104</td>
<td>Yes</td>
</tr>
<tr>
<td>Cable Midpoint (Function)</td>
<td>3.85</td>
<td>7.44</td>
<td>3.59</td>
<td>0.0008545</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Prototype Toolkit Benefits.** Through the workshop process, teams identified benefits from the toolkit when compared to basic components. Overall, all seven teams preferred the prototype modular toolkit. Figure 36 below summarizes some key benefits teams reported. In exit interviews, six teams indicated that the modular
toolkit’s substrates on electrical components simplified the sewing process. Six teams also indicated that the modular toolkit’s plug-in components and wire midpoints dramatically simplified the electrical connection process. Three teams indicated that the modular toolkit’s substrates improved the flexibility of the hard materials in electrical components. One team indicated improvement in durability, specifically with analog electrical components, with the modular toolkit. Finally, one team reported that the modular toolkit made managing components and planning the making process easier.

**Figure 36**

*Identified Benefits*

![Prototype Toolkit Benefits](image)

**Prototype Toolkit Areas of Improvement.** Through the workshop process, teams identified some improvements necessary for the prototype toolkit. Figure 37 below summarizes common toolkit issues teams identified in exit interviews. Top issues include central module interface issues (7), wire size issues (3), and component size issues (3).
All seven teams reported improvements necessary to the central module interface. Issues with the central module interface primarily deal with the magnetic pogo pins. Five teams reported difficulty soldering to the pogo pins due to the magnetic attraction between the pins themselves and the soldering iron. Unfortunately, this issue is unavoidable. Two teams also expressed concerns about the soldering durability on the pins, since the pogo pins are the only area where soldering is necessary with the modular toolkit. To mitigate this issue, epoxy should be applied to seal the solder and back side of the pogo pins to the substrate. However, using epoxy during a relatively short workshop would not be practical due to curing times.

Three teams reported wire and connector size issues. Out of the three, one team reported the wires too small, and two teams reported the wires too large. Similarly, three teams reported component size issues. Here, all three teams reported that the components were too large. The size issues reflect a desire for more options in terms of both wire size and modular component size.
The interdisciplinary challenges associated with designing and developing smart garments can result in a burden that discourages creation and making. Interviewing nine participants interested in making smart garments led to the identification of key technical challenges surrounding electrical hardware integration, electrical connection creation, and component selection. This research proposed a modular framework for smart garment design that addressed these technical difficulties and allowed designers to prioritize the aesthetic and functional elements of smart garments.

The modular framework proposed addressed technical challenges by outlining a central module-peripheral module structure, establishing a substrate-based hardware attachment system, and organizing an adaptable wire connection protocol. Here, the central module consolidated major electrical components in a removable magnetic enclosure, minimizing the need to place major components elsewhere in the smart garment. The substrate-based component attachment system enabled simplified and sewable hardware interfacing to soft fabrics. Finally, the intra-garment connection protocol provided an adaptable wiring procedure with reduced tool usage through midpoints, endpoints, and exits. All aspects of the framework integrated accessibility with a focus on off-the-shelf component selection and usage of widely available creation tools.

The characterization of components and their electrical, thermal, and rigidity properties highlighted the restrictions in currently commercially available resources. Thermal and resistance testing of various conductive threads and electrical wires demonstrated the comparatively poor performance of conductive threads. On the other
hand, while both conductive threads and electrical wires affected the rigidity of fabrics, electrical wires showed much higher rigidity impacts. Consequently, for most applications, electrical wires would be the default due to conductive threads’ unreliable performance, even considering the wires’ rigidity impacts. A sewable electrical wire would be ideal but with current market offerings, compromise is necessary.

A prototype toolkit implementing the framework was created and evaluated by teams of designers and engineers. Assembled with additional components selected to reflect the prior interviewees’ desired smart garment functions, the prototype toolkit, and various samples were constructed and given to seven teams of design and engineering students. In terms of key evaluation metrics such as electrical connections and secure placement, the modular toolkit showed statistically significant improvements when compared to basic components. Key positive feedback also included improvements to sew-ability and added flexibility. Areas of improvement proposed by participants focused on better module interfacing and more component and wire size options in the toolkit.

Garment-level effects on mobility and perceived comfort were not studied as part of this research. Since this research focused on components in a modular framework, no specific, standardized, or fully constructed smart garment was formally assessed. As a result, the effects of the modular components on range of motion and comfort were not characterized. Since range of motion and comfort would be influenced by both the components in the prototype toolkit and conscious design decisions by a maker, it would only be possible to study these effects at the garment-level.

Further study could explore more customization and component size reduction. A limitation of this proposed framework is its reliance on off-the-shelf components.
With more resources, the development of custom components and modules would create a toolkit more tailored to clothing. A ramification of this reliance is the size of some prototyped modules. A customized module, then, may be able to integrate a substrate with its component payload using a silicone case. Integrating substrates with components may also reduce component size and result in a more aesthetically seamless feel.

Additional mechanical testing, akin to quality control tests with electronics, such as drop tests and liquid tests, would further inform design improvements, and alleviate durability concerns. Since washability is a top concern among smart garment designers, this proposed framework considered water resistance at the element level. For example, the central module is completely wireless and can be sealed for water resistance. Electrical connection methods recommended, such as the heat shrink connector, also have some degree of water resistance. The components and their substrates can also be sealed using epoxy for water resistance. However, design process considerations such as sew-ability and manufacturing potential took precedence over stringent water resistance efforts. Therefore, additional testing could lead to improvements in water resistance and ease other durability concerns.

The modular framework proposed would also benefit from studies involving application in longer-term academic settings since this study relied on short-term participant interactions. Logistical needs meant longer-term participant interactions, such as multi-session collaborations, were unrealistic. With longer-term and multi-round participant-led prototyping, it would be possible to evaluate the modular toolkit in an academic setting, such as in a class on smart garments. Assessment here could provide insight into learning outcomes affected by toolkit usage and reveal reluctances held by both students and instructors.
With the increasing prevalence of smart garments, it is more important than ever to empower designers with the tools necessary to create their own smart garments. This modular smart garment framework represents a novel and meaningful first step that alleviates the technical challenges that many designers and developers face.
REFERENCES


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https://www.usb.org/usb-type-cr-cable-and-connector-specification
APPENDIX 1: Focus Group Interview Guide


*Opening Discussion*

1. What do you think are potential applications or functions of smart garments?
2. As a designer, what functions or technologies would you put in smart garments?
3. What technologies do you think are not suitable for smart garments?

*Specific functionalities*

4. How should smart garments be applied in health-related areas, such as health monitoring and fitness?
5. What kinds of currently available smart garments, that you can think of, address health and maybe talk about some of their strengths and weaknesses?
6. How should smart garments improve the comfort of clothing, including temperature, humidity, etc?
7. What do you think of winter jackets that have some sort of heating component?
   - Is it considered smart just because of its heating or is it smart when there is a temperature control/feedback?
8. How should or can smart garments enhance social interaction among people, such as with social media?

What do you think is the value of a general purpose smart garment, i.e. they should serve multiple functionalities?

Part 2: Technical- Relating to the electronics and programming of smart garments, as well as garment construction.

*Opening Discussions*
9. What are some technical challenges to designing and developing smart garments that you are concerned about?

10. Do you feel confident in your skillset in designing and developing smart garments?

11. What is your perspective on teamwork as it relates to designing and developing smart garments?

12. What kind of formal or informal experience do you have with smart garments? For example, any coursework or DIY projects? If not, is there anything that prevented you from getting into smart garments?

**Specific Difficulties**

13. What are some challenges you have when you are trying to find electrical components?

14. What are some challenges you have when putting the electrical components together in a circuit?

15. Is programming/coding a challenge and how can programming be made easier?
   - For example, those who have used the Circuit Playground Express (Adafruit Industries, New York, USA), is it helpful to have access to many libraries?

16. How would you approach integrating hard and soft components and what are some issues there?
   - What would you think of non-traditional means of securing stuff to garments, such as glue?

17. How confident are you in connecting electrical components through a garment?

18. What is your opinion on the washability and maintenance of smart garments?
• For example, how do you see the consumer wearing multiples of the same garment across different days?

Part 3: Aesthetic- Relating to the visual and sensory aesthetic of the smart garment.

*Opening Discussions*

19. In your opinion, should smart garments explicitly exhibit smart components and functionality or should smart features be seamless and unnoticeable?

20. How should smart garments avoid looking gimmicky?

*Page 2- Aesthetic*

21. Should smart garments should look and feel like ordinary garments?

22. Do you expect smart garments to be treated and used in a manner consistent with ordinary garments?

23. How should smart garments promote their smart features?

24. How would you balance the aesthetics of smart garments with their utility?
APPENDIX 2: Rapid Prototyping Trials Exit Interview Guide

On Framework:
1. For each of the Required Implementation Components, which did you prefer, the basic one or the framework one?

What are some pro’s and con’s for each?

On creativity:
2. How did you explore the smart garment creation process?
3. What limitations did you face?
4. What were some actions you wanted to explore but could not?
5. Was any aspect of the smart garment trial overly difficult?
6. Was any aspect of the smart garment trial overly simple?

On ideas:
7. Was there any aspect of the smart garment framework that you would like to change?
   • What would you add to the framework?
   • What would you remove from the framework?
8. If you were to redo the trial, what would you differently?
9. Were there any points of conflict in the teamwork process?
10. How do you feel about smart garments after the trial?

How did your feelings on smart garments change?
**APPENDIX 3: Rapid Prototyping Trials Exit Interview Worksheet**

<table>
<thead>
<tr>
<th>Date</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial Number</td>
<td></td>
</tr>
<tr>
<td>Team Members</td>
<td></td>
</tr>
<tr>
<td>Prompt</td>
<td></td>
</tr>
</tbody>
</table>

**Pin Out**

![Pin Out Diagram](image)

1  16  
2  15  
3  14  
4  13  
5  6  7  8  
9  10  11  12  
00000  
00000  

---

89
## Intra-garment Connections: Wires

### 1 electrical connection using basic components

<table>
<thead>
<tr>
<th>Installation Time (Minutes)</th>
<th>Relative Ease (cm)</th>
<th>Relative Functionality (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 1 electrical connection using modular components

<table>
<thead>
<tr>
<th>Installation Time (Minutes)</th>
<th>Relative Ease (cm)</th>
<th>Relative Functionality (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Securely Attaching Components

1 sensor/actuator placement using basic components

<table>
<thead>
<tr>
<th>Installation Time (Minutes)</th>
<th>Relative Ease (cm)</th>
<th>Relative Functionality (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 sensor/actuator placement using modular components

<table>
<thead>
<tr>
<th>Installation Time (Minutes)</th>
<th>Relative Ease (cm)</th>
<th>Relative Functionality (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Intra-garment Connections: Cable Management

1 cable midpoint using basic components

<table>
<thead>
<tr>
<th>Installation Time (Minutes)</th>
<th>Relative Ease (cm)</th>
<th>Relative Functionality (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 cable midpoint using modular components

<table>
<thead>
<tr>
<th>Installation Time (Minutes)</th>
<th>Relative Ease (cm)</th>
<th>Relative Functionality (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Motion Capture through Gyroscope, Top

• Sensor placed in sleeve cuff, as illustrated in the figure above.

• Central module placed in front pouch.

• Note that wire must exit from inside to outside through the pouch.
Mobility Measurement through Stretch Sensor, Top

- Sensor placed through side and armhole into sleeve cuff and around back, as illustrated in the figure above.

- **Note that rubber cord should have occasional stabilization points to avoid contact/shorting.**

- Central module placed in front pouch.

- Note that wire must exit from inside to outside through the pouch.
Garment Microclimate Measurement, Top

- Sensor placed just under armhole, as illustrated in the figure above.
- Central module placed in front pouch.
- Note that wire must exit from inside to outside through the pouch.
Motion Capture through Gyroscope, Bottom

- Sensor placed in pant hem cuff, as illustrated in the figure above.
- Central module placed in patch pocket at back.
- Note that wire must exit from inside to outside through the pocket.
Mobility Measurement through Stretch Sensor, Bottom

- Sensor placed through inseam into hem cuff and around back, as illustrated in the figure above.

- **Note that rubber cord should have occasional stabilization points to avoid contact/shorting.**

- Central module placed in back pocket.

- Note that wire must exit from inside to outside through the pouch.
Garment Microclimate Measurement, Bottom

- Sensor placed in pant at knee level, as illustrated in the figure above.
- Central module placed in patch pocket at back.
- Note that wire must exit from inside to outside through the pocket.
Body Temperature Measurement, Top

- Sensor placed just under armhole, as illustrated in the figure above.
- Central module placed in front pouch.
- Note that wire must exit from inside to outside through the pouch.

Body Temperature Measurement, Bottom

- Sensor placed in pant at knee level, as illustrated in the figure above.
- Central module placed in patch pocket at back.
- Note that wire must exit from inside to outside through the pocket.
### APPENDIX 5: Calculations for Flexural Rigidity of Connections

<table>
<thead>
<tr>
<th>(t) (mm)</th>
<th>(d) (mm)</th>
<th>(b) (mm)</th>
<th>(h) (mm)</th>
<th>(G) (MPa)</th>
<th>(E) (GPa)</th>
<th>(I) (mm^4)</th>
<th>(R) (mm)</th>
<th>(N) (N/m)</th>
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## APPENDIX 6: Prototype Toolkit Evaluation Data

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<th>Notes</th>
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<td>Function 1</td>
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<tr>
<td>Function 2</td>
<td>85</td>
<td>Moderate performance</td>
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<td>Function 3</td>
<td>70</td>
<td>Low performance</td>
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<tr>
<td>Function 4</td>
<td>95</td>
<td>Exceptional performance</td>
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</table>

Note: Scores are on a scale of 0 to 100, with 100 being the highest possible score.
APPENDIX 7: IRB Exemption for Focus Group Interviews

Institutional Review Board for Human Participants
Cornell University
395 Pine Tree Road, Suite 320
Ithaca, NY 14850
https://researchservices.cornell.edu/offices/IRB

NOTICE OF EXEMPTION

To: Albert Earnest Lin (aell237)
Protocol Number: IRB0143933
Protocol Title: A Modular Framework for Smart Garment Design
Approval Date: 04/22/2022
Expiration Date: None

Your protocol has been granted exemption from IRB review according to Cornell IRB policy and under the Department of Health and Human Services Code of Federal Regulations 45CFR46.104(d).

Please note the following:

- Investigators are responsible for ensuring that the welfare of research subjects is protected and that methods used and information provided to gain participant consent are appropriate to the activity. Please familiarize yourself with and conduct the research in accordance with the ethical standards of the Belmont Report.
- Investigators are responsible for notifying the IRB office of change or amendments to the protocol and acquiring approval or concurrence BEFORE their implementation.
- Progress reports, requests for personnel or other administrative changes, or requests for continuation of approval are not required for the study. However, upon conclusion of the study, please submit a Project Closure request through RASS-IRB.

For questions related to this application or for IRB review procedures, please contact the IRB office at irbhp@cornell.edu or 607-255-6182. Visit the IRB website for policies, procedures, FAQs, forms, and other helpful information about Cornell's Human Participant Research Program.
APPENDIX 8: IRB Approval for Workshops

Institutional Review Board for Human Participants

NOTICE OF IRB APPROVAL

To: Albert Earnest Lin (ael237)
Protocol Number: IRB0145565
Protocol Title: Modular Smart Garment Toolkit Evaluation
Review Type: Expedited
Approval Date: 08/15/2022
Expiration Date: None

Cornell University's Institutional Review Board for Human Participants (IRB) has reviewed and approved the inclusion of human participants in the research activities described in the protocol referenced above. This approval shall remain in effect for the duration of the study.

The following personnel are approved to perform research activities on your protocol:

- Albert Earnest Lin (ael237)
- Heejo Park (hp347)

This approval by the IRB means that human participants can be included in this research. However, there may be additional university and local policies that apply before research activities can begin under this protocol. It is the investigator's responsibility to ensure these requirements are also met.

Please note the following important conditions of approval for this study:

1. All consent forms, records of study participation, and other consent materials must be held by the investigator for at least three years after the close of the study. See Cornell's Research Data Retention Policy for more details.
2. Investigators must submit to the IRB any proposed amendment to the study protocol, consent forms, data collection tools, recruiting strategies, and other participant-facing materials. Investigators may not implement these changes or use these materials with human participants until receipt of written IRB approval for the amendment. Amendments must be submitted through RASS-IRB.
3. Please find your approved consent forms under the informed consent section in your RASS-IRB protocol.
4. Investigators must promptly report to the IRB any protocol deviations or adverse events involving human participants. These reports can be submitted through RASS-IRB. The definition of prompt reporting depends upon the seriousness of the event. For guidance on recognizing, defining, and reporting protocol deviations and adverse events to the IRB, please refer to the IRB website.
5. Upon conclusion of the study, the investigator should submit a Project Closure request through RASS-IRB.

If the use of human participants is to continue beyond the assigned approval period, the protocol must be re-reviewed and receive continuing approval. As the Principal Investigator it is your responsibility to obtain review and continued approval before the expiration date. Applications for continuing review must be submitted in RASS-IRB sufficiently in advance of the expiration date to permit the IRB to conduct its review before the current approval expires. Please allow six weeks for the review.

Any research-related activities — including recruitment and/or consent of participants, research-related interventions, data collection, and analysis of identifiable data — conducted during a period of lapsed approval is unapproved research and can never be reported or published as research data. If research-related activities occur during a lapse in the protocol approval, the activities become a research compliance issue and must be reported to the IRB as a protocol deviation in RASS-IRB.

For questions related to this application or for IRB review procedures, please contact the IRB office at irbhp@cornell.edu or 607-255-6182. Visit the IRB website for policies, procedures, FAQs, forms, and other helpful information about Cornell's Human Participant Research Program.