MANUFACTURING CUT-AND-SEW GARMENT-INTEGRATED TECHNOLOGIES: AN INVESTIGATION OF SURFACE-MOUNT FABRICATION FOR ELECTRONIC TEXTILES

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Dedication

To my mom, Mamtaj Begum, my lovely wife, Sabirat Rubya, and my family members

……… thank you for your love and support

Abstract

The current wearable industry often uses custom made techniques (e.g., craft-based, hobbyists) that utilized proprietary equipment in a laboratory setting with specific applications in mind. While craft construction of textile-integrated electronics is common, these methods are typically not efficient enough for larger-scale production. For larger-scale production, the barriers to textile- and garment-integration have restricted the ability to spatially distribute technology over the body surface, particularly sensing and actuating components that may rely heavily on or be strongly affected by their specific location on the body. Industrial fabrication of e-textiles requires an efficient and scalable process that allows spatial distribution of components with a careful balance of automation and human labor. This research project aims to develop, characterize, and assess a scalable manufacturing method for garment-integrated technologies that preserve user comfort and work within the constraints of typical apparel manufacturing processes while providing required electrical performance and durability needed by the system. We have developed a method for attaching discrete surface-mount components and characterized the method. The method uses an industrial pattern stitching machine to stitch conductive traces onto a fabric surface in a 2D pattern and a reflow technique to integrate electronic components. Several prototypes from small fabric swatches to completed e-textile garments were made and tested to evaluate the durability, efficiency, and effectiveness of the method. We show a durability of 3% joint failure after a 14-hour wear test with no insulation and 0% failure rate after a washability test with insulation for the best manufacturing conditions. To investigate the scalability of the method at a garment scale as compared to manufacture of non-electronic garments, forty pieces each of regular and temperature sensing fire-fighter turnout gear coat liner garments have been produced. This manufacturing case study was used to evaluate the successful functionality of the manufactured garments as well as the impact of integrating electronic technology on labor, equipment, and cost. The study results show that the average manufacturing time to produce a sensor-integrated thermal liner was 3.27 times higher than producing a regular thermal liner garment, given that all the materials, labor, and machines remain constant. The sensor-integrated thermal liner garment cost around 3.44 times more to produce compared to the regular thermal liner garment. However, further analysis showed that by optimizing some of the processes, and using fully functional machines and skilled laborers, the production cost of the same sensor-integrated garment could be cut down by almost 51% and if the production takes place in a developing country where labor cost is much lower than in developed countries, the cost of production could be cut down to as much as 72%. Moreover, it would require more skilled laborers and better training of the laborers to produce e-textile garments compared to regular garments. We show that with strategic design and using existing machines and tools, technologies could be integrated into clothing during the assembly process using existing apparel manufacturing technology without a significant impact on labor, equipment, and cost. Furthermore, results of this case study were used to identify the more abstract challenges including machine optimization, human errors, and process variables involved in transitioning from one-off production to a larger-scale context in a Cut-Make-Trim (CMT) factory setting. The manufacturing method could be potentially used as an alternative for manufacturing e-textiles in mass.

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THESIS OVERVIEW

Wearable technology has the ability to improve people lives by allowing personal devices to become context-ware, providing continuous and imperceptible monitoring of the body, enhancing human-clothing and human-device interaction in social contexts, and allowing seamless integration of technology into daily activities through facilitating widespread development of textile-integrated soft, intimate, and unobtrusive sensors, actuators, and interface technology. However, durable, reliable, and scalable manufacturing of electronic-textile circuits and textile-integrated electronics remains one of the major obstacles to large-scale development of garment-integrated applications of wearable technology. Though there have been significant improvements in the electronics industry, it remains a major challenge to fabricate electronic circuits as flexible and complex as textiles to date. The disparity between typical electronics or hard goods manufacturing practices and typical apparel manufacturing practices presents unique challenges for design and manufacture of electronic-embedded textiles. The start-up costs of garment-integrated technologies are very high.

The primary objective of this dissertation is to develop flexible and adaptable garment-integrated technologies that can be used for wide variety of applications without the need for new hardware development. Using methods, tools, and machines that already exist in the industry, it aims to lower the barrier-to-entry to garment-integrated technologies while simultaneously preserving aesthetics, comfort of the apparel, and desired functionality of the embedded technologies. It also attempts to fill the gap in the literature by addressing both common and subtle manufacturing challenges in merging two very unique and different manufacturing practices (electronics manufacturing and apparel manufacturing) and to extend our existing knowledge about mass-manufacturing garment-integrated technologies. More specifically, this dissertation aims to develop, characterize, and assess a novel scalable manufacturing method for manufacturing of garment-integrated technologies. Furthermore, it aims to identify the major abstract challenges involved in transitioning from one-off production to a larger-scale context in a Cut-Make-Trim (CMT) factory setting. It is organized into six chapters. The first two chapters discuss the background and objectives of the study. Chapter 3, 4, and 5 describe the development and deployment of the manufacturing method. Finally, Chapter 6 discusses the conclusions of the research.

"Chapter 1: Introduction" introduces the motivation behind developing a scalable manufacturing method, the research topic, and the primary objectives of this research. "Chapter 2: Background of the study" reviews the relevant literature on e-textiles development, discusses e-textiles manufacturing strategies, identifies the challenges of e-textiles manufacturing, and introduces industrial approaches of designing manufacturing system for textile-integrated textiles. "Chapter 3: Development of a fabrication method for e-textiles" introduces the fabrication method and describes the method in detail. Later, chapter 3 talks about several tests that were performed to assess the durability and washability of the developed e-textiles samples. The last part of Chapter 3 introduces several e-textile examples from fabric swatch to complete garments that were developed using the fabrication method, from which a guideline is developed for designing manufacturable e-textiles garments. "Chapter 4: Development of a case study manufacturing process" describes the development of an example e-textile prototype garment which is later produced in higher-volume production in a CMT factory case study scenario. Later, Chapter 4 describes the designing of a production system, identification of manufacturing variables, and reflection on abstract challenges involved in transitioning from one-off production to a large-scale context in a CMT factory setting. "Chapter 5: Deployment of the surface-mount fabrication method for e-textile garments" discusses the deployment of the manufacturing method. Chapter 5 starts with the introduction of a manufacturing case study followed by a method section, data analysis section, and results and discussion of the case study. Finally, Chapter 6: "Conclusion and future work" discuss the overall summary of the project followed by future recommendations. All these chapters have the same structure with initial abstract followed by contribution, and a final summary. More introductory details about each of the chapters are provided in the introduction sections specific to the chapter.

CHAPTER 1: INTRODUCTION

There have been significant advances in the development of body-worn technologies in recent years. With the increase in popularity of body-worn technologies, the mass manufacturing of these technologies is getting more and more attention from engineers, scientists, and researchers day by day. So far, the majority of these technologies are developed using techniques and machines prevalent in the electronics industry. There are several benefits of using a popular and convenient manufacturing method like those typically used in electronic manufacturing. Traditional electronic manufacturing techniques produce durable, predictable electronic circuits. However, these techniques are suitable mostly for stiff substrates, which may bring discomfort and inconvenience to users when worn close to the body. Furthermore, traditional manufacturing techniques promote localization of all system components in a single unit, which limits the availability of the body areas that can be used by a body-worn technology. Components like sensors and actuators which may benefit from specific on-body placement are constrained to fixed physical locations [13]. In contrast, textile-based methods are often not cost-efficient or scalable, and maybe foreign to companies immersed in product development based on hard goods. The development of wearable devices which provide required electrical performance and durability in a form factor more similar to typical apparel may offer expanded functionality and comfort. By integrating electronics into a garment form, we can make wearable devices that will have the physical shape and softness of the garment while still providing the necessary electrical performance and durability required by the system.

Even though integration of technologies into textiles and garments seems very promising for the future of the wearable industry, it has its limitations, too. The future of garment-integrated technologies largely depends on the development of scalable manufacturing methods for these technologies. Garments are commonly made from soft goods which require a very different set of resources (workers, machines, and materials) compared to hard goods such as electronics. The electronics industry is highly automated, and most of the assembly is done by machines. On the other hand, the apparel industry is very traditional, uses manual labor heavily, and has low manufacturing start-up costs. Therefore, the apparel industry is largely dependent on the skill sets of its laborers and the advancement of technology does not have a significant influence on the overall quality of the production.

However, the disparity between the apparel and electronics industries also opens a world of opportunity to explore the potential of merging these two domains. The recent developments in the field of electronics, material science, and textile engineering make us hopeful for the future of wearable technologies. Higher levels of integration are now possible by using electronics having more textile-compatible size and shape so that they could be processed on traditional machines using existing manufacturing technologies [30]. Therefore, with strategic design, these technologies could potentially be integrated into clothing during the assembly process using existing apparel manufacturing technology with minimum modifications. Therefore, the methods that are viable within the existing apparel production would lower the obstacles to large-scale manufacturing of garment-integrated technologies. However, such methods must also produce e-textiles that are durable enough to withstand the conditions of everyday wear.

While craft construction of textile-integrated electronics is common, these techniques are not sufficient for large-scale production. The durability, reliability, and efficiency of these techniques are not up to the mark to produce low-cost and reliable garment-integrated technologies in mass compared to traditional consumer electronic goods. Current mainstream wearable technology developers typically manufacture electronic packages and apparel as a separate process, and the systems are later combined at the end. However, for many applications the garment and electronic system must be more tightly intertwined than the simple attachment of two uniquely different materials and a more advanced level of integration is necessary for fully embedded e-textiles. The few e-textile developers that produce electronic-embedded garment technologies use proprietary equipment, which is a major obstacle to developing a universal manufacturing process for e-textile products. The use of proprietary equipment increases the overall cost of production and creates major barriers-to-entry to smart clothing and wearable technology for apparel manufacturers and technology developers. It is very clear that there is an urgent need for development of a durable, reliable, and scalable fabrication method for e-textile circuits and textile-integrated electronics, which remains one of the most persistent obstacles to large-scale development of garment-integrated applications of wearable technology.

The objective of the fabrication methods used in this dissertation is to make electronic circuitry minimally perceptible in clothing by replacing rigid circuit boards with textile-based flexible circuitry, but to retain the efficiency and scalability offered by traditional electronics by using typical component packages and soldering techniques. The ultimate goal of this research is to characterize the challenges and opportunities of scalable garment-integrated technologies following a hybrid manufacturing process while leveraging the benefits of both the traditional labor-intensive apparel industry and the automated electronics industry. I propose the following objectives:

- **To develop an effective and efficient manufacturing method for integrating electronics into a garment while minimizing the need for new equipment in a cut-and-sew environment,**
- **To implement this method in a test prototype manufacturable garment,**
- **To evaluate the impact of technology integration on the labor, equipment, and cost of manufacturing via a case-study manufacturing process.**

This research has the potential to facilitate the development of flexible, adaptable, and distributed garment-integrated technologies for sensing, interface, and displays that will promote the development of a wide variety of applications for consumer, medical, and military industries.

CHAPTER 2: BACKGROUND

A textile is formed using interlacing and modification of millions of separate fibers and has a complicated structure with rather unpredictable properties. However, those special properties of textiles make them unique from other materials. The level of drapability, porosity, and lightness combined with robustness and strength form a rare set of properties which is hardly seen in any other materials [30]. One method of achieving more high-tech functionality in textiles is by making them smart. The “smartness” of a material or structure is defined as the ability to sense something and respond appropriately without being controlled by a user. Smart textiles are therefore textiles that have the ability to respond to external stimuli. Different levels of “smartness” of textiles can be achieved by integrating different materials depending on the application. For instance, a textile made of shape-memory materials can change its shape in response to temperature stimuli, or a textile made of chromogenic materials can change color in response to optical, electrical, or thermal stimuli. However, the change of these materials is often simplistic, where only one external variable is taken into account as input and the reaction is always the same.

For textiles, a higher level of “smartness” can be achieved with electronic technology. In electronics, multiple active electronic components having non-linear behaviors can carry out logical applications and deliver an output by using data from multiple inputs [30]. In fact, electronics enable us to translate multiple input parameters into an user-controlled objective-oriented outcome [30]. Often an electrical stimulus is required to perform a smart function, which makes electronics a necessary component of a special kind of smart textiles: electronic textiles or e-textiles. E-textiles are materials with electronic properties integrated into fabric-based substrates. Through embedded conductors, processors, sensors, and actuators e-textiles are able to function as flexible electronics. Initially, the first textile-integrated technologies were heterogeneous where textile and electronic parts were attached rather than really integrated. Nowadays, higher levels of integration have been developed in parallel with the advancement of the electronics industry.

One of the major advantages of the integration of electronics into clothing is that it allows the user to continually access information and communicate with other people at a distance seamlessly [61]. Unlike other wearable devices, e-textiles can provide easy and non-intrusive access to information and react accordingly without creating any discomfort to the user. It is often vital to distribute sensors or actuators to different parts of the body to get the best output using integrated technology. Textiles provide a larger area for the integration of components such as sensors and actuators which might be impossible in traditional wearable devices such as wristwatches (where all the electronics are placed in a small area). Textiles bring softness and comfort to the human body which also makes them strong candidates for the future of wearable technology. Despite these indications that the future of e-textiles looks very promising, they have not yet become a substantial part of the mass market and instead are restricted to niche solutions and novelty items [14]. One of the major reasons behind that is the challenge of manufacturing. Electronics and textiles are both integral parts of e-textiles. Hard electronics and soft textiles differ from each other in terms of physical properties as well as manufacturing methods. Therefore, integration of these two diverse materials brings unique challenges for e-textiles. The manufacturing methods that are suitable for textiles might be unsuitable for electronics and vice versa. For instance, while it is common for textiles to be washed with water during the manufacturing process, water may diminish the performance of electronics or even permanently damage the electronic components. By nature electronics are water sensitive and they are not typically made to be washed. The mechanical stress and chemical reaction during washing may significantly impede the functionality of integrated electronics, hence may nullify the sole purpose of using a wearable technology. Similarly, the automatic nature of electronics manufacturing might create additional problems for integration with the predominantly manually controlled clothing manufacturing processes. The three-dimensional shape and soft structure of the garment is typically not suitable for automation and hence, often may not compatible with electronics manufacturing practices. Therefore, it is important to have a good understanding of both clothing and electronics manufacturing, as well as the functional requirements and development processes of each. The next section will briefly describe the basic principles, development, and production of electronic systems, and the following sections will describe the basic principles, development, and production of textile and garment systems.

2.1 ELECTRONIC CIRCUIT DEVELOPMENT

To understand how e-textiles work, it is important to have a basic understanding of the systems that are used in typical electronic devices. In an electronic system, electric current is the medium through which information flows from one component to another component. The unit of current is coulombs per second which also referred as ampere (A). Changes in the flow of electrical energy through sensors are used to deduce information about the environment. All electrical systems rely on a source of power to operate. Electrical power comes from many different sources and batteries are the most common source of power for portable electrical devices.

An electric system is composed of one or more circuits. An electrical circuit is a path that electricity follows. A circuit consists of a power source and a ground or sink and current generally flows from the source to the ground. Voltage is measured as the difference between two points in the circuit and generally decreases as it moves from a voltage source to a sink. Voltage is measured in volts where 1 volt equals 1 joule/coulomb. The ratio between how much current (in Amps) flows through a material when a given voltage is applied across it is measured as resistance in ohms, where 1 ohm= 1V/1 A. An electric circuit is composed of individual components, such as resistors, inductors, capacitors, transistors, and diodes, connected by conductive wires or traces through which electric current can flow [56]. The combination of components and traces allows various simple and complex operations to be executed so that computations can be performed, signals can be amplified, and data can be moved from one place to another. To have a better understanding of how a typical electrical circuit is made, here, I will briefly discuss the steps involved in building a working circuit: drawing a circuit schematic, building a prototype, making a permanent circuit, and applying a sequence of troubleshooting steps to fix improperly functioning circuits.

Step 1: Drawing a circuit schematic

The circuit schematic, or circuit diagram, is a blueprint of a circuit [56]. The schematic should include all the information necessary to build a circuit including details of the parts, a guideline on parts, and information on the possible output behavior to expect. The schematic design can be done using a pencil and paper or computer-aided design (CAD) tool. There are many CAD tools available online. For example, EAGLE CAD and

Altium are popular tools for developing circuit schematics [66,67]. An example of a circuit diagram is shown in Figure 1.

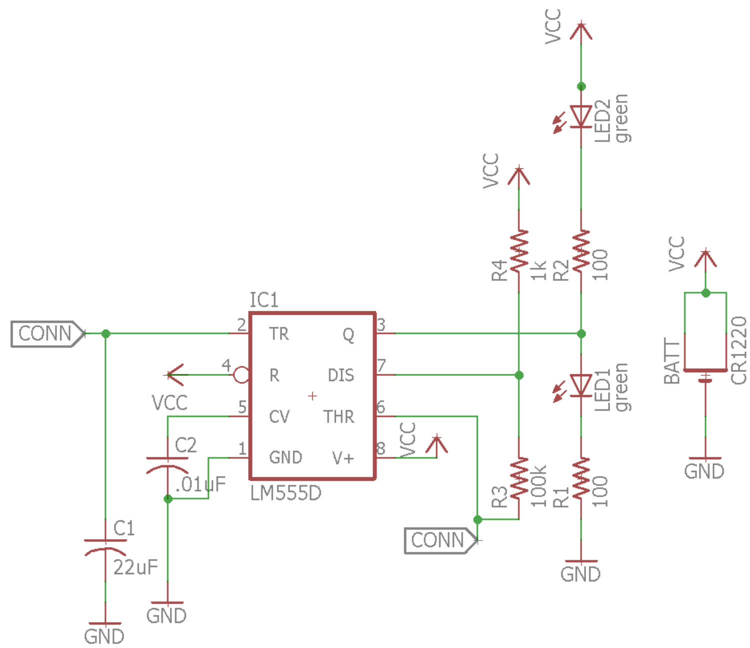


Figure 1: Circuit Diagram

Step 2: Making a prototype of the circuit

Once we are satisfied with the schematic, the next step is to make a prototype of the circuit. The solderless modular breadboard is the most popular tool used during the prototype phase (see Figure 2). A breadboard can be considered as a temporary assembly board. Electric components such as capacitors, resistors, and ICs are placed and connected underneath the surface of breadboard by wires or hidden built-in conductive pathways. Breadboards contain an array of small square sockets with a distance of 0.10 inch from center to center. A spring-like metal sleeve built into the socket which is used to hold the wire or component lead when inserted into one of these sockets.

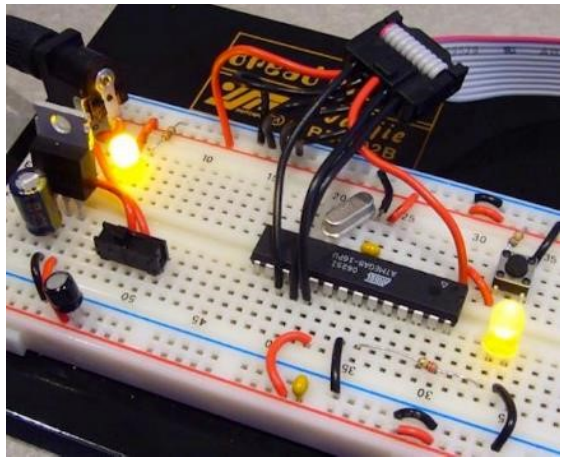


Figure 2: A circuit built on a solderless breadboard [68]

Step 3: Making a more permanent circuit using a perforated board

Once we have a prototype board, constructing a more permanent circuit is the next step. Perforated boards are popular and commonly used as more permanent circuits during the prototyping process (see Figure 3). Perforated boards are typically insulated and consist of an array of holes drilled into it. Similar to the breadboard, component leads are placed in adjacent holes to make interconnections within the board. Later, the lead ends (which are protruding through the backside of the board) are soldered to connecting wires and/or to traces embedded in the board. In general, perforated boards are suitable for developing simple and basic types of circuits.

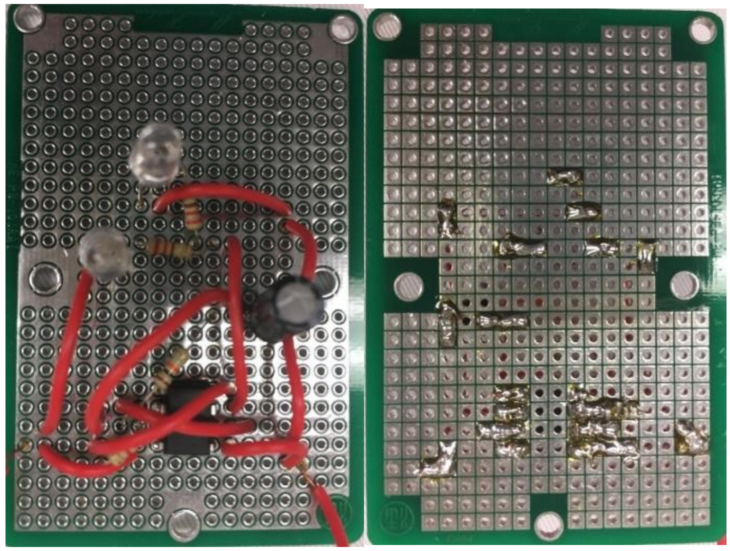


Figure 3: A circuit build on a Perforated board-front side (left) and back side (right)

Step 4: Developing a PCB layout

In addition to the schematic, the CAD system provides the capability of translating the schematic into a printed circuit board (PCB) layout (see Figure 4). The PCB layout is made once we have the circuit schematic and when we are ready to develop the PCB. To be able to lay out a PCB, the CAD package needs to know about the geometry of the component package. A catalog of components is supplied that contains information about the component package dimensions and pin assignments. A PCB layout can be made using different layout constraints. Two-layer (Top and Bottom) boards are more popular for simple circuit designs. To develop a two-layer PCB board layout, all the components included in the schematic need to be organized inside the PCB board. Once the components are placed within the PCB outline, the next step is routing the traces between components. The printed circuit connections on the PCB are directly derived from the circuit schematic and any change in the board should be reflected in the schematic design. An autorouter can be used to automatically route and lay out a PCB from the schematic, or traces can be laid manually. Finally, the production file set is created using a computer-aided manufacturing (CAM) processor. Production files are then used to produce the PCB.

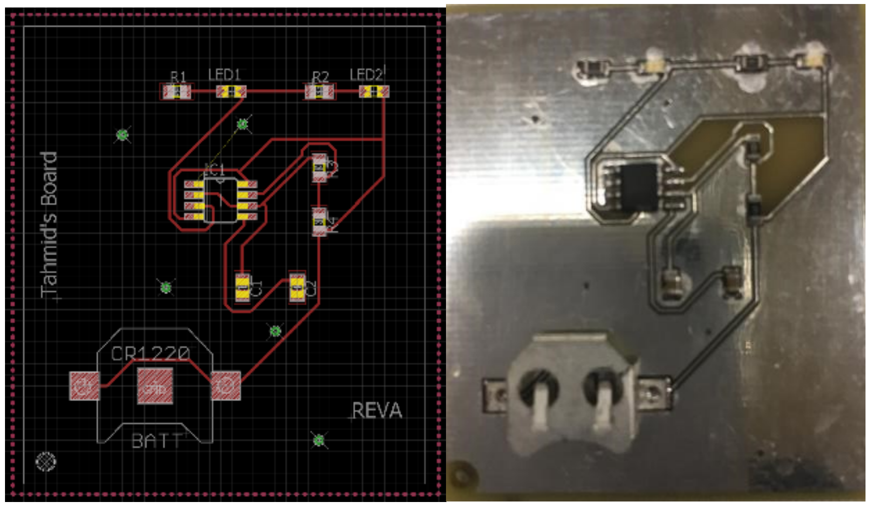


Figure 4: Developing a PCB: A PCB layout (left) and a PCB board (right)

Step 5: Making a PCB

Once we have the design, there are several ways to create a PCB board. Some of the techniques that are commonly used for creating PCBs are: using graphic and chemical techniques to covert a copper-covered board into a custom-etched one (photo-etching with overhead projector transparency film, printing the PCB layout using a laser printer and then using an iron to transfer the toner onto the copper-clad board); using a computer-controlled CNC router to cut away the unwanted copper from a copper-clad PCB; or the PCB can be printed with the help of a PCB service provider. The design files that need to be sent to a PCB service typically consist of a file for each trace layer, Silk Screen (Top), solder stop mask (top), solder stop mask (bottom), and drill file. Each of these files has a different extension that indicates its contents. The computer-aided manufacturing (CAM) job feature of a CAD package will produce these files automatically using a CAM job file. These files are sent to the PCB service to turn them into a printed circuit board (PCB).

Step 6: Joining circuit components

Solder is a tin-lead (lead-free solder is also common) alloy used to join component leads together. A hand-held soldering iron, for instance, is used to melt the solder and make the connection between two metal pieces. To get good soldering connections, the two metal pieces to be joined are heated first, and later solder is melted. While soldering, one should make sure not to splatter on the board. A short-circuit may occur if a small piece of solder falls between two separate conductive lines. Once done with the soldering, careful inspection should be done to avoid solder spatters and ensure a good sound joint. Sometimes a solder mask is used while soldering the components. A solder mask is a thin lacquer-like layer of polymer that is usually applied to the copper traces of a printed circuit board (PCB) for protection against oxidation and to prevent solder bridges from forming between closely spaced solder pads [18]. A solder mask can be very useful while working with small components. A picture of a final PCB board is shown in Figure 4 (note this board does not include a solder mask). While manual soldering is suitable for small scale production, there are two other soldering methods namely wave soldering and reflow soldering commonly used in the industry. Wave soldering involves passing a wave of molten solder on a preheated board. Wave soldering is more common with through-hole components and when used with surface-mounted (SMD) components it is necessary to use some means of holding components in position. On the other hand, reflow soldering involves temporary attachment of tiny electrical components to their contact pads using a solder paste, after which the entire assembly is subjected to controlled heat to melt (reflow) the solder paste and form the electrical connection between the component and the contact pad. Reflow soldering is more popular for small scale production and commonly used with SMD parts.

For very small components, two additional soldering techniques, wire bonding and flip-chip bonding are used for assembling PCB circuits. For wire bonding**,** tiny fine wires are used for creating an electrical connection with the printed-wiring board (PWBs). The PWB provides a surface for mounting components on one side of the board, and allows component-to-component connections through a wiring system. Often, solder is used to make the connections among components. In flip-chip bonding, a solder bump is used to connect the bond pad of the chip to the substrate. The flip-chip technique uses a top surface metallurgy on the substrate bond pads, the solder bump, and a ball-limiting metallurgy on the chip bond pads [11]. A higher number of closely-spaced connections underneath the package body are possible using this technique.

In addition to soldering, several other techniques are used to join conductive materials in electrical circuits such as resistance welding, thermocompression bonding, and epoxy. In case of *Resistance welding, an electrical current pass through two plain metals to make connections.* The electrical current, the electrical resistance of the metals, and contact resistance between the metals generate the heat. For the *ultrasonic welding* process, ultrasonic acoustic vibration is used to generate heat and pressure to make permanent bonding between two workpieces. Ultrasonic welding is the most widely used industrial welding process. *Thermocompression bonding (TCB)* is often used to join metal surfaces. In case of the TCB, the electrical current runs only through the electrode and generates the welding heat which destroys any insulation layers of the materials instantly and make bonding between metal surfaces. Finally**,** *conductive epoxy* is often used in electronics manufacturing. When the chip mounted on top of the conductive epoxy, it works as an electrical connection. Epoxy can be applied as either a film or paste.

2.2 E-TEXTILE DEVELOPMENT

Similar to an electronic circuit, e-textile circuits are composed of components such as ICs, resistors, etc. that are arranged to manipulate voltage and current in specific ways to provide a goal-oriented output. In the case of e-textiles, a fabric substrate is used instead of a PCB board, and all or some of the electronic components are made using textiles. For instance, the circuit design explained above can be replicated in an e-textile form where the PCB board would be replaced with a fabric substrate and all the electronic components used in the board (such as the IC, resistors, capacitors, battery holder, and battery, etc.) could be connected according to the layout on top of the fabric substrate. The whole e-textile circuit can be made from textile-based e-textile components (i.e. using fabric-based capacitors, resistors, or ICs), or using traditional electronic components which are later permanently affixed (i.e. soldered) onto the fabric substrate and connected using a textile conductor (i.e. conductive thread).

To have a solid understanding of how electronics are integrated into textiles, it is particularly important to know how textiles and apparel are made.

2.3 TEXTILE FABRICATION

The first step in textile fabrication is the production of fibers (see Figure 5). Fibers are the smallest units of textiles and have an extremely long length compared to their diameters. Textile fibers are generally divided into two major classes: natural fibers and manufactured fibers. Natural fibers usually come from plants (i.e. cotton), animals (i.e.

wool), or minerals (i.e. asbestos). On the other hand, manufactured fibers are generally made from processing natural fibers (i.e. rayon) or are made from different synthetic materials (i.e. polyester).

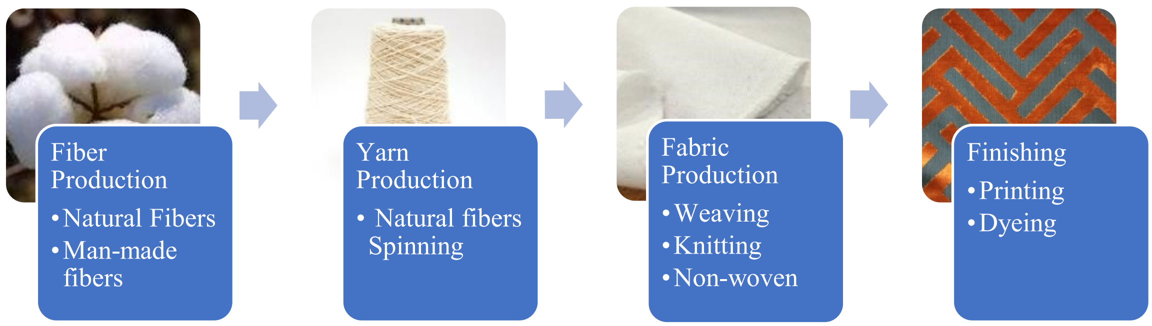


Figure 5: Textile Fabrication Processes

Yarns are made of fibers. To form a yarn, several fibers are twisted or laid together to form a continuous strand that can be made into a textile fabric. The process used to transform a loose fiber bundle to an actual yarn is called spinning. Staple fiber spinning, ring spinning, and rotor spinning are some of the techniques that are commonly used to convert a set of natural fibers into a yarn. The basic principle of each technique is similar. At the beginning of the spinning process, natural fibers such as cotton fibers are separated from the seeds and other materials (e.g. dirt, leaves, etc.) [18]. Later, the fibers are combed using a series of rotating drums and moving bars to form sliver. Finally, sliver is passing through the drawframe which consists of revolving wheel pairs. The revolving wheel pairs of the drawframe draw the sliver apart and make it a finer yarn which is finally wound onto a bobbin. In the case of man-made fibers (e.g. polyester, nylon, etc.), melt-spinning and solution spinning are commonly used. For man-made yarn manufacturing, polymeric granules are fed into an extruder where the polymer granules are melted and mixed. A spinning pump is used to press the molten polymeric spinning mass into a spinneret which converts the polymer a thin molten polymer, called filaments. The filaments are then processed into yarns.

Finally, fabrics are constructed from fibers or yarns. Three techniques are commonly used to produce fabrics: weaving, knitting, and employing a nonwoven process such as felting (see Figure 6). Woven fabrics are made on looms by interlacing two sets of

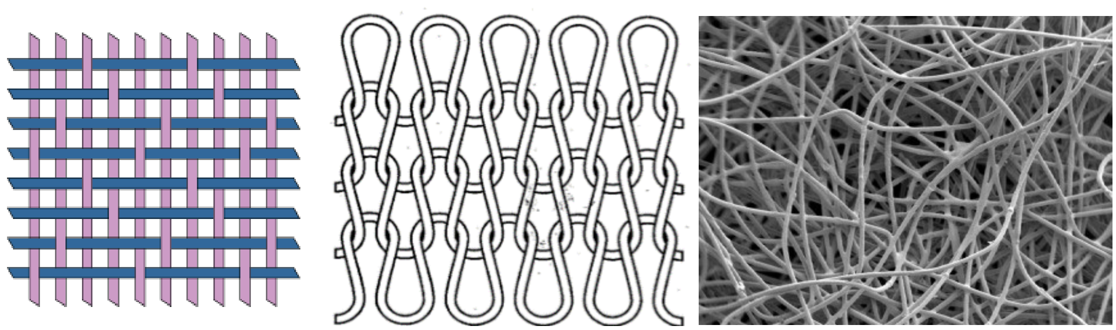


Figure 6: Different types of fabric structures. 1. Woven structure (left), 2. Knit structure,

yarns at right angles. Warp yarns are threaded onto the loom and weft yarns are interlaced with the warp yarns. Knit fabrics are made by linking loops of yarns on needles. Knit fabrics can be made from linking loops of one single yarn, while at least two threads are required to produce woven fabrics. For non-woven fabrics, fibers are held together using chemicals, adhesives, heat, or stitching together to form a fabric structure. To modify the appearance or enhance the performances, different types of finishes (e.g. dyeing, and printing) are used for fibers, yarns, or fabrics.

2.4 APPAREL MANUFACTURING

The apparel industry is labor-intensive and requires relatively little capital and technological skills [23]. Sewing, the central process in apparel manufacturing is primarily responsible for that. Although fabric needs to be cut and pressed and the quality needs to be tested after production, sewing dominates the output of an apparel factory. A sewing machine is a power-operated needle that produces a series of continuous stitches. Operators control most of the tasks required to sew a product. From shaping the sewing line to matching and fitting of one fabric piece against another to quality testing, most processes are controlled by an operator. Even though automatic machines are used to perform small operations, the majority of the operations are largely controlled by operators.

Figure 7 describes several steps involved in apparel manufacturing such as production pattern making, marker making, fabric spreading, piece cutting, sewing, and finishing. These processes are briefly described below.

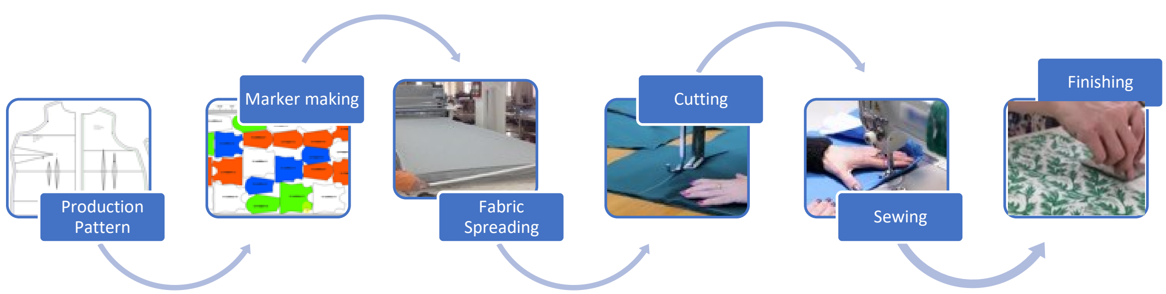


Figure 7: Apparel Manufacturing Process

2.4.1 Patternmaking and Cutting

The first step in apparel production is pattern making. The patterns developed in the apparel industry are two-dimensional in shape. They are developed from original measurements of pre-existing apparel or sketches. The pattern holds the exact shape of each garment piece as well as production markings and placements. For each garment, at least one pattern is developed. Later, different sizes of patterns are produced from the original pattern using grading techniques. To cut a large number of garments at once, a lay is created which consists of many plies of fabric spread on top of each other. The fabric pieces are then cut in bulk from that lay. The pattern shapes for these garments may be drawn on a paper marker placed on top of the fabric lay, or can be used using a computer-aided design (CAD) software to drive an automatic cutter. The marker is aligned with the fabric lays in terms of length, width, and placed without tension. The marker widths are usually 1 inch smaller than the fabric width, so that the edge can be cut away and discarded. The fabric lays are then cut as separate fabric parts using the maker. Once the cutting is done, cut pieces are then delivered to the production line for assembling.

2.4.2 Joining Technologies in the Apparel Industry

Sewing

Sewing is the most dominant process in the apparel industry and is the best possible way to achieve seam strength and flexibility. A wide range of stitch types is used in apparel construction. Stitches can be formed either by intralooping (where a loop of thread passes through another loop formed by the same thread), interlooping (where a loop of thread passes through another loop formed by a different thread), or interlacing (where a thread passes over or around another thread or loop of another thread).

In sewing, the appearance and performance of seams, as well as the characteristic of fabric joins (i.e. smooth and unobtrusive) are controlled by a mechanism that feeds the fabric(s) past the needle controls. A basic sewing machine feed system contains three main parts- the throat plate, the presser foot, and the feed dogs [23] (see Figure 8). The throat plate is the most passive of the three parts and provides a flat surface over which fabric passes as successive stitches are formed. The needle passes through the one or more slots in the throat plate as it goes up and down. The feed dogs allow fabrics to move between successive stitches. A stitch length regulator is used to control the movement of the fabric. The feed dogs consist of a toothed surface which rises through the openings in the throat plate, engages the upper surface of the fabric, moves that fabric along towards the back of the machine, and drops away again below the throat plate before commencing the whole cycle again [23]. The pressure foots hold the fabric down against the throat plate (so that fabric remain constant due to the movement of the needle) and hold the fabric against the teeth of feed dogs as they rise up to move the fabric forward. Most sewing machines form a stitch that progresses linearly, parallel to the orientation of the feed dogs and perpendicular to the orientation of the machine, and the position of stitch lines relative to the fabric is guided by the operator's hands. Therefore, for these machines, the accuracy of a stitch line or a seamline primarily relies on the hand movement of operators which is not always efficient for sewing precise or complex patterns in e-textiles.

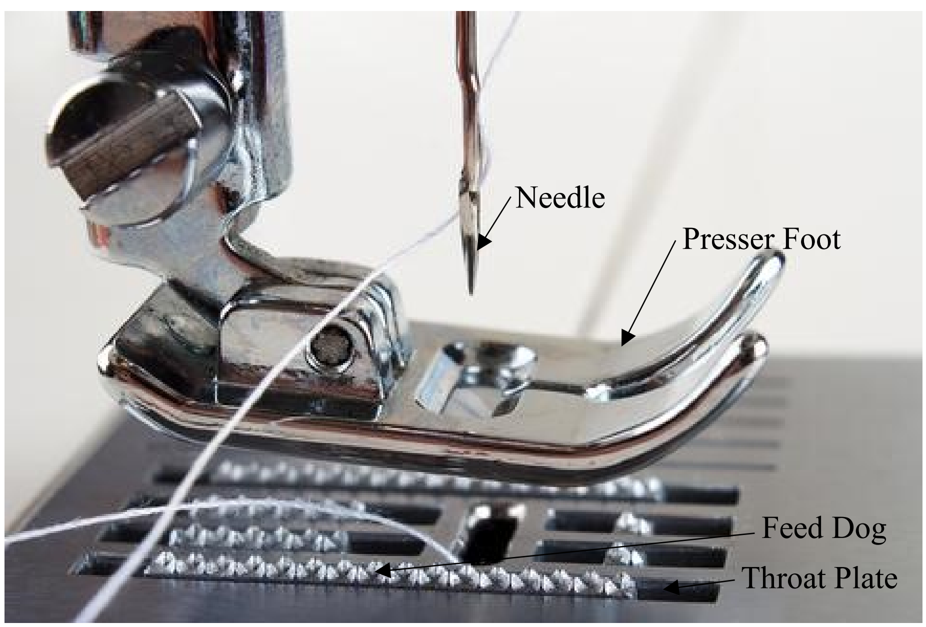


Figure 8: Feeding mechanism of a sewing machine [69]

A few different types of sewing machines used in the apparel industry. Single-needle sewing machines are more common in the apparel industry. Single-needle sewing machines use one needle to create a stitch. These machines are widely used in woven fabric stitching. They can be categorized into two major classes: lock stitch and chain stitch. In lockstitch machines, two different types of threads are used: needle thread and bobbing thread where loops of needle thread are passed through the fabric and are interlaced and secured by the bobbin threads. On the other hand, chain stitch machines use only one (needle) thread to form a chain stitch where one or more loops of threads are passed through the fabric and secured by intralooping with a succeeding loop or loops after they are passed through the fabric. Multi-needle machines typically form stitches with two or more groups of threads with interlooping of the two groups, in which loops of one group of looper threads are passed through the fabric and are secured by interlacing and interlooping with loops of another group of needle threads. A three-thread coverstitch is a common type of multi-needle machine stitch. However, both single needle and multi-needle sewing machines sew basic continuous stitches and they need to be controlled by an operator to perform a more complicated task. There are a few CNC controlled advanced sewing machines that can sew complex designs on their own. CNC Embroidery machines and pattern sewing machines are the two most common type of advanced machines that can sew 2D patterns on their own.

CNC embroidery machines are an advanced type of sewing machine that uses short zig-zag lockstitches and is mainly used for sewing embellishments like motifs and logos. An industrial embroidery machine typically uses multiple needles and bobbins and can stitch multiple garment pieces at the same time. They can sew both straight stitches and covering stitches but often used for sewing covering stitches. In an embroidery machine, the tension balance is tighter on the bobbin thread since the bobbin thread is much heavier than the needle threads. Therefore, the back of the fabric has a poor appearance compared to the face of the fabric. Since embroidery stitches are never load bearing, they have poor durability.

On the other hand, pattern sewing machines consist of only one needle and one bobbin and can create nonlinear patterns primarily by moving the fabric, and sometimes the needle. The tension between the needle and bobbin threads is more balanced for pattern stitching machines than for embroidery machines. The stitches produced are also more durable compared to embroidery machines and can be more suitable for e-textile manufacturing.

Even though sewing is the most dominant process in the assembly of garments, several other methods are used as alternatives to sewing. While these are very important, their application is more limited. Some of the alternative techniques of assembly of garments are described below.

Fusing

Fusing is extensively used during attachment of interlinings. The fusible interlining consists of a base cloth that carries a thermoplastic adhesive resin, usually in the form of small dots, which will melt when heated to a specific temperature. Often adhesives are used as a fusing material. Adhesives can take the form of a film transferred from silicone paper that sticks immediately, or a similar material which must be heated so that it melts and sticks. Adhesives can be used to waterproof garment materials especially when the materials are waterproofed by a coating on the inside of the garment. The fusing process is very economical but not all fabrics can be fused and sometime sewing is needed in addition to fusing. However, this method might be applied to garment-integrated technologies, especially if we have flexible electronic materials made with adhesive resin.

Welding

Welding also involves the fusing together of thermoplastic materials, but in this case, the heat is not applied externally. Heat is generated within the thermoplastic materials. If two hard materials are vibrated against each other, they become hot at the point of contact. If plies of thermoplastic materials are placed between the points of vibration, heat will be generated internally in the materials where they touch [38]. If this heat is sufficient, they will melt and can be pressed together so that a bond is formed. A transducer is used to generate heat by converting an input of electric current into mechanical vibrations. The materials to be welded must be at least 65 percent thermoplastic [23]. Higher concentrations of natural fibers can be used if a plastic film is inserted between the plies being sealed together. Welding can be used to produce waterproof seams which may have many applications in garment-integrated technologies. Several mechanisms can be used to produce heat in thermoplastic welding processes, including dielectric or high frequency, ultrasonic, and laser welding.

Fully-fashioned garments

Although most garments are made from cut pieces joined together in some way, garments can be made as fully-fashioned garments, made using a single machine with no need of joining pieces together. For fully-fashioned garments, individual pieces are engineered such a way so that each garment is made with the exact shape of the body and the pieces are knitted together at the seams. The shape of different pieces of a fully-fashioned garment are usually changed by changing the number of needles use to knit the garments. Molding is often used to change the shape of the garment pieces. The molding process involves heating the fabric until it just begins to soften, deforming it into the required shape, and then cooling it so that the new shape becomes permanent [23]. Knitted fabrics are mostly used in molding since they have the capability of being both stretched and compressed. However, the fabric should contain at least 65% synthetic materials.

2.4.3 Planning production operations in the CMT factory

In an apparel production line, all activities are categorized as individual operations. Each operation consists of a work cycle which is the sequence of elements of cutting, sewing, fusing, or pressing, that are required to perform a job. The actual length of production is influenced by the predicted quantity of output of an individual style, the amount of work content in the style, and the number employed to manufacture it, with the consequent potential for specialization among its operators.

In the apparel industry, two themes are primarily observed in the design of operations-the technical requirements of the process and the managerial requirements of planning a production line [23]. To fulfill the technical requirements, the operations are categorized based on several principles. First, the operations proceed from the inside of the garment to the outside - interior pieces on the surface of a piece like pockets, motifs, or darts are completed before sewing body. Second, operations are sequenced in such a way so that the garments remain in a flat configuration to some extent since it is comparatively easier to stitch flat pieces together compared to sewing 3D components. Third, the structural requirements of the order of operations are taken into account, which is influenced by the geometry and design of the garment. Certain operations must be performed before another operation has taken place since certain operations are irreversible.

The managerial requirements largely depend on several factors including the availability and sophistication level of the machines, the availability and skill sets of sewing operators, and the production capacity of the production line. The production line itself could take several forms, varying gradually between the make-through and the Progressive Bundle Unit (PBU). Make-through methods require a single operator to make the entire garment. These methods are used for very small volume garments, also for sample production (single prototype garment) in a factory, and for runs of maybe a few hundreds of styles for the high fashion retail sector. On the other hand, in a PBU, the successive operations in the garment are performed by different operators, using the most appropriate machinery for each operation. In TPU, operators are generally highly skilled on a specific tasks that form the sequence of operations and create well-balanced workflow. These requirements create new challenges and limit the placement and timing of integration of technology in garments.

2.4.4 Finishing

Once garments are assembled, they are sent to the finishing section for quality checking and pressing. Sometimes the garment goes through some additional steps such as printing or garment dyeing before going to the finishing section. Some of the major steps in the finishing process of apparel manufacturing are described below.

Pressing

Pressing makes a significant change in appearance of finished garments. Typically, pressure, moisture (usually as steam), and heat are used as means of pressing in fabrics to achieve the intended effect. There are several reasons for pressing garments in the apparel industry [23]. First, creases and crushing occur in garments due to handling during garment manufacturing. Pressing is used to smooth away these unwanted creases marks from the clothing. Second, sometimes pressing is used to create marks on the garment for design purposes. Third, pressing can be used to mold the garment to the contour of the body. Several types of pressing equipment are used in the apparel industry including irons, steam presses, steam air finishers, and steam tunnels.

Printing

Printing is used to produce colored designs on a localized area of fabrics using pigments or dyes. Printing offers great design flexibility and can produce a relatively inexpensive patterned fabric. Commonly used printing processes are direct printing, discharge printing, and screen printing. In direct printing, color is directly applied to the desired location of the fabric in the pattern. For instance, Ink-jet printing is a popular direct printing where colored liquid ink microdrops are applied onto the fabric surface at precise points through tiny nozzles. The specific color inkjet, amount of ink, and location of the microdrops are controlled by computers. Discharge printing is done on dyed fabrics by removing color in selected fabric areas. In screen printing, printing paste is forced by a squeegee through the openings of a coated screen that contains sealed openings. Sublimation printing technique is another popular method of printing designs or artworks directly onto fabric pieces or finished garments. During sublimation printing, a design is created in a sublimation paper and which is later transferred to fabric or material using heat and pressure.

2.5 ELECTRONIC TEXTILE INTEGRATION STRATEGIES

As mentioned above, several approaches are used for embedding electronics into textiles. These approaches can be categorized into three different categories [13]:

- Integration of electronics directly into textiles e.g. fibers, yarns or fabrics
- Surface attachment of fully-fabricated electronic systems onto a textile
- Attachment of individual electronic circuit components to the surface of a textile

2.5.1 Integration of electronics directly into textiles e.g. fibers, yarns or fabrics

Electronics can be integrated into textile construction during the production of the textile material (e.g., during the fiber, yarn, or fabric level). Over the years, a significant research has been done for the development of fully integrated electronic-textiles. The shape and size of electronic components have been made more textile compatible so that they could be more feasibly processed on traditional textile machines and incorporated directly into fibers, yarns, and fabrics [30]. Therefore, the integration of electronics directly into textiles ensuring that e-textiles have the physical shape and structure of textiles and the functionality of electronics.

Conductive fibers and yarns

The ability to conduct electricity is commonly of interest in e-textile fabrication, to create connections between electronic components. Fibers can be made conductive in several ways such as:

- **Mixing conductive fibers with traditional fibers: Traditional fibers such as cotton, polyester, etc. can be mixed with conductive fibers to form a yarn which will have a certain level of electrical conductivity. For example, the inner lining of firefighter jackets contains a mixture of heat resistance aramid**

fiber and a low percentage of (usually 2%) electrically conductive carbon fibers [18].

- **Winding or twisting with conductive materials: A fine metal wire can be twisted and winded around a multifilament core yarn where the core yarn acts as a load bearer to achieve electrical conductivity. Elektrisola Feindraht AG [70] produced metal monofilaments which can be blended with regular fibers or can even be directly used during weaving or knitting. The company Swiss-Shield [71] also produced metal monofilament yarns to incorporate with traditional fibers such as cotton, aramids, polyester, etc.**
- **Spinning intrinsically conductive materials: For man-made and synthetic fibers, conductive polymers or additives are added in the spinning mass to achieve electrical conductivity [18]. The conductivity of the polymer increases with the increase of conductive particles; however, the mechanical properties of the yarns subside the impact of adding increasing number of particle materials into the polymers.**

Conductive fabrics

Different techniques are used to produce electrically conductive fabrics. Conductive yarns can be directly integrated into a textile structure e.g., by weaving, knitting, braiding, etc. For woven fabric, conductive yarns are typically used in the weft for convenience since warp yarns are exposed to more process steps, machine elements and therefore, are more vulnerable to friction and tension during weaving [38]. Different weaving techniques can be utilized to get desired conductive properties. For instance, a combination of jacquard technology and a three-layered woven technique can allow a great degree of design flexibility while integrating electronics into fabric. An electrical contact can be established at a defined position in a woven fabric by using multiple weaving frames and electrically conductive warp and weft threads along with an insulation layer in between two conductive layers [18].

Several studies have been done on developing e-textiles where conductive fibers, yarns, and fabrics were used instead of traditional electronic components and wires. For instance, Locher et. al. produced a plain-woven textile consisting of polyester yarns twisted with copper threads [40] (see Figure 9). Dhawan et al. used conductive threads to produce fabrics where conductive threads followed a desired electrical circuit design with the interlacing of warp and weft threads in a woven structure, and interconnects were developed at the crossover points of orthogonal conductive threads [12]. Bhattacharya et al., Locher and Zysset et al. also made woven fabrics where conductive fibers crossed each other to make a connection [8,39,65]. Some researchers have investigated methods of weaving ICs and other discrete component packages into textiles. Zysset *et al.* explored converting components and circuits to strip-form flexible PCBs which were later woven into a textile [65].

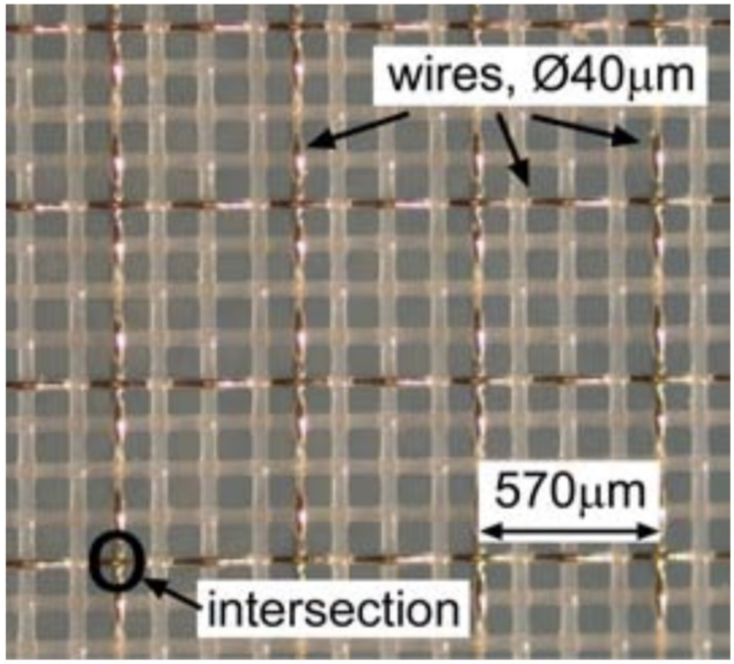


Figure 9: Textile substrates with embedded copper (PETEX hybrid fabric) [40]

Several companies such as Baltex have developed knitted fabric where metal wires are incorporated into textile structure which can be used for heating and electromagnetic shielding purposes [72]. Tremshield LLC and Ohmatex also produce fully conductive woven fabrics [17,73]. In the Profitex project, copper yarns are used during braiding of ropes as integrated data leads [74].

A few attempts have been made to make discrete electronic components in fiber or yarn form. For instance, Lee and Subramanaian developed transistors using conductive fibers [32]. Transistors have been developed by using two yarns crossing with each other where one yarn served as the gate contact for the transistor while the other served as drain and source contact and an electrolyte is placed at the crossing of the two yarns [18, 14, 25]. Veja created functional woven e-textile soft-circuits, such as soft battery holders, soft switches, connectors, and resistors [46,59]. Poupyrey et al. (2016) developed woven textile structures that allow multi-touch capacitive grids [54].

The major benefit of integrating electronics directly into fibers, yarns, and/or fabrics is that the electronics are not visible and they do not change the desired look and feel of the textile. In some cases, they can be easily processed using traditional textiles and/or apparel manufacturing processes. For example, the entire conductive textile may be made from conductive fibers and yarns having conductive properties, while preserving the mechanical properties of a typical textile. Electronic connections made using these textiles would require no foreign materials to be added to the surface of the textile (such as wires or PCBs) [53]. Conductive textiles produced using these techniques are typically more comfortable for users.

However, the manufacturing process for many of these approaches is not scalable yet, particularly for more advanced structures like fiber- or textile-form components (transistors, etc.) or circuits. The integration of electronics is a comparatively new area and often requires new machines and techniques which are not always readily available in the apparel industry. So far, relatively few examples of textile-based electronics have been made and their applications are still limited. Moreover, since the integration of fully textile-integrated electronics occurs at the early stages of textile production, the design cannot be modified once the textile is made. Using this approach, functional regions must be predesigned, and spliced into the fabric structure through strategic inclusion or exclusion of conductive materials [53]. The technique requires that the textile design and fabrications methods be adopted upstream of the clothing manufacturing processes and might have several implications for clothing manufacturing operations. Therefore, they ask for significant changes in the overall manufacturing systems. As the nature (elasticity, feel) of metal fiber is in some cases different from conventional fibers, they are not often suitable for traditional yarn-production techniques. Several modifications need to be applied to make the yarn applicable for machine weaving or knitting which significantly increases the time and costs of manufacturing.

2.5.2 Surface attachment of fully-fabricated electronic systems onto a textile

Another approach of integrating electronics into clothing is attaching pre-fabricated electronic systems onto the surface of a garment, for instance where electronics are housed in pockets and cables are run through conduits or channels in the garment [13] (see Figure 10). In some cases, cables are permanently attached or fused to the surface of the garment. Using this technique, the electronic system is made in such a way that it can be easily removed from the garment when needed. For most of these systems, electronics and garments are manufactured separately, and they are joined together via connectors at the final stage. Often, they are` combined by the end-user once they purchase the item.

Figure 10: Electronic systems are attached on a garment surface [22]

To attach an electronic system to a garment, conductors can be integrated selectively to connect specific sensors to a detachable processing unit. Conductors can be integrated by the techniques (e.g. weaving, knitting, etc.) mentioned in the previous section, although this increases the complexity of manufacturing. In some methods for conductor integration (such as weaving), conductors are the most easily oriented orthogonal to the textile structure. However, they are often used for very small areas, therefore, orthogonal placement is not always a major barrier for this kind of electronic integration. While weaving and knitting are the most common techniques for integrating conductors into textile structure, stitching is also commonly used for creating a connection between components. In practice, Buechley and Eisenberg used conductive thread to stitch connections to prefabricated PCBs where PCB connections were broken out to through-holes with plated flanges [9]. Linz et. al. (2005) used a programmable embroidery machine to layout a stitch to mark the PCB location and then stitched an electrical connection to the board, where conductive threads were passed over and around the PCB through-holes [35].

The main advantage of using pre-fabricated circuitry is that the majority of the system can be manufactured separately and attached directly to the fabric. Often the electronic systems are attached at the final stage of manufacturing. Therefore, there will be a maximum level of flexibility in terms of manufacturing. Often the electronic system and the garment are sold separately, and these two are attached by the consumers (post-purchase). Since it takes full advantage of traditional electronic manufacturing, the system will be more durable. Moreover, the impact on traditional textile and/or electronics manufacturing will be minimum here. It will be less expensive since it minimizes the integration of two different manufacturing practices (apparel and electronics). Here, consumers just have to pay the combined manufacturing price of the garment and the electronic system instead of buying them separately.

Another advantage is that circuit elements can be designed to be removed in contexts like washing, which is one reason that this approach is commonly used for commercial products. For instance, the Google Jacquard project used the same technique where the electronic system can be removed from the garment separately for charging a battery and other relevant purposes [75].

The main disadvantages of this method are that since pre-fabricated electronics tend to be more bulky and stiff, the electronic systems will be more easily visible from the outside and may not be always convenient for users. Adding a complex electronic system may make the garment very bulky and cumbersome. This can often create discomfort for the users, since they would carry an extra device in their clothing. In some cases, the system needs to be removed before washing and the exception of that may completely damage the e-textile garment. Finally, localized prefabricated circuitry often requires that all components be in the same location (attached to the pre-fabricated circuit board).

2.5.3 Attachment of electronic circuit components to the surface of a textile

The third approach of integrating electronics into textiles is attaching traditional electronic components directly onto the surface of the textile as shown in Figure 11. This kind of hybrid manufacturing process leverages the benefits of the electronics industry by using easy-to-assemble electronics and the textile industry by using the comfort properties of flexible textiles. Several techniques are currently applied to attach discrete surface-mount electronic packages onto textile surfaces. One of them uses textile-integrated conductors to join components, where insulated conductive threads are used in either warp or filling direction and connections are made in the desired location by removing the insulation and adding conductive paste [38]. Electronic packages are attached on top of the conductive trace using standard joining methods. Another approach is to mount flexible electronic components on top of the textile and use uninsulated conductive threads to make permanent connections among the electronic components [35] that will complete a circuit. In both systems, a strong, durable, and reliable joining method is paramount.

In practice, Linz et al. used non-conductive adhesive and pressure to attach flip-chip components to a textile [36]. Kim et al. developed a method to attach an IC to a printed textile [62]. Using this approach, electronics are applied onto a fabric substrate as a separate process once the fabric is complete. Thus, even though this approach utilizes the fabric as a base support material to hold the electronics, the electronics are applied after the production of the fabric. The benefit of this technique is that adjustments in the design can be made after garment pieces are cut or even after garments are assembled to

Figure 11: Attachment of Electronic components onto a fabric substrate: A shirt embellished with LED sequins [9]

some extent. This allows designers some flexibility to adjust the circuit design after the fabric is produced rather than having to design the circuit at the weaving or knitting stage. It can leverage both the apparel manufacturing process and the electronics manufacturing process. Unlike integration of electronics into textiles, there is more flexibility in terms of manufacturing, since this technique can utilize readily available electronic components and directly integrate them on the textile surface. It is comparatively easier to place and distribute components strategically, too. A few companies have adopted this technique to manufacture electronic-textiles. For instance, Forstner Rohner used embroidery machines to affix proprietary LEDs on textiles [76]. Sefar has developed fabric circuits using proprietary components and a hybrid woven fabric consisting of PET and insulated copper monofilaments in warp and weft [77].

Using this method, traditional textile and garment equipment can be used to integrate electronics into clothing (e.g., conductive stitches can be made using a sewing machine). The method can be implemented with minimum modification of the textile and apparel machines and processes, and thus, will be less expensive for e-textile production. This technique also leverages the benefits of two different methods of e-textiles fabrication described above since it can provide a level of comfort and flexibility which is quite similar to that achieved by integrating electronics into fibers, yarns or fabrics, while at the same time it provides the benefits of using readily available electronic components without adding the level of stiffness onto the fabric like surface attachment of an electronic system would. Therefore, this thesis will use the technique of attaching electronic components onto textiles while leveraging the benefits of both electronics and apparel manufacturing techniques.

2.6 CONDUCTORS USED IN E-TEXTILES

In e-textile circuits, the electronic components need to be connected with each other to complete a circuit. The materials typically used as connectors between electronic components are described below:

Conductive yarns

Conductive yarns are one of the most fundamental technologies for developing e-textiles. Common conductive yarns have one of the following structures: multifilament core yarns with a metal coating, multifilament metal fiber yarns, and multifilament yarns with wrapped metal fiber [38]. Conductive yarns are commonly used for connecting multiple components in an e-textile circuit. Conductive yarns can be directly integrated into textile structures i.e. weaving and knitting or they can be applied as a surface-applicant on the surface of a textile. Conductive yarns in surface-applied methods create connections either by sewing or embroidery. However, a sewing connection does not establish a solid electrical connection compared to traditional attachment techniques such as soldering or welding. In sewn connections, the electrical contact is created using surface contact and yarn tension, hence, the resistance value is undefined and may vary over time. In addition, conductive yarns are vulnerable to moisture and water, and can experience contact corrosion and oxidation over time [38].

Conductive inks

Conductive inks are typically used to add conductivity to specific areas of fabric. Particles such as silver, copper, carbon, etc. can be added to conventional inks which can be used to directly print conductive traces. For e-textiles fabrication, both inkjet printing and screen printing are commonly used. However, inkjet printing offers several advantages over screen printing for e-textiles including deposition of controlled quantities of materials in precise locations on the fabric, hence, allow more sustainable use of materials and water. Karim et. al used inkjet-printed graphene to produce breathable e-textiles [28]. However, the key challenge with printing is to achieve continuous highly conductive traces on the rough and porous textile surfaces [28]. Many approaches to using printed conductors print traces onto films (that have better temperature stability and more uniform surface texture) that are subsequently laminated onto a fabric. Moreover, metal inks have several limitations such as they are non-biocompatible, expensive, environmentally unfriendly, and often require higher temperature which is often incompatible with textiles.

Ribbon cable or wire connectors

Ribbon cable or wire connectors are also used to create a reliable connection. Lehn et al. used a ribbon cable connector between e-textile bus wires and electronic units to provide a robust solution of integrating soft fabrics to traditional electronics mounted on printed circuit board [33]. However, cables or wires add stiffness into the fabric and may cause discomfort to the user.

Making connections to Insulated conductors

Insulated conductors are often used to establish connections in e-textiles. In the case of insulated conductors, the insulation needs to be removed in the contact area to set up an interconnection. Different techniques are used to remove insulation from conductors. For instance, Locher used laser ablation techniques to remove insulation from individual copper conductors using standard laser machines, added a small drop of conductive adhesive for interconnection between the conductors, and later used an epoxy resin to protect the interconnection [39].

While using insulated conductors during apparel production, there is a risk of accidently damaging insulation in the cable since the cable could be pierced by a sewing needle. While working with insulated cables, stitching should be done carefully so that the insulation remains protected. Several techniques can be used to protect insulated cables. One approach could be using a satin stitch that can float over the insulated cables without creating significant changes in the stitch structure. In addition, stitch length and seam length of the sewing machine can be recalibrated so that the needle holes skip over the conductor.

2.7 ELECTRONIC COMPONENT ATTACHMENT TECHNIQUES FOR E-TEXTILES

As discussed earlier, the purpose of using joining methods in electronics is to provide a stable continuous transfer of electricity. On the other hand, connections in textiles are mainly used for holding a garment together. When we talk about connections for garment-integrated technologies and e-textiles, these connections should maintain the properties of both electronics and textiles. The ideal connection for e-textiles should be highly conductive and withstand regular wear and tear and washing, but at the same time it should be flexible enough so that it does not create discomfort for the user. Previously, I have discussed the common joining techniques for electronics and textiles separately. In the following section, I am going to discuss about how these techniques can be used to attach components or join conductors in e-textiles.

Sewing

Sewing is one of the most popular and widely used joining processes in garment-integrated technologies. Sewing allows attachment of electronic component directly to a fabric surface using thread alone. Linz et al. used sewing to attach PCBs on textiles [35]. Threads leading out of an e-textile component can be stitched, punched, or woven through the substrate containing the components to attach them to specific locations [9,45,59]. However, sewing creates an electrical connection mainly through the mechanical connection that is formed between the thread and the textile structure, and therefore can be a weaker electrical connection (since the thread and the component must stay in close contact during movement to ensure that the circuit functions).

Soldering

Soldering involves mounting components directly onto the surface of a textile. Soldering is commonly used for permanent connections in the electronic worlds and often used in e-textiles manufacturing. For instance, soldering can be used to affix surface-mount LEDs on textiles [51]. Soldering provides small, light, comfortable and non-noticeable connection, durable physical connection, and solid electrical connection [35]. However, one of the major concerns with soldering is that the soldered components are often toxic and could harm the skin when they are in contact with a user's body. Several other limitations of soldering include high melting temperatures, comparatively slow connection process, alignment issues, and the need to protect exposed conductors.

Welding

Welding involves the sealing together of thermoplastic materials where heat is generated within the thermoplastic materials. However, welding is limited to thermoplastic fiber content materials only. Several types of welding have been used in e-textiles manufacturing such as high-frequency welding. resistance welding, ultrasonic welding, laser welding, and hot air welding. [2,12,45].

Crimping

Crimping has high mechanical strength and unlike other joining methods, crimping quality can be tested by logging the crimping force curve [38]. In textiles, crimping is used to attach components like snaps, studs, and other embellishments by passing metallic flanges through the fabric and bending them to form a crimped attachment. Crimping can be used to make connections through insulation. However, crimping might not be suitable for thin and soft conductors such as copper alloys. The wire can easily break if the mechanical force is not controlled properly [16,33]. Another example of a crimping technique is stapling. Components can be stapled into conductive stitched circuits to create electronic textile circuitry. When the substrate flexes or bends the conductive trace is free to move [45]. Stapling has several limitations such as flexing stretches the pins that attach the component to the substrate, accelerating wear and tear on the textile [9,45].

Adhesives

Adhesives, both conductive and nonconductive, can be embedded into textile substrates in e-textiles. There are mainly three types of conductive adhesives currently in use- isotropic conductive adhesives (ICA), anisotropic conductive adhesives (ACA), and non-conductive adhesives (NCA) [38]. Non-toxic, highly durable, highly conductive, and moderate flexible conductive adhesives can potentially be used to permanently bond flexible textile substrates with rigid electronic components [45]. Linz et al. used nonconductive adhesives to join electronics to e-textile circuits [36]. Jones and wise used conductive adhesive to bond large LED leads to a silver-coated nylon conductive fabric

[27]. However, adhesives are unstable at high temperatures, provide relatively weak connections in bonding large objects with a small bonding surface area, and may increase the stiffness of the fabric near the area of application.

Temporary interconnects

Temporary connections such as snaps are easy to connect/reconnect, and they are very common in textiles [33]. Snaps are commonly used for temporary connection and they are typically attached in garments using crimping or sewing. However, snaps have several problems, such as slow connection process, problems arising in soldering or welding, low connection size, weak physical connection, and exposed leads [33].

2.8 CIRCUIT ROUTING OF E-TEXTILES

When electronics are integrated into different parts of a garment, electrical connections need to be established between components to make all the pieces work as a complete system. However, routing interconnections is a major challenge for garment-integrated technologies. As previously discussed, the integration of technology can happen in different stages of apparel manufacturing. Each stage brings unique challenges for routing interconnections.

2.8.1 Weaving

Weaving is one of the most popular techniques of fabric manufacturing. In weaving, two sets of orthogonal yarns are interlaced with each other according to a weave design to form a fabric. The yarn that moves along the vertical or length direction is called warp yarn and the yarn that moves along the horizontal or crosswise direction is called weft or filling yarn. The position of the filling yarns with respect to the warp yarns is determined by the weave design. Using weaving, different warp, and filling yarns (both conductive and insulating) can be arranged in any desirable order and each yarn can be individually addressed and manipulated to form interconnects. The regular geometric structure of yarns in a woven fabric structure allows interconnects between two or more points within the same layer as well as interconnects between layers, like vias in PCBs, without much difficulty [1,41] (see figure 12).

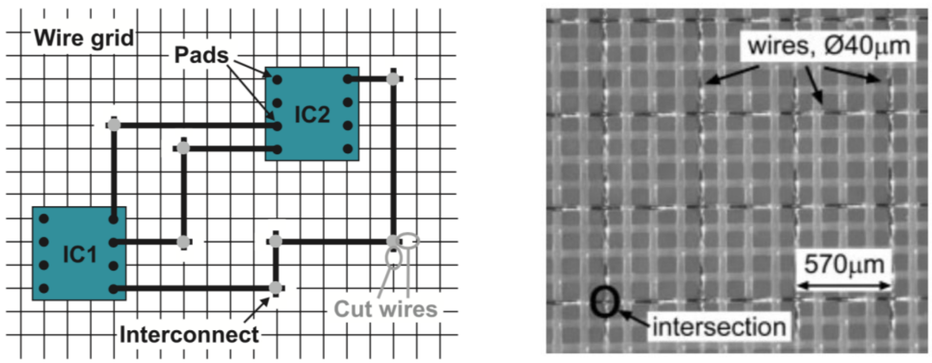


Figure 12: Interconnections in e-textiles: Electrical components interconnected via the wire grid in the PETEX hybrid fabric by Sefar Inc. (left) and PETEX fabric (right) [41]

2.8.2 Knitting

Knitting is formed by interlacement of loops. In the simplest knit structure, a single yarn can be manipulated to create rows of loops (see Figure 13). Similar to weaving, the crosswise loops in knitting are called courses and the lengthwise loops are called wales. Due to the nature of its structure (one yarn is used to create rows of loops), interconnections are formed in knitted fabric structures only in the cross direction or course-wise. The larger curvature of the knitted structure also limits the choice of yarns in terms of materials and dimensions [1].

2.8.3 Stitching on fabrics

Sewing is one of the simpler forms of creating interconnections on fabric (unlike weaving and knitting) when interconnections need to be made inside the fabric (see figure 13). Stitching allows traces to be placed in almost any orientation and position on a fabric piece or fully assembled garment, and therefore provides ample flexibility for trace layout [13]. In addition, stitching can be applied to any kind of fabric and can provide more flexibility in the location and orientation of interconnects. CNC Embroidery machines and pattern stitchers are often used for routing interconnections since these machines can create complex designs automatically. In a sewing factory, both insulated and uninsulated conductors can be directly integrated into textiles by sewing. Stitching is commonly used for creating interconnections in e-textiles. For instance, Linz et al. used embroidery to connect metallic pads of surface-mount components [35]. Hamdan et al. developed an interactive embroidery system to create interconnections on e-textiles using stitching [21].

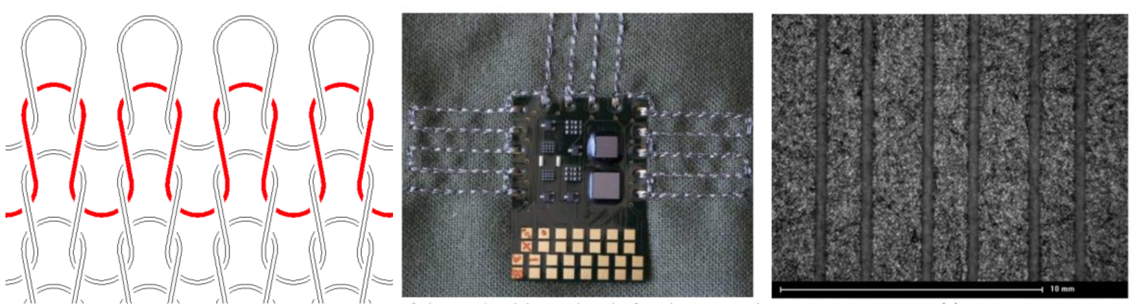


Figure 13: Interconnections in e-textiles: Knit Structure [50] (left), Creating interconnections with embroidery [30] (middle), and Printed transmission line on the fabric [21] (right)

Eichinger III et al. used stitching to create PCB layout onto textiles [19]. Buechley et al. used stitching to develop a LED matrix display onto a garment [9]. Several other work used stitching for creating interconnections among electronic components in e-textiles [9,19–21,27,35,38,45,54]. However, almost all of the above studies used conductive thread directly stitched through the components to make an interconnection in contrast to using a separate joining technique (i.e. soldering, welding) to connect the stitched traces with electronic components. One of the disadvantages of directly stitching conductive threads through the components is that stitching is only suitable for custom-made component packages and usually not suitable for off-the-shelf electronics, thus, is less scalable. In addition, stitching has not been extensively used for developing complete circuit layouts in a complete e-textile garment (i.e. stitching has been mostly used for creating circuits for fabric swatches and small localized areas in the garment) using automatic sewing machines and routing traces in e-textile garments. To our knowledge, none of the above studies explored stitching as a medium for trace crossing and seam crossing in a garment scale.

2.8.4 Printing on Fabrics

Printing on textiles is an application of dyes/pigments in the form of a coating. Similar to stitching, printing processes can be used to create a conductive trace on textiles substrates a specific predetermined area (see figure 13). Printing can be used in any kind of fabric as long as the conductive material mechanically affixes with the fabric surface. Printing is usually done in a flat area, whereas it is very difficult to print a continuous connection around a body or body part in circumference [13]. Several research projects used conductive inks for printing conductive traces on textile surfaces. Jin et al. developed mechanically and electrically robust interconnections for e-textile applications by controlling conductive ink permeation [26]. Karim et al. used graphene-based inkjet printing to develop e-textile circuits [28]. They also performed a washability study to test the durability of the conductive particles and their samples were able to survive 10 washing cycles, though resistance of the conductive traces increased with the increase of the number of washing cycles. Kim et al. used screen printing to develop interconnections in e-textile circuits [29]. Zeagler et al. used conductive ink to create conductive paths in e-textile circuits [63]. Similar to stitching, most of these studies used conductive ink to print conductive traces on to a small swatch or a small segment of a garment where trace crossing and seam crossing were avoided. None of these studies explored the potential of printing conductive elements to connect or develop spatially distributed electronic components in a finished garment.

2.9 CIRCUIT ROUTING IN APPAREL MANUFACTURING

2.9.1 During Pattern Layout

During the production of apparel, 2D patterns are used for cutting the exact shape of each piece. In addition to the exact shape, these pattern pieces also hold production markings and placements. To indicate crossing seams, sometimes the edges of the patterns are notched. Markings also indicate placement of features like pleats, darts, pockets, or where two fabric parts should connect while assembling the final garment. Similar techniques can be used for e-textiles, to show the placement of electronics. For instance, if an e-textiles developer knows that s/he is going to put the electronic system at the center back of the garment, s/he can add a marking at the back part of the pattern to indicate the position of the electronic system. Similarly, markings can be added at the edges of pattern pieces to show where traces should merge together between two garment pieces.

2.9.2 During Marker Layout

Markers are used to cut garment pieces in batches. A marker is a long layout that contains all the sizes and pieces of the 2D pattern required to make a particular garment style. Markers are drawn either by hand or by a plotter. All production markings and placements should be transferred to the marker. Pieces are laid into the marker according to their orientation requirements. The width of the marker is typically one inch smaller than the width of the fabric to allow for variability in fabric width and to eliminate the selvedge edge.

In e-textiles, electrical connections often need to be made between two fabric pieces (e.g. an electrical connection needs to establish between a cuff and the back part of the garment) and components or connectors need to be routed across that seam. For e-textiles that involve pre-woven or pre-knitted interconnects or components, therefore, conductors or components should not be routed around the edge of the fabric (otherwise, they could be detached during cutting). Within the marker, pattern pieces would need to be re-arranged so that the conductors or components are routed at appropriate points on each pattern piece, which may increase the overall complexity and inefficiency of the marker.

2.9.3 During Fabric Spreading and Cutting Fabrics

Electronics can be integrated after cutting the garment pieces but before assembling the pieces together to form a garment. If a manufacturer intends a stitched ornament to join between two different garment pieces, such as a connection from a collar onto the body of a garment and down the sleeve, it would be feasible to pre-embroider each piece using notches and placement marks before the garment is assembled. However, routing interconnects among different pieces in the garment while retaining both electric and aesthetic properties will pose challenges.

2.9.4 During Sewing

Interconnects can be applied during apparel production. In this case, the designer doesn’t have to be worried about the placements and positions of notches and placement marks and their alignment with the electronic systems. Implementing interconnects during the production will give more flexibility in the location and orientation of interconnects. A single stitched trace may able to connect a collar-mounted component to the body of the garment and down the sleeve. However, it would not always be convenient or possible to run a complete garment in the sewing machine, especially with a large electronic system. The size of the sewing machine bed can limit the size of the pattern having garment-integrated technologies. Typically, sewing machines have beds which are fixed in lengths and widths. Therefore, the pattern size must be smaller than the bed size. This is particularly true for fully automated sewing machines, such as programmable pattern stitching machines. For a manually operated machine, there may be a little flexibility on the pattern size since the operator can manually control the stitches.

2.9.5 Order of Operations

Geometry and design of the garment play an important role while sequencing the operations. It might not be possible to perform a certain operation before another operation has taken place and vice versa. For e-textiles, the order of operations might create unique challenges. While creating a trace connection between two garment pieces which also conducts electricity, the sequence of the operations may need to be adjusted to ensure electrical integrity as well as the aesthetic integrity of the trace. In some cases, one operation must need to happen before another operation to avoid unexpected results. For instance, if someone wants to use insulation to protect electronic components from moisture or regular wear, s/he should perform that after developing solid connections among the components, not the vice versa.

2.9.6 Seam Crossing Techniques

Several approaches are used to integrate conductors into textiles and some have been discussed earlier. In an apparel factory, several strategies can be used to achieve seam crossings between two different fabric pieces. Seam crossing may happen between different layers too. The most common approach to integration of conductors is by using a weaving or knitting approach [12,13,39,59,64]. In this case, conductors will be pre-embedded into textiles when they arrive in the apparel factory. These pre-embedded conductors need to be aligned together while creating a seam between garment pieces.

In the case of uninsulated conductors, connections can be made across seams by careful alignment of the bare conductors. To strengthen the mechanical bonding between seams, a short stitch can be used to provide enough mechanical stability to make an electrical connection[13]. Uninsulated conductors can be insulated several ways during seam crossing while insulation is needed. For instance, the conductor can be sealed with an insulation material such as silicone [37], a tape [4,78], fabric paint [9], or an additional cover layer of textile can be stitched over the conductor.

In the case of insulated conductors, the insulation must be pierced or stripped in the desired location to make a connection. Connections can be made using any kind of standard technique such as soldering, conductive adhesive, or conductive ink. In a CMT factory setting, conductors are directly integrated into the garment and removing insulation without damaging the rest of the fabric structures is a difficult task. Having operators manually strip insulation is likely an expensive process as well. Several techniques have been used to remove insulation from conductors such as knife, thermal stripper, laser ablation, chemical stripping agents, application of heat, micro-abrasive blasting [39,79,80]. However, out of all these techniques, only laser ablation has been used for removing insulation of conductors in e-textiles [39]. The rest of the techniques are common in chemical, electronics, and other relevant industries but could potentially be applied for e-textiles applications with some modifications.

2.9.7 Trace Crossing Techniques

For garments having a complex embedded circuit in which a large array of interconnects are connected to a central processor, it may be necessary for traces to cross in the garment. In a PCB, multiple board layers are used to allow traces to pass under and over each other. However, in fabric, many layers get cumbersome and inconvenient. In addition, these traces often require making a connection between different layers of fabric. Therefore, making interconnects between traces and using insulators among different traces created new ranges of challenges while integrating electronics into clothing.

One way to perform trace crossing in the garment is by stitching with a sewing machine. In a lock-stitch machine, two threads-bobbin threads and needle threads are used to form a stitch. Traditionally, conductive threads are used as bobbin threads for durability issues and non-conductive threads are used as the needle thread. By adjusting the tension balance of the two threads such that conductive thread floats on the surface of the textile while the non-conductive thread is pulled through from one side to the other, conductors can be stitched on either side of the fabric [16]. The textile between stitches works as the insulator between conductors on each side.

The same technique can be used to create multi-layer e-textiles where both sides of the fabric can be made conductive using conductive threads so that each side of the fabric will work as one side of the board and together they will complete the circuit. Connections between layers can be made using a similar technique to those used for PCB, where perpendicular interconnections are made using vias or through-holes. For instance, a crimping technique can be used to make interconnection, in which a connector with metallic legs is inserted through the fabric and the legs are clamped around the fabric from the reverse side.

2.10 CHALLENGES AND RESEARCH GAPS FOR INTEGRATING ELECTRONIC COMPONENTS ON TEXTILES IN THE CMT FACTORY

In the previous sections, several challenges have been identified for integrating electronic components into textiles. In this section, several other challenges which are particularly important for the manufacturing of e-textiles in a CMT factory set up will be discussed.

Electronics and textiles are very different in structure. Therefore, integrating electronics onto textiles creates additional challenges. While integrating electronics into textiles, one should confirm that the e-textiles maintain the functionality of electronics and flexibility of textiles. At present, the goal can be achieved by compromising in both areas. Adding electronic components in textiles limits the flexibility and washability of fabric products. On the other hand, the flexible structure of fabrics is greatly hampered by adding stiff electronic components onto the surface. Moreover, electronics manufacturing systems are mostly automated, high-speed, and reliant on hard materials with very foreseeable mechanics. In electronics, accuracy of production in the nanometer scale is feasible. Chips and circuits are easily replaceable with a very low manufacturing cost. On the other hand, apparel production is almost completely manual, slower, and designed around on soft, flexible materials with rather unpredictable properties. In textiles, the precision of manufacturing ranges in some tenths of a millimeter. Apparel manufacturing produces dust and during production, some fibers will break and be set free. Methods that work well for apparel manufacturing might create new challenges for developing and integrating electronics into apparel. Therefore, marrying these two partners is a delicate task.

2.10.1 Size and shape limitations of the electronic components

The size and shape of the electronic components create additional challenges for the e-textile. It has been noted that the larger the size of the electronic components, the easier it is to integrate components into textiles. However, the size and rigid edges of the electronic system may increase the weight of the garment to some extent and cause discomfort to the users. The fabrication processes of smaller size electronic components are extremely difficult to execute. Moreover, the smaller the size of the components, the higher the chance of connection failures [51]. So far, relatively large-sized LEDs and ICs have been widely used in garment-integrated technologies manufacturing. For example, Forster Rohner uses two different sizes LEDs: 8 x 8 mm and 4 x 8 mm in his e-textiles [76]. Berglund et al. used 5mm, 3mm, and 1mm size in their e-textiles testing [5]. Things get complicated as the size of the electronic components is decreased, or the number of pins is increased. For example, 8 pin ICs are more complicated to fabricate onto textiles than 2 pin LEDs, assuming both of them have the same size. The techniques used in the electronics industry to fabricate miniaturized components can be applied to integrate tiny components on textiles. However, new problems might arise for the CMT factory. Further research is needed to analyze the feasibility of different sizes and shapes of electronic components that can be integrated into textiles in a CMT factory setting.

2.10.2 Limitations of using textiles and textile-based conductors

Textiles are undefined substrates having uneven surfaces and skew. Because of their deformability, textiles do not have a consistent shape which makes them difficult to use in automatic machines.

Moreover, the electromagnetic capability of fabrics is very poor and they can carry high static charges in dry air which can easily damage the integrated electronics when moved [38]. Fabrics often lack grounding for shielding and for defining line impedance. Integrated circuits can be unreliable due to noise and other disturbances. Thermal limitations of fabrics also need to be considered. Fabrics are typically more sensitive to high temperatures compared to electronics and could be burned or melted while handling high temperatures during the electronics integration process.

Electrical traces integrated into fabrics typically have higher resistances than traces on PCBs due to the uneven surfaces and skew shapes of textile conductors [38]. Redundancy in electrical connections may improve their performance, but also increases the cost of manufacturing [63]. Conductive threads used in e-textile manufacturing have many loose fibers that may create shorts in the circuit, especially when traces are placed too closely [51]. Uneven edges of conductive threads create additional problems during interconnections or routing of traces. Some highly conductive threads are made from metal wires, which often cannot be easily woven, knitted, or sewn. In addition, most of the conductive threads available in the market are not suitable for high-temperature physical interconnections such as soldering, welding, etc. The structure of fabrics and threads add certain granularity in the dimension that reduces the precision of circuit routings [38]. All of these problems combine to create unique challenges for e-textiles.

2.10.3 Durability of component joints and traces

The durability of e-textiles is a major concern for e-textile developers. Most electrical connections must be protected from mechanical stresses and moisture, since they cannot withstand high-intensity or repetitive mechanical impacts [38]. Traditional on-body devices such as fitness trackers, smartwatches, etc. are typically placed on a stable location of the body where minimum movement happens, often placed in a single rigid or semi-rigid compartment, and can be easily removed from the body whenever necessary. Most of the commercially available e-textiles have detachable electronic systems which can be removed from the body for charging or before taking a bath [13]. Therefore, durability has not been a major concern for these devices until now. However, durability might be the single most important issue for textile- and garment-integrated devices. The problem intensifies when electronics are directly integrated into textiles or similar soft materials. A typical e-textile circuit consists of two major segments: a rigid area with electrical components and connections and a flexible area with electrical traces where body movement happens. Consider an e-textile where multiple sensors are placed in different parts of the body and they are all controlled by a central power unit connected by conductive wires. Therefore, both the centralized, rigid electronic components (e.g. central power unit and sensors) and the connecting conductive traces need to be protected during regular wear and tear and washing.

The durability of e-textiles can be affected in several ways. The movement of the body of the user can create mechanical stress on the electronics as well as connections and may lead to system failures. Textile-integrated electronic components can be exposed to different levels of tensile strains, which can vary based on the textile structure, size of the components, and location of the components on the body [60]. For example, the shoulder blades of stretchy garments can experience strains up to 20% [43]. So, if an e-textile developer wants to put electronics on shoulder blades, the electronic systems should be flexible enough to withstand this amount of strain. However, the bending radius of traditionally available flexible electronics such as flexible displays is as much as centimeters, whereas the bending radius of e-textile components is as small as millimeters [10]. Therefore, traditional electronics used in e-textiles are not as flexible as textile materials and are often unable to withstand strain during regular wear and tear.

The mass adaptation of e-textiles largely depends on the durability and scalability of the manufacturing process. However, very little research has been done to address the durability issues of e-textiles. Most of the time the focus is on the technological advancements of the system while mostly ignoring the durability issues. So far, a significant portion of the development of e-textiles has been done in craft systems where durability is the last thing to be addressed. However, durability is a major concern for commercially available e-textiles. Therefore, there is a huge research gap regarding the durability of e-textiles in the e-textile community.

2.10.4 Washability challenges for e-textiles

Unlike traditional electronics, e-textiles often need to be washed like regular clothing. Therefore, washability is a major concern for e-textiles. During washing, garments go through mechanical stresses and high temperatures as well as chemical resistance against moisture and detergents [60].

Washing can impact wearable electronics in several ways described below.

- **Electronics are water sensitive:** Many electronic components used in e-textiles are water sensitive and washing can significantly degrade their performance. In some cases, water can permanently damage electronic components and make the whole system useless.
- **The mechanical stresses during washing and drying:** The durability issues mentioned in the previous section also apply to washing. The mechanical stresses during washing can degrade the connections between traces and electronic components. Continuous washing and drying cycles can lead to unstable or even broken connections. Washing can significantly increase the resistance of the conductive wires or threads if they are not insulated [63]. In addition, the loose, hair-like components of conductive threads can entangle with each other during washing and create a short circuit [78]. By nature, fabric shrinkage occurs when fabrics are washed. Fabric can be pre-washed before integrating electronics to avoid that [78]. However, fabrics that wrinkle may still put additional strain on integrated traces and make the system vulnerable.
- **The chemicals used during washing:** The chemicals used in washing may negatively impact the useful life of electronics. For instance, oxidation may occur if electrical traces are exposed to water and detergent for a long period of time.
- **The use of high temperature during washing and drying:** Use of high temperature during washing can also impact joints if the materials used in the joining are temperature sensitive. For example, solder joints may melt if temperatures cross its melting threshold point, which can severely damage the connections of electrical circuits.

Several studies have been done on the washability of textiles. However, fewer studies have evaluated the washability of embedded electronics in textile applications [34,63]. These studies found that washability has a direct impact on the durability of e-textiles. Both electronic components and their connections are affected by water and moisture. In addition to water and moisture, fabric drying machines also significantly degrade the useful life of e-textiles. Further studies need to be done to validate feasible methods of protecting electronics during washing and drying.

2.10.5 Lack of availability of suitable protection methods for e-textiles

There are two popular approaches commonly used in e-textiles to protect sensitive electronic components from water and moisture. One approach is to make electronic components removable before washing (e.g., hexoskin.com) as shown in Figure 14 [24]. Currently, most available commercial e-textile garments are designed with only the printed or fiber-based conductive interconnects and electrodes integrated directly into the garment, and require the wearer to remove control circuits and power sources before washing. For instance, Phillips developed e-textiles with embedded mobile phones and GPS technology for kids with localized, removable electronics [81]. The major problem with that is that one needs to remove the electronic parts every time he or she wants to wash the clothing, which is not always convenient. In addition, all the components stay in a single compartment, which limits the spatial distribution of electronic components in different parts of the body and limits several functions of e-textiles. Moreover, consumers, in general, expect to be able to launder e-textile garments in the traditional manner. To ensure widespread use of e-textiles, washing of e-textiles should be as convenient as washing typical garments.

Therefore, electronics should be integrated into textiles as an integral part of the e-textile and they should be fully washable.

Another approach is to apply a surface treatment barrier to insulate and/or encapsulate the electronic component and therefore protect from mechanical stresses and moisture. One of the major problems with surface treatment is that the extra protection layer can cause the garment surface to become stiff, impermeable, and/or otherwise uncomfortable to the user. Therefore, the materials used for encapsulation should be protective, lightweight, flexible, and comfortable. Further, compatibility with textile and garment manufacturing processes is important for scalability.

Figure 14: Removable electronics [82]

Many commonly used fabrication techniques in electronics involve encapsulating components in a liquid-form impermeable coating. Epoxy resin or low-pressure injection hot melts can be used to seal small printed circuit boards (PCBs) whereas silicone and polyurethane (PU) encapsulations are more effective in larger areas [38]. A special UV curable resin can be used to seal a bare die on a PCB [38]. This approach is similar to the method developed by Linz et al. [37] for fabricating encapsulated, textile-integrated printed circuit boards where they used mold encapsulation (LOCTITE Hysol GR 9800) to protect a flexible PCB as well as the silver-coated polyamide traces.

Another approach to encapsulation is to apply an impermeable film on top of the protected area, on one or both sides. Berglund et al. [4] used fusible polymer film to insulate a stretch sensor. PU films were used by the company Stretchable Circuits to encapsulate LEDs [83]. Welding spots can also be encapsulated using PU film [38].

Neijad et al. used polymer coating (PDMS) to protect a strain sensor from environmental factors such as exposure to water and moisture [52]. They found that the hydrophobic nature of PDMS made the sensor less vulnerable to washing.

Tao et al. [84] used two different types of barrier protection methods to protect their electronic system. In their study, TPU films (thermoplastic polyurethane) were used to protect the conductive thread and electrical contacts, in combination with a full-surface barrier made of latex. They found that TPU films did protect the electronic components, and stiffer silver-plated-silver copper tinsel thread showed better resistance performance compared to the more flexible silver polyamide thread and nickel-plated copper wire.

Even though some of the materials and techniques mentioned above provided strong and reliable protection against washing and drying, they are not always suitable for the large e-textile application. For example, even though silicone is widely used to insulate electronics in e-textiles, it significantly affects the stiffness and handling of the fabric. Therefore, it might not be suitable for large-area applications. For example, consider a garment where electronics are distributed all over the body and many traces are routed through a garment. Adding silicone at each of the component locations and overall traces will make the fabric bulky and inconvenient for the user. Therefore, alternative materials should be explored for large scale e-textiles applications that will provide the same level of durability and protection as silicone does but add minimum stiffness to the fabric.

2.10.6 Challenges for automated mass manufacturing processes for e-textiles

The main reason behind dominance of labor-intensive operations in the clothing industry lies in the nature of the raw materials used in clothing. First, fabrics are soft and flexible, and they flex in all directions. Therefore, it is more difficult and expensive to develop automatic machines for performing sewing operations compared to electronic industry which primarily deals with rigid materials. Second, fabrics vary in extensibility. Both low-and-high extensibility pose challenges for assembly operations. Third, fabrics comes with different thickness and by using different layers of fabric, the thickness can very within the same product. Fourth, due to its handle, drape, and flexibility, sewing is still the preferred method of joining fabric. These characteristics of apparel manufacturing bring many interesting challenges for the integration of automatic technologies.

Several approaches have been explored for the mass production of electronic systems on textiles. Locher and Sefar [38] describes three major approaches of production of e-textile garments. One approach is to follow the business models of the mainstream wearable technology industry, where garment production and electronic systems are made separately, and later they are combined at the final stage. Another approach is to design the manufacturing process with proprietary equipment for a specific product that allows the textile and electronics systems to be more tightly intertwined. The disadvantage of this approach is that the manufacturing process will change every time in making a new product. The third approach utilizes the equipment of the PCB industry and thereby, develops a universal manufacturing process for different products. However, to enable this flexibility, the production costs increase significantly for equipment development. Depending on the product and the skillsets of a company, one approach might be more suitable than another.

Several other processes could be introduced in future manufacturing chains to develop a reliable, durable manufacturing process for e-textiles. Position adjustments using optical orientation, automated stenciling, and pick-and-place operation could be introduced to ensure high-volume production [51]. Low-temperature solders or conductive adhesives could be introduced in fabrication, since fabrics are usually more sensitive to heat than electronics. New testing tools and equipment should be developed for testing electronic components in textiles during manufacturing. The use of traditional electronic apparatus for testing such as flying probes and needle adapters might not be the ideal solution for the textile nature of the substrates [38]. Fraying of threads or fibril breaks in textiles may cause shorts and failure of the circuits. Manufacturing cost is another important issue. New machines and processes will add additional cost to the production of electronic-embedded textiles. The automated machines that are used in electronics fabrication may improve the overall accuracy and durability of the garment-integrated technologies.

2.11 QUALITY ASSESSMENT IN THE ELECTRONICS INDUSTRY

There are two main uses for a PCB inspection system [85]. A PCB inspection system should highlight any defects during the production process so that they can be corrected before they move to the next stage. It is extremely necessary to identify faults as early as possible in the production process. In addition, a PCB inspection system should provide feedback into the manufacturing process so that it can be adjusted to reduce or eliminate the occurrence of a given problem.

There are three major ways surface-mount electronics are tested in the electronics industry [85]. First, a manual inspection of the faulty system. This approach is costly and often produce poor results. Second, an automatic or automated optical inspection utilizes an optical system that compare an image of a newly assembled system to an image of a good assembly to detect any faults in the system. This type of inspection system is commonly used and operates very reliably. Third, an automated X-Ray Inspection, AXI, that is able to look under the chips to view the solder joints is more useful where solder joints are not easily visible. This type of inspection is more expensive and usually used for a small proportion of the solder joints. In the case of e-textiles, an inspection system that works well for a garment system might not work well for the electronics system or vice versa. For instance, a metal detector is commonly used in garment inspection to detect if there is any needle or metal in the garment during the final inspection. However, this might not be suitable for electronics inspection. Therefore, there is a need for the development of a new inspection system for e-textiles.

2.12 QUALITY ASSESSMENT IN THE APPAREL INDUSTRY

In the apparel industry, the quality of the product is assessed in terms of standards for fabric construction, design, and the finished garment. From the initial stage of raw materials to the final garment, quality is checked in almost every stage. Quality assessment is performed prior to production (pre-production QA), during production (production QA), and after production (post-production QA). Pre-production quality control involves testing of each component of the garment prior to assembling. Fabrics, interlining, accessories, etc. are evaluated before production. Quality assessment is also performed during each stage of garment production including pattern making, fabric cutting, assembling, pressing, and finishing. A final post-production inspection is performed once the whole garment is completed.

In the apparel industry, quality assessment is mostly done manually. In most cases, a visual inspection is performed to see if there are any faults in the garment. A measurement tape is often used to check the sizing of the garment. During the final inspection, a metal detector is often used to detect unwanted metals such as broken needles in the garment.

2.13 E-TEXTILE SYSTEM DESIGN FOR MANUFACTURING

Designing a workflow for the development process of an e-textile garment is necessary for the production of the garments. The e-textile system design involves disparate yet interdependent stages in a critical path. The functionality, comfort, and aesthetic of a smart garment are highly dependent on the coordination among stages. For an e-textile garment, the integration of technology should be considered simultaneously with the development of clothing throughout the product development process. A few studies discuss the design process of functional clothing. For instance, Suh et al. [58] suggested a design process model that involves five major steps: idea generation, design, prototype development, evaluation & design refinements, and production planning. The model derives from earlier work and gives a general guideline about steps involved in the e-textile products development.

Several design variables are involved in the e-textile garment development stages that determine what needs to be considered to make the finished garment functional, comfortable, and wearable. These design variables could be general or could be unique for specific e-textile garment development process depending on their applications. A few studies have considered the design variables for e-textile garments. Martin et al. [42]

identified eight design areas that were critical for designing e-textile garments including sensor behavior, physical movement, human body and motion, draping of clothing, networking, power consumption, manufacturability, and software execution. Dunne et al. identified five manufacturing variables that emerged for adding electronics into garments including stiffness, thermal and moisture management, flexibility/durability, sizing and fit, and device interface [15]. While Martin et al. [42] provided a guideline for general e-textile product development while emphasizing the development of a well-functioning electronic system, Dunne et al [15] mostly emphasized the wearability and comfortability of the e-textile garments. Neither study considered the process of making the e-textile system.

A few studies describe steps involved in designing a manufacturing method for e-textiles. For instance, McCann et al. [44] described a design process for electronic-embedded smart clothing that addressed end-user needs and involved seven major steps: Identification of end-user needs, textile development, garment development, integration of technology, garment manufacture, distribution/product launch, and end of life recycling. Koncar et al. describe a framework derived from the development process involved in designing a smart shirt that can assist visually impaired persons to navigate among obstacles in an indoor environment [3,31]. The e-textile shirt contains sensors, actuators, power supplies, and a data processing unit. Koncar et al. [31] identified ten steps that were used for the development of e-textile shirt: determination of requirements for the smart garment, determination of system components, integration of components into textile structure, garment design, electronic circuit design, microcontroller programming, development of prototype garment, testing and controlling of prototype, production, and quality testing. However, all these studies describe the fabrication process as one general step which was “integrate electronics” and neither specifically considered the sub-steps that are required during integration of electronics.

Several commercial e-textile manufacturing companies have also described techniques they used for the mass manufacturing of e-textiles. For instance, Elitac [86] describes four manufacturing steps in their production process: research and development, testing the electronic circuit, prototyping e-textile garment, and production. Another e-textile clothing brand Clothing+ uses a slightly different manufacturing strategy for their e-textiles manufacturing [87]. They use five major steps for manufacturing e-textiles and the steps are: material selection, designing the garment, development of the prototype, industrialize i.e. build scalable product and manufacture the e-textile garments. However, most of the currently available e-textiles companies use off-the-shelf circuit boards where the circuit board is developed separately from the actual garment and the circuit board is later attached to the garment with some joining techniques such as those described earlier.

Summary

The above studies provide an overview of designing a process for e-textile garment at a conceptual level, but none of them explicitly identify the known and unknown challenges of making e-textile garments. Most of the industrial processes primarily focused on developing e-textile circuit separate from the apparel manufacturing process. When the distribution of electronic components over the garment is necessary, it is often not possible to centralize or isolate the processes used to attach electronics from those used to assemble the garments. Hence, the integration of technology into apparel should be performed simultaneously while performing apparel manufacturing processes. The garment and the electronic system are much more tightly intertwined than simple attachment of a stand-alone system to a stand-alone garment and a more granular understanding of the steps of the "integrating electronics" process is needed to facilitate manufacturing. These integration challenges are more nuanced and detailed for processes that involve spatially distributed electronics and fully-embedded e-textiles, and even more so in a CMT factory setting in which manual labor forms the basis of most of the assembly process. Therefore, there is a gap in literature to develop a more comprehensive manufacturing process that can address all the nuanced and detailed steps involved in the e-textiles manufacturing process.

2.14 Overview of research and research questions

Chapter 2 provides a state-of-the-art review in the field of e-textile garments development processes both in academia and industry. In addition to the review of the e-textile garments development processes, I have also pointed out the gaps in the literature when discussing individual topics. In the following section, I will start with the three major objectives of this dissertation project and later break down the major objectives into several research questions and sub-questions. I will point out the research gaps under each research question and how I am proposing to address them in this dissertation work. As described in Chapter 1, this dissertation project has three major objectives:

Objective 1: Develop an effective and efficient manufacturing method for integrating electronics into a garment while minimizing the need for new equipment in a cut-and-sew environment.

Objective 2: Implement this method in a test prototype manufacturable garment.

Objective 3: To evaluate the impact of technology integration on the labor, equipment, and cost of manufacturing via a case-study manufacturing process.

In the previous sections, I have discussed several e-textiles fabrication methods such as printing, embroidery, weaving, and knitting [32]. Though some of these techniques provided satisfactory results in developing successful e-textile prototype products, most of these techniques are custom-made techniques that utilize proprietary equipment in a laboratory setting with specific applications in mind. While craft construction of textile-integrated electronics is common [9], these techniques are typically not efficient enough for larger-scale production. Furthermore, when manufacturing e-textiles in mass, the current mainstream wearable technology industry typically manufactures electronic systems and apparel as separate processes, and systems are later combined at the end. However, the garment and electronic system are more tightly intertwined than the simple attachment of two uniquely different materials and a more advanced level of integration is necessary for fully embedded e-textiles. The few e-textiles developers that produce textile-based electronic-embedded technology typically use proprietary equipment which is a major obstacle to developing a universal manufacturing process for e-textile products. Forster Rohner, for instance, uses proprietary LED packages (limiting potential translation of the technique) [76]. Some e-textiles companies still use hand-made techniques in manufacturing e-textiles which aren't suitable for large scale applications. Therefore, industrial fabrication of e-textiles requires an efficient, scalable process with an emphasis on automation. It is very clear that there is an urgent need for development of a durable, reliable, and scalable fabrication method for e-textile circuits and textile-integrated electronics, which remains one of the most persistent obstacles to large-scale development of garment-integrated applications of wearable technology. Further, the barriers to textile- and garment-integration have restricted the ability to spatially distribute technology over the body surface, particularly sensing and actuating components that may rely heavily on or be strongly affected by their specific location on the body. For example, without motion sensors distributed over the body, a system that relies on activity recognition can only recognize movements of one point on the body. Actuators and displays that may benefit from spatial distribution for resolution and bandwidth (such as tactile displays) or accessibility and usability (such as for visual displays) are similarly limited when restricted to a single location. At the same time, it remains difficult to fabricate electronic circuits on substrates as flexible and complex as textiles. When electronic components must be integrated all over a garment surface, it is often not possible to centralize or segregate the processes used to attach electronics from those used to assemble the garment [55]. Therefore, methods that are feasible within the constraints of existing CMT apparel production would lower the barrier to larger-scale manufacturing of smart garments. However, such methods must also produce e-textiles that are durable enough to withstand the conditions of everyday wear. This dissertation aims to fill out the gap in literature while addressing all the challenges discussed earlier. Hence, the first objective of this dissertation project is:

Objective 1: Develop an effective and efficient manufacturing method for integrating electronics into a garment while minimizing the need for new equipment in a cut-and-sew environment.

To fulfill this objective, I explored all the fabrication methods for e-textiles currently available in academia and industry. As discussed in Section 2.5, each manufacturing method has its pros and cons and none of them has the complete solution for all the issues that arise during manufacturing of e-textiles. After careful consideration, I decided to focus on the manufacturing technique of "attaching traditional electronic circuit components to the surface of a textile". As discussed in Section 2.5.3, this kind of hybrid manufacturing process leverages the benefits of the electronics industry by using standardized electronic components and the textile industry by using the manual methods necessary to join flexible textiles, and therefore minimizes the need for new equipment in a cut-and-sew environment. Moreover, this work is motivated by an emphasis on developing hybrid manufacturing processes that facilitate distribution of only those components of a system that rely on spatial localization, while continuing to leverage the durability and manufacturing efficiency benefits of centralized electronics. Further, it explores the potential of the apparel or sewn products factory as a key partner in fabrication of the distributed portion of the system, without imposing a radical change to the technology, capability, or workflows of a typical cut-make-trim (CMT) apparel fabrication facility.

In our lab, we have developed a stitched method of fabricating e-textile circuits with surface-mount components [5,51]. The method provides a generic process of developing e-textiles where traces and interconnects are stitched to a textile substrate, and surface-mount components are populated using reflow soldering techniques. There are several benefits of using stitching in the e-textiles manufacturing process, some of them already mentioned in the background section. Unlike other e-textile fabrication methods, such as weaving and knitting, where routing and interconnections are defined by the structure of the fabrics, stitching provides flexibility benefits, as well as relatively un-constrained layout patterns. Stitching provides durable interconnections to the e-textile structure and is widely used as the most dominant process for garment assembly. Soldering is one of the most popular techniques for joining electronics. Soldering provides strong connections between the components. Standard commercial off-the-shelf surface-mount electronic components are utilized for this work. These off-the-shelf components are widely available which means they are easily suitable for standardization of the method, which is one of the major drawbacks of some of the leading e-textiles manufacturers. Unlike other e-textile components where electrical performance needs to be compromised to some extent to adjust the feel and shape of textiles, off-the-shelf electronic components provide the best electrical performance.

Once the manufacturing method is established, the next step is to evaluate the effectiveness of the method. The next research question addresses durability of the manufacturing method.

Research Question 1: Is the stitched e-textile fabrication method durable and reliable?

To answer this question, I tried to answer several sub-questions that would lead me to the answer to the final question.

Sub-question 1.1: Can the textile-embedded circuitry able to withstand regular wear and tear? If yes, then how long?

To answer this question, we have developed e-textile swatches using the manufacturing method. Later, e-textile swatches were tested using a tumble dryer for hours to simulate regular wear and tear. Swatches were tested after each drying cycle to measure the functionality of the electronic system.

Sub-question 1.2: Do implementation variables of trace width, component size, and trace orientation affect durability?

To answer this question, we experimented with different types of fabrication variables for the stitched-based fabrication method including trace width, trace orientation, and component package size and evaluate their effect on durability of the e-textile swatches.

Sub-question 1.3: What are the major sources of joint failures and can they be improved upon?

After a thorough analysis of the failed systems, we identified some of the major reasons behind system failures. Later, we refined the manufacturing process for solder deposition and reflow. Durability testing was performed again to ensure that the refined method could produce more durable e-textile products than the original method.

Sub-question 1.4: How can we make the process reliable and scalable?

To test the reliability of the process, hundreds of e-textile swatches were made and tested to ensure test results showed consistent results all the time. Later, to test the scalability of the method, several craft-based tool and machines were replaced with machines and tools that are currently available in the industry and has potential for mass-production with no or minimal modifications.

Section 3.1 in Chapter 3 discusses all the above questions in detail. The results of each study were described in detail and abstract challenges of manufacturing stitched-based e-textiles are identified and addressed.

The next manufacturing variable I decided to evaluate was the washability of the manufacturing method. While technical development of wearable interactive devices tends to focus on the interaction of the user with the embedded functionality, for garment-integrated applications the needs of the embedded system must be balanced with the needs related to interacting with the garment itself – in terms of qualities like comfort, hand-feel, and maintenance behaviors. To reiterate the importance of washability of e-textiles, textile-embedded circuitry often must be machine-washable to conform to user expectations for care and maintenance. While consumers, in general, expect to be able to launder e-textile garments in the traditional manner, washability presents additional challenges for durability of e-textiles, as discussed in the previous chapter. Hence, my next research question addresses the washability of e-textiles developed using the manufacturing method.

Research Question 2: ***How does laundering impact the durability of stitched surface-mount e-textiles?***

Under this research question, the following sub-questions were addressed:

Sub-question 2.1: Is textile-embedded circuitry able to withstand regular washing and drying in a home environment? If yes, then for how long?

To answer this question, I extended the fabrication technique and durability test method to evaluate its robustness during home laundering. More test samples were developed and tested using a home washing machine and a dryer for hours. The functionality of the samples was later tested to evaluate the effect of launderability on the durability of stitched surface-mount e-textiles.

Sub-question 2.2: Do implementation variables of fabric structure, component size, intensity of the wash and dry cycles affect the durability of stitched surface-mount e-textiles?

Similar to the durability testing, the launderability test samples were developed with varying fabric structure, component size, and intensity of the wash and dry cycle and evaluate their effect on durability of the e-textile swatches. Section 3.2 describes the launderability test of the stitched surface-mount e-textiles.

For my next research question, I looked for ways to protect the circuit components in the e-textile prototypes. As discussed in Section 2.10.5, most available commercial e-textile garments are designed with only the conductive elements (printed or fiber-based conductive interconnects and electrodes) integrated directly into the garment, and require the wearer to remove more complex circuits before washing. However, if we want to make e-textiles as user friendly as clothing, they should be treated the same way as regular clothing. Rather than removing electronic parts every time one wants to wash the e-textile garment, we should find a way to protect all the e-textile components so that they can be washed like a regular garment. However, for this particular study, we decided to use a removable battery as a power source as we were primarily focused on protecting surface-mount components and other conductive elements (e.g. conductive traces). Several studies have mentioned that encapsulation materials might be able to protect e-textile components from mechanical and chemical reacting during washing [37,63]. However, previous research primarily focused on using silicone or similar techniques which are more common in the electronics industry. These insulation materials add some weight and create a rough surface on the textile, which introduces some discomfort and inconvenience for the users. This leads to my next research question:

Research Question 3: Does insulation help to protect the e-textile structure from laundering?

The following sub-questions were asked to answer the above question.

Sub-question 3.1: Does insulation material protect the surface-mount electronic components (both electronics and conductors) from the effects of water during washing?

To answer this question, we explored different types of film-based encapsulation methods to improve the protection of the e-textile components. Several new samples were developed while varying insulation materials, textile structures, and component types. Samples were later tested using a home washing machine. The functionality of the samples was tested to evaluate the effect of insulation on the durability of surface-mount e-textile components.

Sub-question 3.2: Can film-based insulation material be an effective alternative to traditional insulation materials?

To answer this question, several non-traditional film-based insulation materials were tested along with more traditional insulation material such as silicone. The results were later compared based on the functionality of the e-textile components and their effect on the fabric stiffness. Section 3.3 describes the launderability test of the insulated stitched surface-mount e-textiles.

The research questions under Objective 1 describe the development and evaluation of a stitched-based manufacturing method. In those studies, simple e-textile swatch samples were developed to evaluate the effectiveness of the method. Once we have an effective method, the next goal is to see if the method can be applied toward the development of more complicated system structures. Which leads to my next major goal of this project:

Objective 2: Implement this method in a test prototype manufacturable garment.

To fulfill this goal, the following research questions and sub-questions were introduced:

Research Question 4: Is it feasible to use the method to produce garment-scale e-textile products?

Sub-question 4.1: What new fabrication and manufacturing variables must be addressed when deploying the stitched-based surface-mount method to produce more complex circuits?

Sub-question 4.2: What are the implications of electronics integration for apparel manufacturing workflows?

To evaluate the feasibility of the method for garment-scale products and mass production, the method was extended to more complicated e-textile structures. Several e-textile prototypes were developed of increasing complexity, ranging from a swatch to a complete garment. The development of these prototypes served as an exploratory investigation to discover known and unknown challenges of implementing the method for developing garment-scale e-textile products. From the study results, manufacturing variables were identified and described in detail. A universal framework has been developed particularly for the stitched-based e-textiles product-development process. Section 3.4 describes the complex structures developed using the manufacturing method & 3.5 describes the framework for e-textile manufacturing.

The third and final objective of this dissertation project is:

Objective 3: To evaluate the impact of technology integration on the labor, equipment, and cost of manufacturing via a case-study manufacturing process.

All of the above research questions tried to evaluate the effectiveness of a new manufacturing method for e-textiles and explore what can we do to ensure that the proposed method is efficient, durable, and reliable. These research questions also help us to enhance our understanding on the product development process for e-textiles. However, these research questions don't answer whether the method could be translated into the production of e-textile garments at a larger scale. Manufacturing e-textiles in mass likely involves additional processes and variables not addressed when developing a prototype or individual sample. There could be some manufacturing variables such as equipment, tools, processes which are unique for large scale production and typically ignored during prototyping e-textiles in a laboratory setting. Furthermore, there is a gap in literature in finding the underlying challenges of e-textile manufacturing especially determining the tasks and variables that emerge when manufacturing methods are deployed in a CMT factory setting. The next step of this dissertation aims to identify and explore these potential new factors. Therefore, I proposed the following research question:

Research Question 5: What are the tasks involved in transitioning from prototype development stage to the deployment stage in a factory setting? What additional manufacturing variables emerge during the deployment of the e-textiles manufacturing process?

To answer the above questions, I developed an example e-textile prototype garment which could be later produced in higher-volume production in a CMT factory case study scenario. Here, my goal is to identify the more abstract challenges involved in transitioning from one-off production to a larger-scale context in a CMT factory setting, somewhat independently of the operations used. The main reason behind selecting the case study method is that a case study method is narrowly focused, provides a high level of detail, and can combine both subjective and objective data to obtain an in-depth understanding. Since the manufacturing of e-textiles is a very new area and has not yet been the focus of substantial attention in academic research, a thorough and in-depth analysis of the area is required. The case study method would be useful to provide insights about the variables involved in transitioning from prototype to deployment stage and identify challenges in mass manufacturing of e-textiles. The method can later be used to develop a universal e-textiles manufacturing process that can be deployed in any CMT factory with no or minimum modification of the existing facilities. Chapter 4 discusses the development of example e-textile garment prototype and the tasks involved in transitioning from prototype development to the deployment stage in a factory setting. Which leads to my next research question:

Research Question 6: What is the impact of technology integration into a garment in terms of labor, equipment, and cost during manufacturing of e-textiles as compared to a standard garment?

To answer this question, forty regular and forty sensor-integrated e-textile garments were produced. To determine the impact of technology integration into a garment during manufacturing of e-textiles as compared to standard garments, machines and tools, time, cost, efficiency, and operation workflow for forty regular and forty sensor-integrated e-textile garments were assessed. The ultimate goal of the study was to determine how different it is to mass-produce e-textiles in terms of machine and tools, time, cost, and operation process as compared to regular garments.

Research Question 7: What are the factors that affect the quality and efficiency of e-textile garments?

To answer this question, the major elements that determine the effectiveness of a manufacturing process at the mass level (e.g. efficiency, quality, use of industrial machines and tools, etc.) were assessed. Here, especial focus was on determining the effect of these variables on the overall scalability of the method. Furthermore, a thorough analysis of the manufacturing process and a post-production quality assessment were performed to identify new variables emerging from the case study e-textiles manufacturing process that could be later investigated for future development. Chapter 5 addresses the last two research questions in detail. In the next chapter, I will describe the methods and techniques I used to answer each of my research questions followed by results and discussions.

CHAPTER 3: DEVELOPMENT OF A FABRICATION METHOD FOR E-TEXTILES

This chapter is a combination of several projects related to manufacturing of e-textiles that I have been working for the last two years. All the work presented in this chapter is the result of direct collaboration between me and my colleagues at the Wearable Technology Lab. Due to the highly interdisciplinary nature of this project, a major part of this chapter was collaborative. The development of a fabrication method for e-textiles and the rigorous testing of the method was crucial to determine the feasibility of the method for production and to identify the major tasks and challenges involved in transitioning from prototype development to the deployment stage in a factory setting. While the beginning part of this Chapter is mostly collaborative and performed in a laboratory setting, the latter part of the chapter is my synthesis of these experiences to inform a more abstract e-textile garment prototype development process. The knowledge learned from the collaborative work was further analyzed and summarized for e-textile garment manufacturing in general. All of the prototypes and testing described in the beginning part of the chapter was used to validate the method could be implemented in a factory setting to produce e-textile garments in mass. I would like to thank everyone for their time and effort to successfully completion of the work mentioned here. There have been many people who provided guidance, support, constructive feedback, and suggestions throughout the process. I am grateful to everyone. I will try to credit each individual who has provided a significant intellectual contribution to the project after the end of each project.

3.1 DURABILITY TESTING

Building on prior work that established a generic process where traces and interconnects are stitched to a textile substrate, and surface-mount components are populated using reflow soldering processes, here we evaluate in more depth the parameters of trace design and their effect on durability, refine the manufacturing process for solder deposition and reflow. As discussed earlier, this section addresses following research question and sub-questions.

Research Question 1: Is the stitched e-textile fabrication method durable, reliable, scalable?

Sub-question 1.1: Can the textile-embedded circuitry able to withstand regular wear and tear? If yes, then how long?

Sub-question 1.2: Do implementation variables of trace width, component size, and trace orientation affect durability?

Sub-question 1.3: What are the major reasons of system failures and can they be improved upon?

Sub-question 1.4: How can we make the process reliable and scalable?

The following section describes the fabrication method of stitched surface-mount e-textiles.

3.1.1 Methods: textile circuit layout and durability testing

Test Samples: Characteristics and methods

This evaluation [51] leveraged the method established by Berglund et al. [6], in which interconnect traces are laid onto a textile substrate using a lockstitch sewing machine. That work used a Brother PR-650e commercial embroidery machine, however, which was found to be sub-optimal for 2D geometries due to the different tension requirements of lateral (needle moving side-to-side and up-and-down) vs. progressive (needle moving only up-and-down) stitching. Here, we used a Brother BAS-342G pattern-stitching machine, which differs from an embroidery machine in that it produces a continual progressive stitch (rather than a combination of progressive and lateral stitches), where the textile substrate is moved in X and Y directions but the needle moves only along the Z-axis. This preserves the geometric relationship between the needle and the bobbin, resulting in a more consistent stitch tension. As with [6] we used Syscom Liberator 40 silver conductive thread in the bobbin, with common cotton/poly sewing thread in the needle. The machine's tension was adjusted so that the conductive thread floated on the bottom side of the fabric. This thread is not insulated, and stitched traces were not subsequently insulated prior to testing. A common substrate fabric (100% cotton canvas) was used for all samples (see Figure 15).

Figure 15: Stitching conductive traces using Brother BAS-342G pattern-stitching machine

Following the method in [6], samples of a 5-LED parallel circuit were created in two basic layouts: a "parallel" layout where the connecting traces meet the LED package parallel with its axis, and a "perpendicular" layout where traces meet the package perpendicular to its axis (Figure 16). Three LED package sizes were used, 1mm (0402), 3mm (1206), and 5mm (6-PLCC). Finally, the width or thickness of the trace was varied with redundant stitch lines, in conditions of 2 stitch lines, 4 stitch lines, and 6 stitch lines. Five samples (each with 5 LEDs) were created in each condition with the exception of the 6-stitch condition for 1mm LEDs, for a total of 80 swatches (and a total of 400 LEDs, or 800 solder joints).

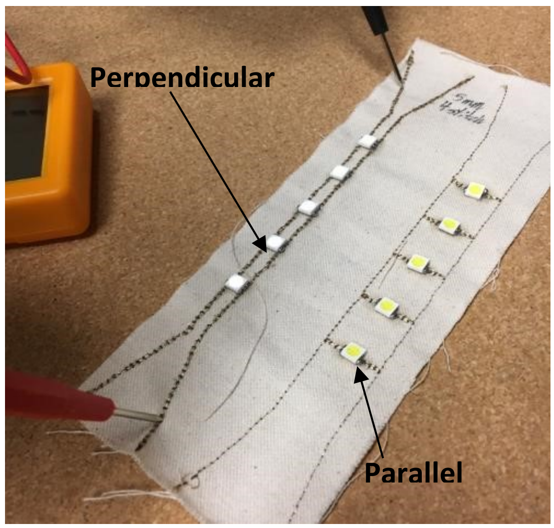


Figure 16: Trace orientations

Importantly, precision in trace layout in the stitched method is not as direct as it would be in a CAD-based traditional PCB fabrication process. Table 1 outlines the stitch spacing at the package pad location in the Brother PS-300B pattern layout software that produced the optimal match between trace and component package. Note that for the parallel architecture, stitches are placed much closer together to account for the pull-back that happens when the stitch direction is reversed.

	Perpendicular			**Parallel**		
	1mm	3mm	5mm	1mm	3mm	5mm

2 Stitch	1.40	1.90	4.80	0	1.50	2.70
4 Stitch	1.80	2.10	4.90	0.68	1.68	2.28
6 Stitch	n/a	2.50	4.83	n/a	1.98	2.68

Table 1: Stitch Spacing for Swatch Conditions

Low-melt solder paste (ChipQuick) was used to attach the LED packages to the stitched traces. Solder paste was applied manually, and melted in an oven at 143°C for 6 minutes. Maximum reflow soldering temperature for 1mm and 3mm LED packages were 260^0C ± 5^0C for 5 seconds, and for 5mm LED package it was 260^0C ± 10^0C, per the manufacturer's specifications. 1mm LEDs were soldered using a manual heat-gun reflow process, due to excessive effects of surface tension on the very smallest packages.

Durability test methods

The developed samples were initially tested to ensure all LEDs were functional by applying a nominal 5V power source. Subsequently, all swatches were tested together using the tumble test method described in [6]: they were placed in a home tumble dryer along with 5 hand towels and 3 tennis balls, and tumbled on the "cool" setting for a pre-determined time increment: 5 increments of 1 minute followed by 18 increments of 5 minutes, 3 increments of 10 minutes, 2 increments of 15 minutes, 3 increments of 30 minutes, 2 increments of 60 minutes, and 4 increments of 120 minutes. The test time was increased at such point as failures leveled off, resulting in all swatches being tested for a total of 845 minutes. At the conclusion of each increment, all swatches were removed and tested for LED functionality, and any LED failures were recorded. All failed joints were photographed using a microscope lens 30X magnification. We took two pictures from opposite directions to get the best viewing angle of each broken joint.

3.1.2 Results and discussion: Preliminary durability testing

Durability effects of layout variables

A total of 170 of the 400 LEDs (42.50%) stopped working after the final tumble test – however, as all failures were caused by one of two joints, this can be interpreted as 215 of 800 joints or 26.88%. Overall, as seen in figures 23-25, failures increased quickly in the first 90 minutes of tumble testing, and then more gradually thereafter.

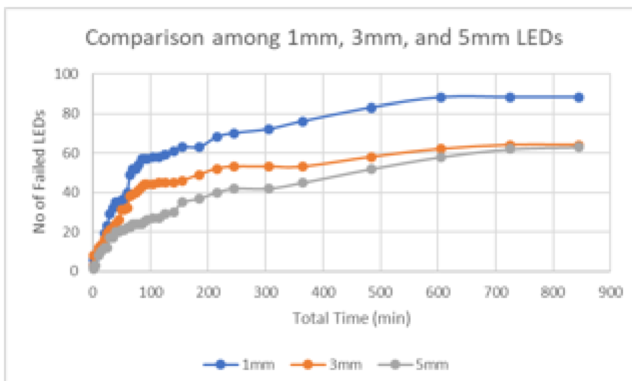


Figure 17: LED failures by package size

Of the 3 package sizes, the test results indicated that the 5mm LED was the strongest by a slim margin, representing only 29.30% of the total failed connections (63 out of 215), followed by the 3mm LED (29.77% of the total failed connections, 64 out of 215) and the 1mm LED (40.93% of failed connections, 88 out of 215) (Figure 17). Out of the total LEDs tested for each size, the 5mm LED had a failure rate of 21% (63 out of 300) whereas 3mm LED and 1mm LED had failing rates of 21.33% (64 out of 300) and 44% (88 out of 200) respectively.

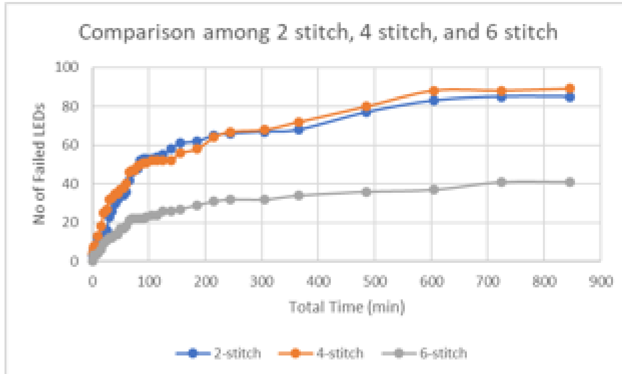


Figure 18. LED failures by trace width

The 6-stitch trace width was stronger (22.33% of failures, 48 out of 215) than the 4-stitch (38.14% of failures, 82 out of 215) and 2-stitch (39.53% of failures, 85 out of 215) (Figure 18). Out of all the swatches tested in each trace width, the 6-stitch trace width had the lowest failure rate of 24% (48 out of 200) whereas 4-stitch trace and 2-stitch trace had failing rates of 27.33% (82 out of 300) and 28.33% (85 out of 100) respectively. However, performance across trace widths was more similar than any of the other variables. (In Figure 24, NB that there were only 200 6-stitch samples total, as compared to 300 of each of the other two widths.)

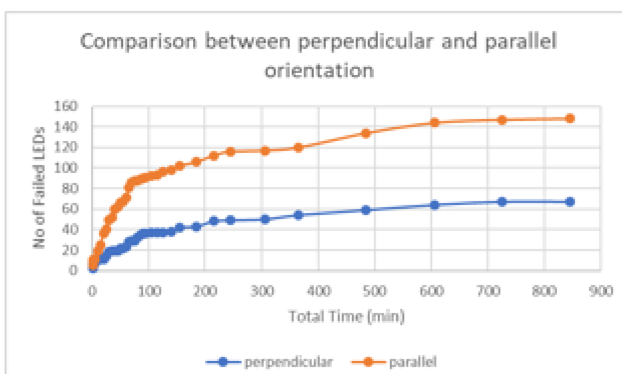


Figure 19. LED failures by trace orientation

As shown in Figure 19, perpendicular traces showed better performance compared to parallel traces. Perpendicular traces represented 31.16% of failures (67 out of 215) vs

68.84% for parallel (148 out of 215). Out of the total number of swatches tested, only 16.75% (67 out of 400) of perpendicular traces failed compared to 37% of parallel traces (148 out of 400).

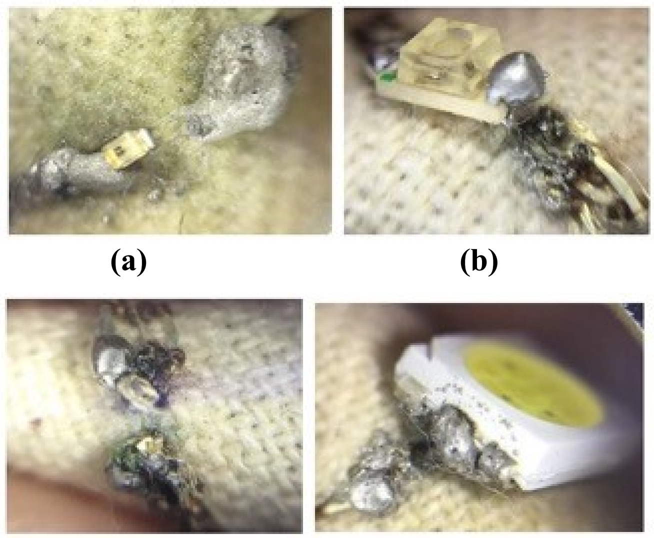
Across the 6 sample conditions, 3mm 4-stitch had the best durability, with 12% failed connections, followed by 5mm 2-stitch (18%), 5mm 6-stitch (22%), 5mm 4-stitch (23%), 3mm 2-stitch (25%), 3mm-6stitch (27%), 1mm 2-stitch (42%), and 1mm 4-stitch (46%) respectively.

Sources of failure

Based on the photographs of failed joints, type of failure was characterized into 4 major categories: a failure between the solder joint and the LED pad (with the pad intact, 47.91%, 103 out of 215 total failures), a failure between the solder joint and the thread trace (44.65%, 96 out of 215 total failures), a failure within the solder joint (2.33%, 5 out of 215 total failures), and a failure within the LED package (separation of the lead pad from the package, 5.12%, 11 out of 215 total failures). These failures are depicted in Figure 20 (a-d). No observed failures occurred within the stitched traces themselves.

By observation, these types of failures were caused mainly by the following conditions: variations in the amount of solder in the joint, quality of the solder joint (cold joints vs. true joints), and quality of the mechanical connections formed by solder between LED & fabric, LED & solder, and solder & thread. Out of 215 connection failures, 81.40% (175) of connections had too much solder whereas 18.60% (40) had too little solder; 67.44% (145) connections were well-formed joints whereas 32.56% (70) connections were cold solder joints; 61.40% (132) had strong mechanical connections between LED fabric and 38.60% (83) had poor connections or did not have any connections at all (meaning the geometry of the solder joint lifted the LED away from the surface of the textile); 78.14% (168) had strong mechanical connections between LED & solder and 21.86% (47) had poor connections; and 67.91% (146) had strong mechanical connections between solder & thread and 32.09% (69) had poor connections.

Cold solder joints significantly affected 1mm LED failures (31 instances). Since we manually attached these LEDs in this condition, solder was not properly reflowed for



(a) (b) (c) (d)

Figure 20. Types of joint failure: (a) between solder joint and LED lead, (b) between solder joint and thread, (c) within LED, and (d) within solder joint

some of the samples and caused poor connections. For 5mm and 3mm, the quality of reflow in the solder joints was less of an issue since they were baked in an oven. Too little solder was the major cause of failures for both 3mm and 5mm LEDs (39 instances), whereas poor connections between fabric & LED (13 instances), LED & solder (31 instances); and solder & thread (54 instances) also played important roles.

From the observed durability test, with an overall failure rate of less than a quarter of connections over a test period of 14 hours of continuous high-intensity wear, it appears that surface-mount soldering of components to stitched conductors is a feasible method of joining e-textiles. However, several challenges were identified in the durability analysis that, if effectively addressed, may significantly improve the durability of the method. Chief among these are more precise control of the amount of solder deposited, and the quality of the reflow joint. In the first case (solder deposition), poor adhesion between the complex surface texture of the stitched textile and the solder paste makes techniques like stenciling challenging. In the latter case (joint quality), there are two major challenges: first, the melting point of low-temperature solder paste (here, 143 °C) is close to the temperature at which cotton begins to scorch (~200 °C). (NB that cotton has one of the lowest burn points of common apparel fibers, however, it is also a very popular fiber for clothing). Second, the reflow conditions and timing must be controlled to combat the tendency of solder to either wick along the twisted multi-filament thread structure (too much wicking results in an inadequate amount of solder at the location of the joint, and therefore a weak joint) or "ball up" into a sphere as surface tension dominates over attraction to the complex topography of the thread trace. Further, the complex topography of the trace/solder/component relationship lends itself to a greater frequency of "tombstoning" effects where reflow happening at one joint before the other creates surface tension that pulls the component into a vertical position before the second joint can reflow.

3.1.3 Method refinement

Based on the results of the previous test, 1 mm LEDs were excluded from our experiment due to both poor durability performance and challenges of manufacture (1mm may represent a "lower bound" of resolution for our method at this time). Further experiments used 3 mm and 5 mm packages only. As thickness of the conductive trace had less impact on the overall quality of the connection, only 2-stitch thicknesses were used going forward. While 4-stitch and 6-stitch traces do provide more surface area for the solder joint, the additional thread used (particularly in the very heavy 6-stitch configuration) gives the traces an added thickness that limits the flexibility of the circuit, and differences in reliability of the trace widths between 2- and 4-stitch configurations were minimal. Finally, perpendicular traces had better durability than parallel traces and were used exclusively in further testing. Development of the manufacturing method focused on refining the two key areas of solder deposition and reflow conditions.

Solder deposition

To reduce the variability in amount of solder applied to the traces, we developed a solder stencil which replicated an approximate shape of the LEDs' lead pads to allow solder to be applied in an exact position over the stitched traces (Figure 21-left). Solder was

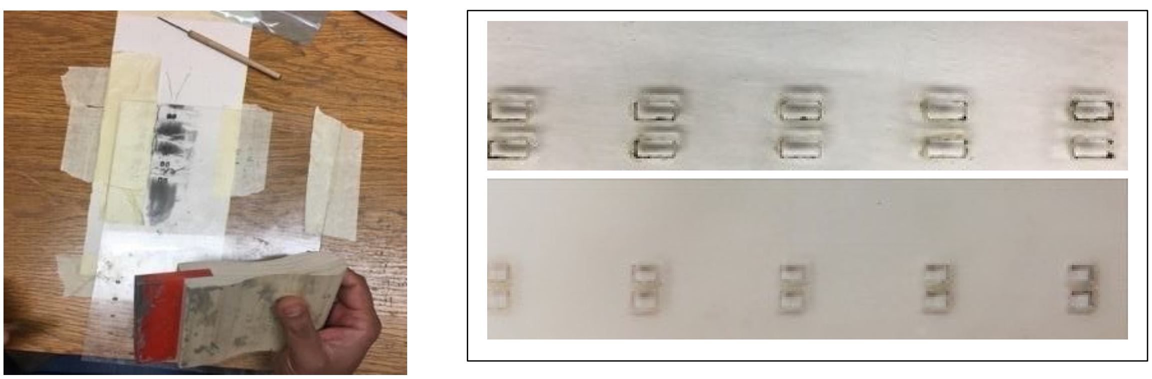


Figure 21: Solder deposition: solder paste screening through the holes onto the fabric via a printmaking squeegee (left) and 3mm solder mask (bottom) & 5mm solder mask

"screened" through the holes onto the fabric via a printmaking squeegee. Solder paste was mixed with an equal amount of gel flux, to lower the viscosity of the solder for easier application and better adherence to the rough surface texture of the stitched textile.

Stencil thickness and pad hole sizes were increased incrementally until a reliable connection was formed for all LEDs on a swatch. Mylar 1/16 inch (62.5 mil) thick was ultimately used and provides an ample, yet consistent amount of solder passing through the mask. Final hole sizes of 1.3mm x 2.1mm for 3mm LEDs and 1.8mm x 4.7 for 5mm LEDs were laser-cut from the mylar sheet, as shown in Figure 21 (right). However, our investigation showed that mylar thickness more than hole size is the best determinant of solder application quantity.

Reflow conditions

Radiant reflow heating in an oven produced uneven results, as discussed in the previous section. Method refinement focused on transitioning from radiant heating to direct-contact heating using a press. In addition to providing a more even distribution of heat, the press puts pressure on the LED packages to counteract the force the molten solder's surface tension enacts on the LEDs that leads to "balling up" and "tombstoning".

Reflow method development involved experimentation with the time and temperature used, and three different heat presses designed for garment pressing and t-shirt printing. Ultimately, the resulting method used a PowerPress industrial plate heat press. 5mm LEDs were soldered at 200 °C for 60 seconds, and 3mm LEDs were soldered at 215 °C for 60 seconds. For the 5mm 6-PLCC chip package, contact with the press melted the plastic chip carrier before reflow was complete. To mitigate this effect, we used a light fabric press cloth on top of the LEDs.

3.1.4 Refined manufacturing method tumble test

Using the refined method, 20 samples were produced using the 2-stitch trace width and parallel trace orientation, both for the 3mm package size and the 5mm package size. Swatches were stitched, stenciled, and populated using the methods previously described.

100% of LEDs were functional immediately after manufacturing (no re-work was required).

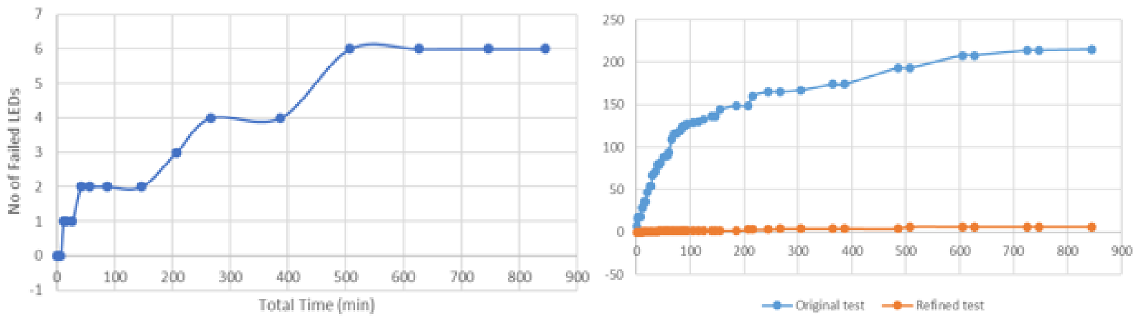


Figure 22: Refined manufacturing method tumble test: LED failures at each time increment, refined method (left) and LED failures over time for refined method as compared to original method

The test procedure from the previous test was repeated for these samples. To replicate the previous experiment, we used 3 tennis balls and 5 towels. In addition, we included 20 old samples along with the 20 new samples in the tumble dryer, so that the mechanical conditions of the test were held constant. Old samples were not measured for durability during this test. Figure 22 (left) shows the number of joint failures over time for the refined manufacturing method. In Figure 22 (right), durability for the new method is compared to the original method.

As seen in Figure 22, only 6 of the 200 LEDs (3% of solder joints) stopped working after 14 hours in the second tumble test. Of these, one 3mm LED did not light up even though its solder joints were intact and conductive (it's possible the component failed in another way). Of the 2 package sizes, the 5mm package had the strongest connections with zero failures (compared to 18% failure for the same conditions in the previous test). The 3mm package had 6 connection failures (6%) which was dramatically lower than the previous test (25%, 25 out of 100).

For the refined method, two major types of failures were identified: between the solder joint and the LED lead (2 instances), and between solder and the conductive thread (4 instances). None of the other previously-observed failures occurred. Failures were caused by poor mechanical connections between the LED and solder and LED and thread, which we believe is due to some lingering variability in the amount of solder deposited, particularly for the smaller package. Package alignment with pads (which was done manually) may also have affected joint quality.

3.1.5 Summary

In summary, this work has demonstrated the feasibility of developing a scalable, durable method of surface-mount fabrication of stitched e-textile circuits. While only small-batch production was conducted, reliant on manual stenciling and population of the stitched substrates, we believe these methods could ultimately translate to higher-volume production using automated stenciling and pick-and-place operations. Further, the method leverages technologies that are common to apparel and sewn product manufacturing. As such, it may present a compelling alternative to traditional hard-goods electronics manufacturing for smart clothing and textile-integrated wearable technologies.

Acknowledgement: I along with Steven Goodman, Nicholas Schleif, Mary Ellen Berglund, and Dr. Lucy Dunne were primarily involved in various stages of this work. Steven Goodman and I together designed the method, developed the samples, performed all the testing. I also performed results analysis. Nicholas Schleif and Mary Ellen Berglund initially developed the method [5] and provided insights at different stages of this project.

3.2 LAUNDERABILITY TESTING: LAUNDERABILITY TESTING WITH NO INSULATION

As discussed earlier, textile-embedded circuitry often must be machine-washable to conform to user expectations for care and maintenance. This section describes launderability testing of the e-textile samples. As discussed earlier, this section addresses the following research question and sub-questions related to washability.

Research Question 2: ***How does laundering impact the durability of stitched surface-mount e-textiles?***

Sub-question 2.1: Can the textile-embedded circuitry able to withstand regular wash and dry in a home environment? If yes, then how long?

Sub-question 2.2: Do implementation variables of fabric structure, component size, intensity of the wash and dry cycles affect the durability of stitched surface-mount e-textiles?

In this work, we extended our method to evaluate the robustness of home laundering of the surface-mount fabrication for e-textile circuits [25]. We performed a durability test based on machine washing and drying while varying the textile substrate, component size, and intensity of the laundering cycle. Our goal was to identify how the conductive materials react against water and agitation with high temperature during washing and drying.

3.2.1 Methods

Textiles

Two different textiles were evaluated and used as the substrate for stitched LED circuits. Below is a table (Table 2) describing the details and characteristics of each textile.

	Textile 1	Textile 2
Fiber Content	100% Cotton	80% Polyester

		20% Cotton
Weave Structure	Plain weave, twill variation	Plain weave, twill variation

Table 2: Textile Properties

Two different LED package sizes were evaluated in this study: 5mm 6-PLCC packages, and 3mm 1206 packages.

Wash and Dry Cycle

Two different intensity conditions for washing and drying were used to test samples: high-intensity ("Cotton/Heavy" wash cycle paired with "High" drying) and low-intensity (Hand Wash/Wool wash cycle paired with "Extra-Low" drying).

Samples

Figure 23. 5mm samples: Textile 1 (top) and Textile 2 (bottom left) & 3mm samples: Textile 1 (top) and Textile 2 (bottom right)

A total of 40 samples (containing a total of 200 LEDs and 400 solder joints) were fabricated for washability and durability testing. 10 samples with 5 LEDs each were produced in each of 4 conditions: varying the textile substrate (as described in Table 1), as well as the LED package size (5 mm 6-PLCC packages and 3mm 1206 packages were tested, as shown in Figure 23.

Each sample included a 2.5" border along vertical (warp) and horizontal (weft) edges of the LED circuit. The LED circuit measured 7" in length (warp) and varied in width dimension due to the pattern design. Both the 3mm and 5mm samples measured 12" in the warp direction. However, because of the component size, and thus different stitching to accommodate, the 3mm samples measured 4.8" and the 5mm samples measured 5.3" in the weft direction. Raw edges on each sample were serged using a JUKI MO-6700 Series 4-Thread Overlock Industrial Sewing Machine, to prevent fraying edges and tangling of samples during wash and dry cycles.

Wash Testing Method

The wash test method used was based on typical home laundering: machine washing and drying. Whirlpool® Ultimate Care II washing and tumble drying machines were used for all wash and dry cycles in this study. All® "Free and Clear" detergent was used with all washing cycles.

Both textiles used as substrates were pre-washed and dried prior to attaching LEDs, with two wash cycles using the "Cotton/Heavy" setting (~80 minutes total; ~40 minutes per cycle), and 60 minutes timed "High" setting dry cycle. Both textiles were ironed using the "Cotton" temperature setting prior to stitching to facilitate consistent stitch patterns.

During the pre-wash process, a shrinkage test was performed for both samples. A 10" warp x 10" weft square was drawn on each textile prior to prewashing and re-measured in each direction after the pre-wash process. The percentage of the fabric shrinkage for Textile 1 was 7% in the warp direction and 13% in the weft direction (this is because warp threads endure more tension during weaving and therefore are more prone to recovery-influenced shrinkage during washing and drying). Textile 2 showed no shrinkage after prewashing and drying. For durability testing, all the samples underwent 10 complete washing and drying cycles: almost 17 hours in total (1000 minutes). To standardize the mechanical aspects of washing and drying for all samples we used the same water fill level (extra-small), temperature (cold), detergent amount (2.4 oz.), and cycle time (40 minutes) during washing and the same cycle time (60 minutes) during drying. After each wash and dry cycle, all swatches were removed and tested for LED functionality by applying the same 5V power source. LED failures were recorded and all failed joints were photographed using a 30X microscope lens. Joint failures were categorized phenomenologically based on visual inspection.

3.2.2 Results

Each sample circuit contains 5 LEDs. Each LED has 2 solder joints, which results in a total of 10 joints per sample (Figure 24). Across all samples, a total of 6 LEDs had stopped working after the final wash/dry cycle, representing 6 failures out of 400 solder joints (1.5%). All the failures for the high-intensity condition were observed after the first wash/dry cycle and no failures occurred after that. The majority of failures for the low-intensity condition occurred after the first wash/dry cycle, with only one joint failure occurring after that.

Textiles

Both Textile 1 and 2 each experienced 3 failed connections (1.5%). Due to its fiber content (100% cotton), Textile 1 had a higher shrinkage percentage (7% in the warp direction and 13% in the weft direction) compared to Textile 2 which did not shrink at all.

Package Size

Of the two package sizes, the 3mm package had the weakest connections with a total of 6 connection failures, while 5mm package had 0 connection failures.

Intensity of Laundering

Samples that experienced the high-intensity wash and dry condition had a total of 3 connection failures over 10 cycles. These failures occurred after the very first wash and dry cycle and no further failures occurred after that.

Samples that experienced the hand wash and dry condition experienced 3 total failures after ten cycles. The first 2 failures occurred after the first wash and dry cycle. The last failure occurred after the eighth wash and dry cycle.

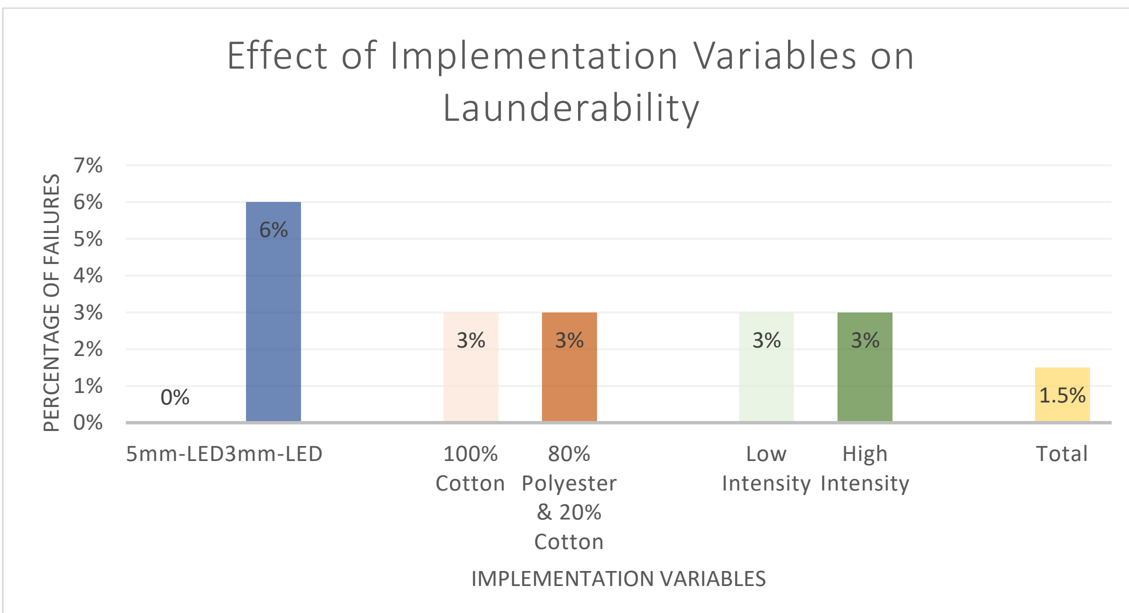


Figure 24: Effect of implementation variables on launderability

Type of Joint Failure

In the low-intensity laundering condition, all observed failures were one of the two joints for a given LED (single-joint failures.) In the high-intensity laundering condition, one of the failures was a single-joint failure, but the other two failures were both joints of a single LED (resulting in the entire 3mm LED coming off)

The detachment of mechanical connection between the component-attached solder and the conductive trace was identified as the only cause of connection failure for all samples (Figure 25).

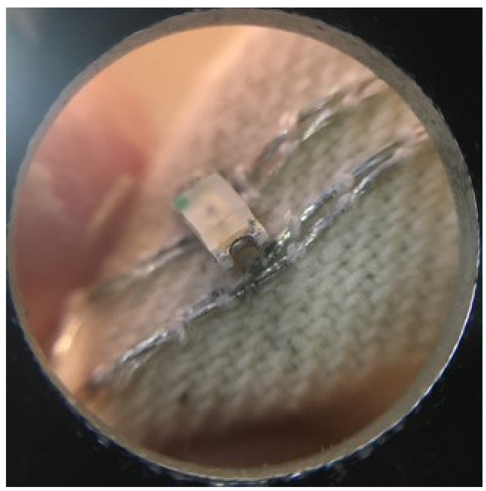


Figure 25: Connection failure on LED

3.2.3 Discussion

Textile Properties

The two textiles evaluated in this study influence the samples in various ways. Textile 1 inherently is heavier weight, has a much stiffer hand, and a harsher drape. In comparison, Textile 2 is inherently lighter weight, has a softer hand, and better drape. These factors contribute to the textile properties both before and after washing. After washing and drying, Textile 1 tends to deform more than Textile 2. Textile 1 tends to curl up, fold, and is much stiffer in comparison to Textile 2, which lays flat, is flexible, and smooth (Figure 6 and 7). While it was hypothesized that a stiffer fabric might provide more strain relief for solder joints, based on the results it appears that fabric structure perhaps did not have a significant impact on the overall connection failures.

The differences in recovery between the cotton-based Textile 1 and the polyester-based Textile 2 are evident in Figure 26. Textiles that wrinkle may put additional strain on integrated traces, although the effect of this difference was not observed in our results. Based on the shrinkage test performed before samples were constructed, it is important to pre-wash any textiles being used for e-textile applications, as Textile 1 shrank in overall size and dimension. When a textile shrinks, conductive traces stitched onto the textile also shrink to accommodate the change in dimension of the fabric, and therefore could create additional pressure on connections which may contribute to an increase in failures. Pre-shrinking the fabrics ensured that there was little to no additional shrinkage after each washing cycle and therefore, neutralized the impact of fabric on the overall connection failures.

Because the solder joints, rather than the integrated conductive traces, were the focus of this test, resistance of the integrated conductive yarns was not measured, However, by the end of the wash testing while individual LEDs were functioning when powered with the source close to the component, the whole circuit was less commonly functional. Li et al. [34] found that integrated traces began to fail after 10 laundering cycles (the end point of our test). Whole-circuit functionality was likely affected by increase in resistance of the stitched traces, and it is possible that in further testing our integrated traces would begin to fail.

Sources of Failure

All observed failures happened between the component-attached solder and the conductive trace, unlike in previous tests [51], where failures were also observed between trace-attached solder and the component lead. However, in the previous test failure between solder and trace was twice as common as between solder and component lead. Therefore, these results would support the observation that adhesion between reflowed solder and the conductive thread trace is more difficult to achieve than between the component lead and solder.

Package Size

Consistent with the results of [51], the 5mm LED package was much more durable in all wash and textile conditions. It is important to note that the 6-PLCC package has three points of connection within each LED lead, as compared to the one point in each of the 3-mm 1206 LED packages.

Due to the size and shape of 3mm LEDs, the stitched conductive traces for those samples require closer proximity to each other (positive and negative traces) compared to traces for 5mm LED samples. Because the 3mm traces are closer together, there is a greater chance for the traces to move slightly during wash and dry cycles and create a short in the circuit. This shifting appears to be a slightly bigger issue with Textile 1 compared to Textile 2, which did not seem to occur quite as drastically (Figure 26).

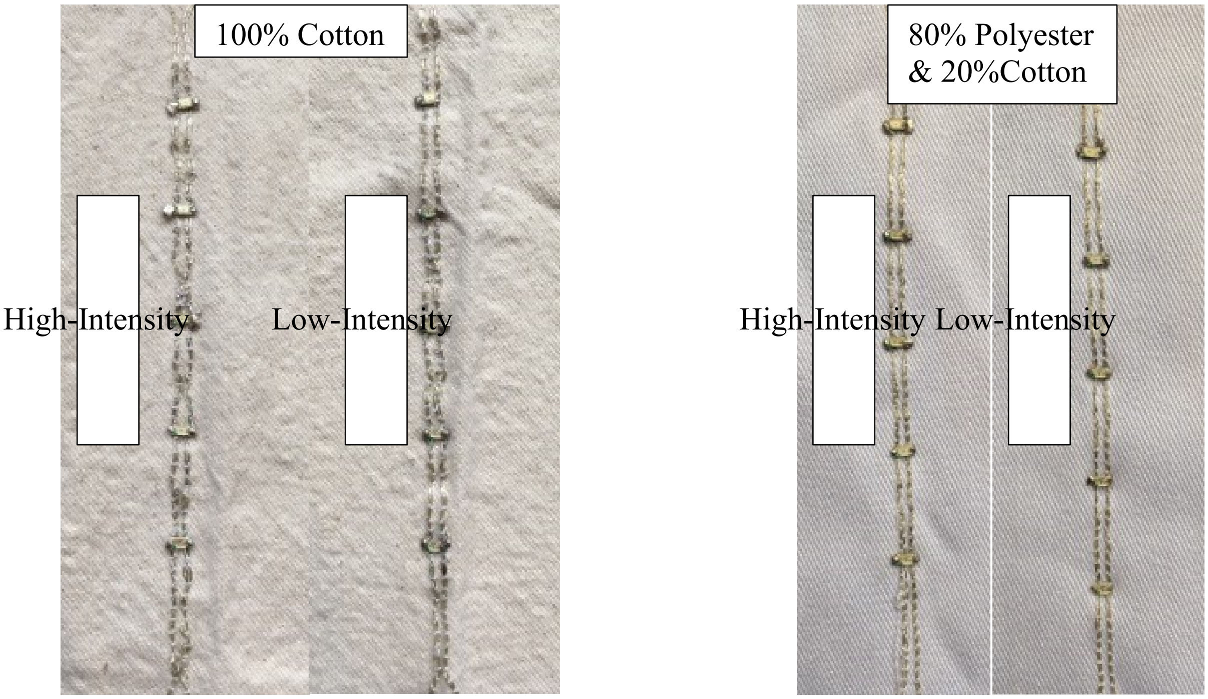


Figure 26. Textile 1 (100% cotton), 3mm stitched conductive traces after high-intensity condition and low-intensity condition (left) and Textile 2 (80% polyester & 20% cotton), 3mm stitched conductive traces after high-intensity condition and low-intensity condition (right).

Wash and Dry Cycle

Interestingly the same failure rate was measured for both low-intensity and high-intensity wash and dry cycles. Both conditions had the same connection failure rate of 1.5%. For the high-intensity condition, all the failures occurred after the first wash/dry cycle. In contrast, for the low-intensity condition, 2 of the 3 connection failures occurred after the first wash/dry cycle and the last connection failure occurred after the eighth wash/dry cycle. It is likely that these failures were caused by poorly-formed solder joints resulting from the manufacturing process (which at this point is still a manually-influenced process). In the high-intensity condition, these poor connections were entirely eliminated after the first washing cycle, whereas one failure was observed later in the test for the low-intensity condition.

However, it is important to note that the overall durability exceeded that measured using the tumble test alone in the previous study [51], despite the overall test time being longer (1000 minutes vs. 845 minutes). This may indicate that the tumble dryer has a greater effect on solder joint durability than the washing machine, although the impact is not likely to be the same for integrated conductive thread traces (which are more likely to show evidence of oxidization effects when exposed to water and detergent).

3.2.4 Summary

To summarize, this work presented the prospect of washability and durability of embedded electronics in e-textiles fabricated with a stitched surface-mount integration method. After around 17 hours of rigorous washing and drying, we measured a 1.5% failure rate for component solder joints. 1.25% of these failures occurred during the first wash/dry cycle. These results demonstrate the feasibility of this technique for machine-launderable e-textile garments. Further improvement in the process will increase overall washability and durability of the samples.

One limitation of this study is a lack of reliable resistance values for each sample before/after each wash and dry cycle. Resistance measurements would reflect the effects of washing on the embedded conductive traces in addition to the effects observed here on the solder joints. Developing a method to reliably measure the resistance of the conductive traces would be useful for future evaluation on this topic.

Uninsulated traces are more vulnerable to both mechanical and chemical effects of laundering. The use of insulated traces might improve their durability, but attention must be paid to the effects of insulation on both manufacturability and wearability parameters like stiffness and breathability.

Acknowledgement: This work is a result of the collaborative work between me, Crystal Compton, and Dr. Lucy Dunne. Crystal primarily helped me by stitching conductive traces on the samples and I developed all the samples and performed the results analysis.

3.3 LAUNDERABILITY TEST: LAUNDERABILITY TEST WITH INSULATION

This section addresses following research question and sub-questions.

Research Question 3: Does insulation help to protect the e-textile structure from laundering?

Sub-question 3.1: Does insulation material protect the surface-mount electronic components (both electronics and conductors) from the effects of water during washing?

Sub-question 3.2: Can film-based insulation material be an effective alternative to traditional insulation materials?

To answer the above questions, the durability analysis of the stitched fabrication method is extended to consider the effects of laundering, as well as the potential mitigating effects of several circuits and protective barrier fabrication methods [50]. Durability and wearability variables evaluated include: trace resistance, solder joint durability, encapsulation durability, and effect of e-textile and insulation components on textile stiffness.

3.3.1 METHOD

Textiles

In the fabrication method used here, the mechanical and chemical properties of the substrate textile affect the performance and durability of the stitched e-textile circuit. For that reason, two different textiles were evaluated: 100% cotton and 100% polyester textile. Cotton (a natural, cellulosic fiber), is hydrophilic and more prone to shrinkage during washing and drying than polyester (a hydrophobic, synthetic fiber). Both textiles have the same structure (plain weave—twill variation) and are of similar weight (measured using the ASTM D3776 standard method).

Both textiles were pre-washed and dried once prior to circuit stitching and LED attachment, using the "Normal–Super Wash Casual/Permanent Press agitate/spin, Cold water" settings (60 min), and 60 min "Low" temperature dry cycle.

During the pre-wash process, a shrinkage test was performed. The cotton fabric shrank 8.13% in the warp direction and 0% in the weft direction (this is because warp threads endure more tension during weaving and therefore are more prone to recovery-influenced shrinkage during washing and drying). The 100% polyester textile showed zero shrinkage after pre-washing and -drying.

Electronic Component Conditions

Two electronic component conditions were evaluated in this study to evaluate the influence of laundering on durability: surface-mount LEDs soldered to stitched traces, and stitched traces without an attached electronic component. Syscom Liberator® 40 AG silver conductive thread (bobbin) with traditional 100% polyester all-purpose sewing thread (needle) was used for all traces. Five 3 mm 1206 package LEDs were soldered onto the stitched traces of half of the samples for each fabric condition (Figure 27).

Circuit Assembly Method

Consistent with [10], a Brother BAS-342G Industrial Sewing Machine (Programmable Electronic Pattern Sewer) was used to stitch conductive traces in two-dimensional (2D) geometries, as shown in Figure 27.

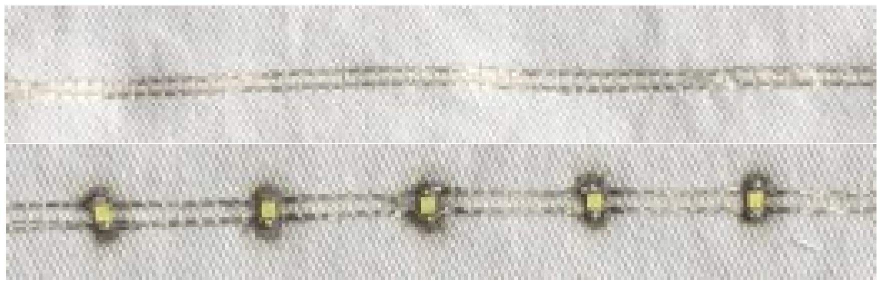


Figure 27. Stitched conductive traces using Programmable Electronic Pattern Sewer a) traces only, b) traces and soldered 3mm LEDs.

For samples with traces and components, the two parallel stitched traces served as power and ground rails to which five 3 mm LEDs were attached, with the rail running perpendicular to the component package axis.

Low-melt solder paste (Chip Quik®) mixed with an approximately equal amount of gel flux was screened onto the traces using a printmaking squeegee and a solder stencil, following the methods in [51]. LED packages were placed on the screened solder pads manually. To ensure even distribution of heat and pressure on the components, a PowerPress industrial plate heat press was used to reflow the solder paste. Once each swatch was fabricated, functionality of the LEDs was confirmed using a 5V power source. 100% of the swatches were functional following fabrication.

Encapsulation of the Traces

Twelve encapsulation materials (listed below) were initially evaluated in a pilot test. These materials emphasized two techniques: liquid encapsulation (consistent with traditional electronic encapsulation methods) and tape-type surface applications (consistent with traditional apparel seam reinforcements).

1. BEMIS™ Seam Tape
2. Heat n Bond® Iron-on Adhesive, Ultrahold
3. Bondex®/MD Mend & Repair™ Fabric Mending Tape
4. Melco™ Iron-on Seam Tape 7/8"
5. Gear Aid Sil-Net™ Silicone Seam Sealer
6. Clover Quick Bias
7. SUNDLEY 20m Seam Sealing Tape
8. FRAMIS ITALIA S.P.A. black tape
9. Liquid electrical tape
10. Plasti Dip multi-purpose rubber coating
11. LED Seal Fast-Dry Spray (silicone spray sealant)
12. CRC Seal Coat clear urethane coating

Each material was applied to stitched conductive traces and washed and dried for one cycle. After preliminary testing of the initial 12 pilot samples, the five best performing materials (in terms of durability and stiffness) were selected to be used for further testing in this study, listed in Table 3. The selected materials prioritize those that can be applied in a fused taping operation (encapsulations 1-4), as taping machines are common in cut-and-sew fabrication facilities. The fifth material, liquid-type Sil-Net™ Silicone Seam Sealer, is included as a comparison method (as it is more similar to full-encapsulation methods used to protect electronics).

ID	Name

(E1)	BEMIS™ Seam Tape
(E2)	Layer 1: Heat n Bond® Iron-on Adhesive, Ultrahold Layer 2: Sheer synthetic textile
(E3)	Bondex®/MD Mend & Repair™ Fabric Mending Tape
(E4)	Melco™ Iron-on Seam Tape 7/8"
(E5)	Gear Aid Sil-Net™ Silicone Seam Sealer

Table 3. Best-performing materials.

Samples

A total of 120 samples (containing a total of 300 LEDs, 600 solder joints, and 240 traces) were fabricated for washability and durability testing as describes in Table 4.

		Textile 1		Textile 2		
Sample	Sample Description	With Traces	With Traces and LEDs	With Traces	With Traces and LEDs	Total
E0	No Encapsulation	5	5	5	5	20
E1	BEMIS™ Seam Tape	5	5	5	5	20
E2	Heat n Bond® Iron-on Adhesive, Ultrahold Layer & synthetic textile	5	5	5	5	20
E3	Bondex® Fabric Mending Tape	5	5	5	5	20
E4	Melco™ Iron-on Seam Tape	5	5	5	5	20
E5	Sil-Net™ Silicone Seam Sealer	5	5	5	5	20
	Total	25	25	25	25	120

Table 4: Total number of samples developed

For each condition, a total of 20 samples were developed, five for each combination of textile/circuit variables (Cotton/trace only; Cotton/components; Poly/trace only; Poly/components). Five control samples were developed with no protective material (E0). Figure 28 illustrates the sample conditions evaluated in this study.

Each sample included a 2” border along the vertical (warp) and horizontal (weft) edges of the stitched circuit. The circuit measured approximately 7.25” in length (warp) and 1” (weft). The samples measured approximately 11.25” in the warp direction and 5” in the weft direction. Raw edges were serged to prevent frayed edges from tangling during wash and dry cycles. Solder balls were applied to the ends of each trace outside the insulation region (5”) to allow for standardized resistance testing.

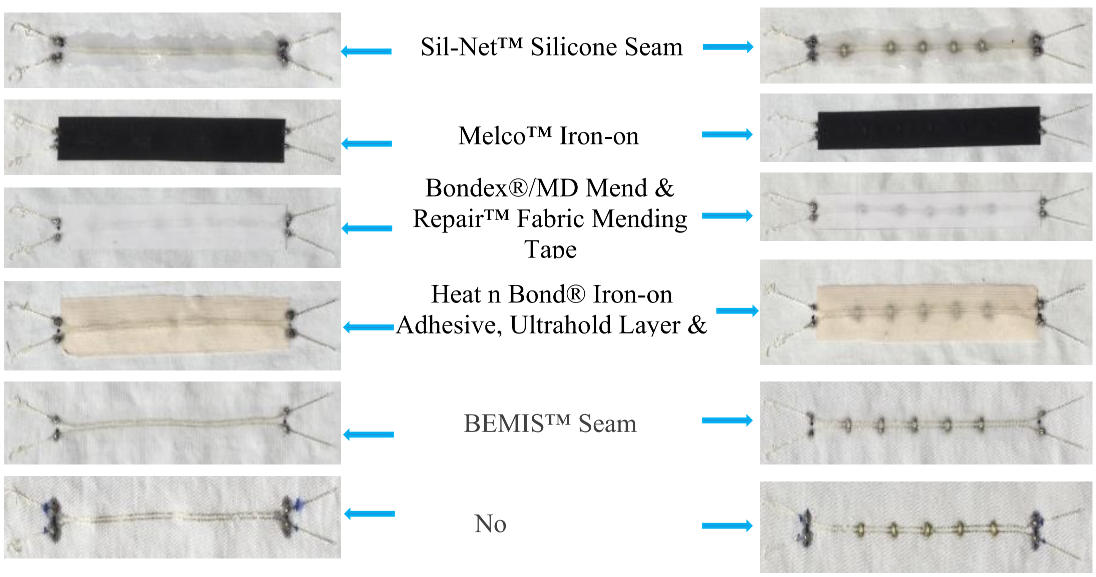


Figure 28: Samples- trace condition (left) (E0-E5) and trace with LED condition (E0-E5) (right)

Barrier Materials: Method

A PowerPress industrial plate heat-press, also used for LED application, was used to fuse materials 1-4 (Figure 28) to the center of the stitched circuit on all textile samples. Each material measured 5” in length and varied in width dimensions (0.5 - 0.75”).

Materials 1, 3, and 4 were heated to 400°F for 10 seconds during application. Material 2 was composed of a thermoplastic adhesive web (fused at 300°F for 10 seconds) used to adhere a textile layer (fused at 300°F for an additional 10 seconds). Material 5 is applied as liquid silicone and does not require heat. This encapsulation was applied to the fabric using a small brush and cured for 6 hours.

To ensure that the encapsulation materials could withstand the temperature in the washing and drying machines, a pilot wash and dry test of all materials was performed using the washing and drying method described earlier. A total of 10 samples were developed for each encapsulation material and samples were tested for one wash and dry cycle (total 100 minutes) to ensure they were able to withstand the machine temperature test settings.

Fabric Stiffness Test Method

The Peirce cantilever test method (ASTM D1388 standard) was used to determine the flexural rigidity of materials used in this study. This method measures the bending behavior of a material under its own weight at a 41.5º angle.

One 8” (warp) by 1” (weft) sample was constructed for each non-LED condition, plus a textile sample with no stitched traces (14 samples total). The raw edges of these samples were not finished. Each sample was tested four times on the face and back side of the constructed sample (8 times total). The bent section of the sample was measured once it reached the 41.5° angle of the testing device.

Wash Testing Method

The wash test method used was based on typical home laundering: machine washing and drying. Whirlpool® Ultimate Care II washing and tumble-drying machines were used for all wash and dry cycles in this study. All® “Free and Clear” detergent was used with all washing cycles.

For durability testing, all the samples underwent ten complete washing and drying cycles: 1000 minutes (approximately 16.67 hours) in total. To standardize the mechanical aspects of washing and drying for all samples we used the same water fill level (medium), temperature (cold setting, approximately 300C), detergent amount (2.4 oz.), and cycle time (40 minutes) during washing. For drying, the same setting was used for all the samples e.g. temperature (low, approximately 300C) and cycle time (60 minutes). Washing at 300C is a common test for textiles and ISO approved [9] and cold temperature is typically used for soft and delicate fabric. After each wash and dry cycle, all swatches were removed and tested for LED functionality by applying the same 5V power source. A digital multimeter (DMM) was used to measure the resistance of both traces using the four-wire resistance measurement method, which provides more reliable and consistent data and has been widely used in prior studies [9,18,19]. A total of 240 traces were measured for resistance after each washing and drying cycle. Trace resistance values and LED failures were recorded. Visible failed joints were photographed using a 30X microscope lens and categorized phenomenologically based on visual inspection.

3.3.2 Results and Discussion

Solder Joint Durability

Of all of the protective materials, Sil-Net™ Silicone Seam Sealer showed the best results with zero failure. Sil-Net™ Silicone Seam Sealer is very popular as an encapsulation material in the electronics world and is widely used to protect vulnerable electronic connections, but is less well-suited to the cut-and-sewn manufacturing environment.

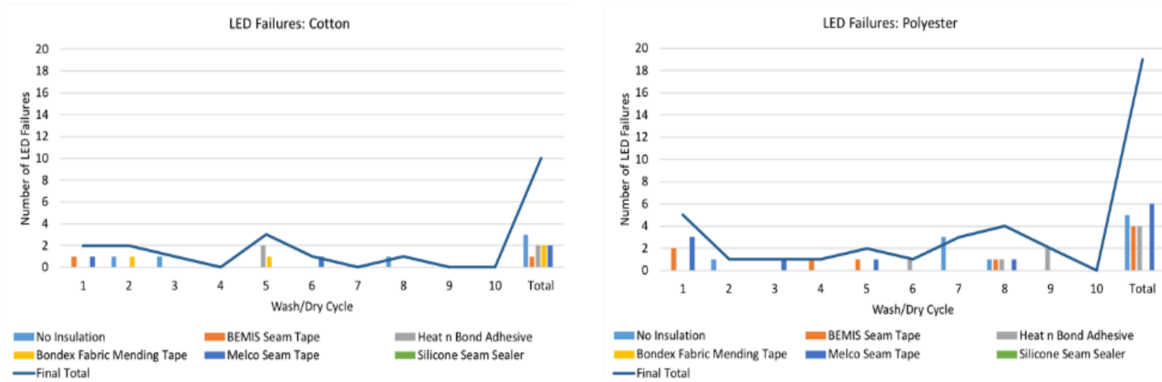


Figure 29. LED failures: cotton (top) and poly (bottom) samples

Of the tape-type materials, Bondex® Fabric Mending Tape was the best for protecting solder joints (2%), followed by BEMIS™ Seam Tape (6%) and Heat n Bond® Iron-on Adhesive (6%). Melco™ Seam Tape showed the worst performance for protecting solder joints (8% failures). Figure 29 shows the number of LED failures observed for each condition after each wash cycle.

Trace Durability

Three trace durability metrics were measured: first, the instances of full breakage where irrecoverable damage resulted in a permanent open circuit. Second, temporary open circuits where large increases (>8000 Ω/m approx.) in resistance were measured (intermittent effects are possible in multi-filament threads). Third, for each trace the maximum percentage increase in resistance over the testing period was calculated using the following formula:

$$\%\Delta R = ((R_{max} - R_i)/R_i) * 100)$$

This value was calculated using data from all trials where the trace resistance was measurable. Averages for resistance of all traces, in each encapsulation condition, for each wash cycle are shown in Figure 30.

Cotton trace-only samples **Polyester trace-only samples**

Cotton LED samples **Polyester LED samples**

Figure 30. Average percent change in resistance for: cotton trace-only samples, polyester trace-only samples, cotton LED samples, and polyester LED samples.

Average resistance of all cotton trace samples for each insulative condition and wash/dry cycle are shown in Figure 30. Overall, resistance of the traces increased as the number of cycles increased. However, trace resistance did not always increase steadily, as it fluctuated between cycles. Melco Tape provided the best results for protecting cotton trace only samples whereas Silicone seam sealer and Bemis seam tape provided the worst results. For polyester trace only samples, Melco Seam Tape provided the best results for insulating, whereas samples with no insulation provided the worst results.

For the trace + LED samples, the resistance values were much higher compared to the trace only samples. For cotton LED samples, Bemis Seam Tape provided the best results whereas Melcro tape provided the worst results. For Polyester LED samples, Silicone Seam Sealer provided the best results whereas Melcro Tape provided the worst results.

Trace Resistance

Overall, resistance of the traces increased as the number of cycles increased. However, trace resistance did not always increase steadily, it fluctuated between cycles.

Effects of Fabric Substrate on Trace Resistance

The average maximum change in resistance values of all the cotton samples (including both traces-only and traces with components) was lower than (1144.73%, 1.79 Ω/m to 22.22 Ω/m) that of polyester fabric (20172.39%, 1.71 Ω/m to 347.64 Ω/m) (see Figure 31). The cotton textile conditions showed a lower resistance compared to the polyester textile conditions when no electronics were used. The cotton traces across all test cycles had lower average resistance values of 3.81 Ω/m (min: 1.67 Ω/m, max: 10.06 Ω/m, and SD: 1.88) across all the protective materials compared to the polyester traces which had an average resistance value of 8.13 Ω/m (min:1.72 Ω/m, max: 238.39 Ω/m, and SD: 28.89). This difference could potentially be due to the affinity for water between textiles. Cotton is a natural, hydrophilic fiber, thereby absorbing more moisture than a synthetic fiber, such as polyester, which has a lower affinity for moisture and is not able to absorb or diffuse water as much. However, as cotton fibers absorb water they swell, which may limit the transmission of water and detergent through the fabric-side of the sample, compared to hydrophobic polyester.

Interestingly, the cotton textile condition showed higher resistance compared to the

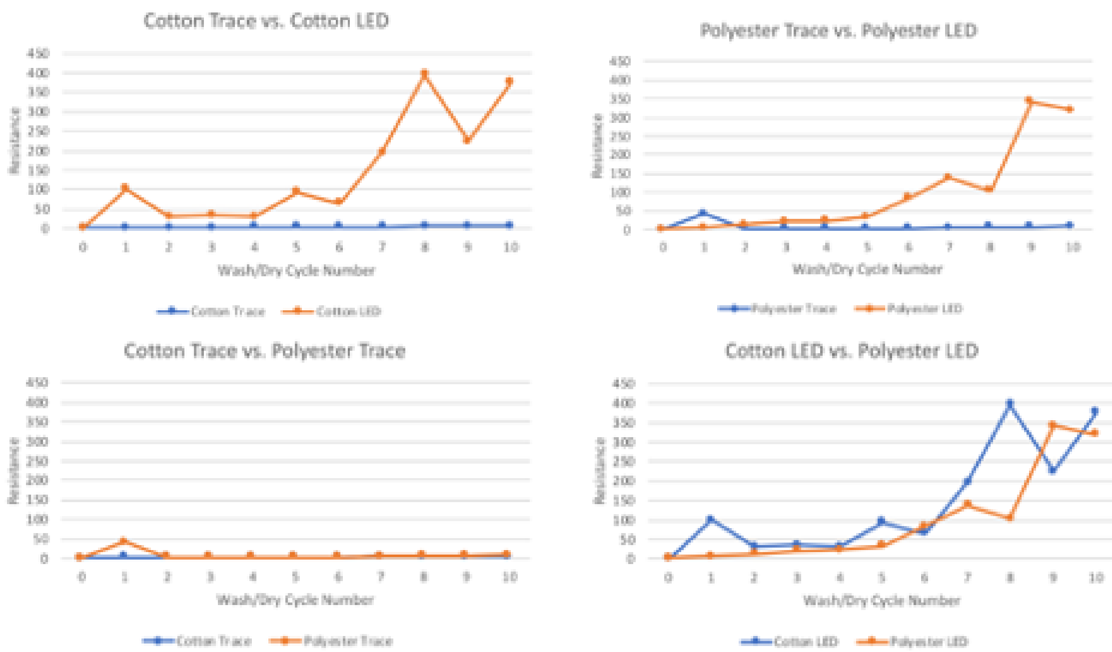


Figure 31: Effects of fabric substrate on trace resistance

polyester textile condition when components were attached. Cotton traces with LEDs across all test cycles had comparatively higher average resistance value of 140.46 (min:1.61 Ω/m, max: 1154.95 Ω/m, and SD: 271.29) Ω/m compared to the polyester traces with LEDs which had an average resistance value of 98.65 Ω/m (min: 1.58 Ω/m, max: 799.31 Ω/m, and SD: 187.76). This could be an effect of the slightly higher stiffness of the polyester textile (Figure 31), which may act as a slight strain-relief for solder joints.

Moreover, cotton fabric had more intermittent failures, but poly had more complete failures (breakages). There were 56 (out of 1200, 4.67%) intermittent open circuit measurements in cotton samples along with 3 thread breakages. On the other hand, for the polyester fabric, there were 46 (3.83%) intermittent open circuits and 7 instances of thread breakage. There was one intermittent open circuit measured for cotton-stitched traces with LEDs and 6 for polyester-stitched traces with LEDs.

To summarize, when considering fabric substrates, the cotton trace samples had lower average resistance values (3.81 Ω/meter) compared to polyester trace samples (8.13 Ω/meter). Cotton textile conditions showed a lower resistance compared to the polyester textile conditions when no electronics were used. Our assumption is that hydrophilic cotton fibers absorb water they swell, which may limit the transmission of water and detergent through the fabric-side of the sample, compared to hydrophobic polyester. Interestingly, the cotton textile conditions showed higher resistance when components were attached compared to the polyester textile conditions. This could be an effect of the slightly higher stiffness of the polyester textile, which may act as a slight strain-relief for solder joints.

Effects of Component Attachment on Trace Resistance

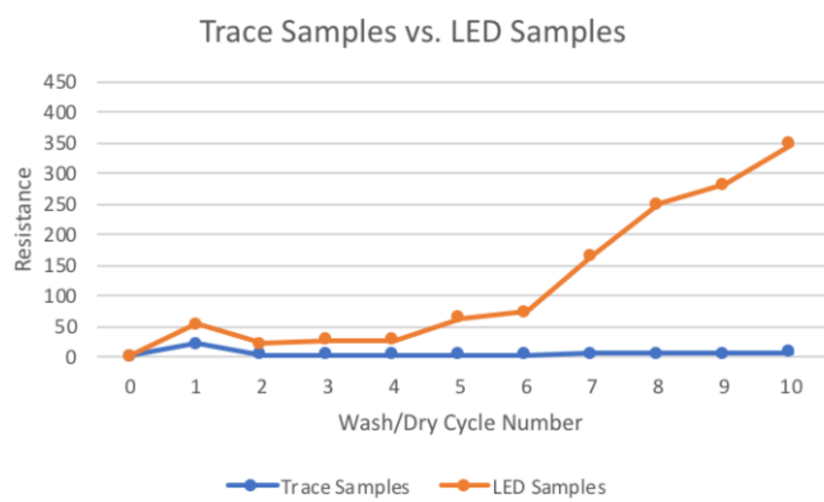


Figure 32: Effects of component attachment on trace resistance

More failures were noticed for traces with electronics compared to traces with no electronics as shown in Figure 32. There were exactly 11 (0.92%) intermittent open circuits for the trace-only samples compared to 91 (7.58%) for the traces with components attached. However, the number of broken traces were same for both trace samples and LED samples

(5). There were 7 intermittent open circuits, all observed in LED samples. For all conditions, trace-only samples had a lower overall resistance and lower variability (1144.73% maximum increase of resistance over the initial resistance) than samples that contained traces with attached LEDs (avg: 119.55 Ω/m, SD: 233.35). For un-protected trace-only samples, the maximum increase of resistance over initial value was 6573.16% (1.80 Ω/m to 120.22 Ω/m), whereas for un-protected samples with LEDs the maximum increase was 32097.5% (1.65 Ω/m to 531.25 Ω/m) which was much higher than the un-protected trace-only samples. The same pattern was observed for protected samples. For example, for BEMIS™ Seam Tape, the maximum change in the resistance value of the trace-only samples was much lower (387.33%, 1.82 Ω/m to 8.86 Ω/m) than the samples with LEDs (4416.13%, 1.76 Ω/m to 79.53 Ω/m).

Cotton traces had lower maximum change in resistance (251%, 1.74 Ω/m to 6.12 Ω/m) than polyester traces (2201.36%, 1.83 Ω/m to 42.07 Ω/m) whereas cotton traces with LEDs had higher maximum resistance change (22456.86%, 1.67 Ω/m to 375.68 Ω/m) than polyester traces with LEDs (19272.22%, 1.76 Ω/m to 341.76 Ω/m). For the trace-only samples, Melco™ Seam Tape did the most to protect traces from breaking and/or increasing in resistance. On the other hand, Heat n Bond® Iron-on Adhesive (E2), Sil-Net™ Silicone Seam Sealer (E5) and even, BEMIS™ Seam Tape (E1) (excluding one outlier) provided better performance in keeping the resistance values low for the traces with LEDs.

To summarize, when considering component attachment, more failures were noticed for traces with LEDs compared to traces with no LEDs. For all conditions, trace-only samples had a lower overall resistance and lower variability than samples that contained traces with attached LEDs. For both insulated and un-insulated trace-only samples, the maximum increase of resistance over initial value was much lower than samples with LEDs. Cotton traces had lower maximum change in resistance compared to polyester traces. However, cotton traces with LEDs had higher maximum resistance change compared to polyester traces with LEDs.

Effects of Protection Method on Trace Resistance

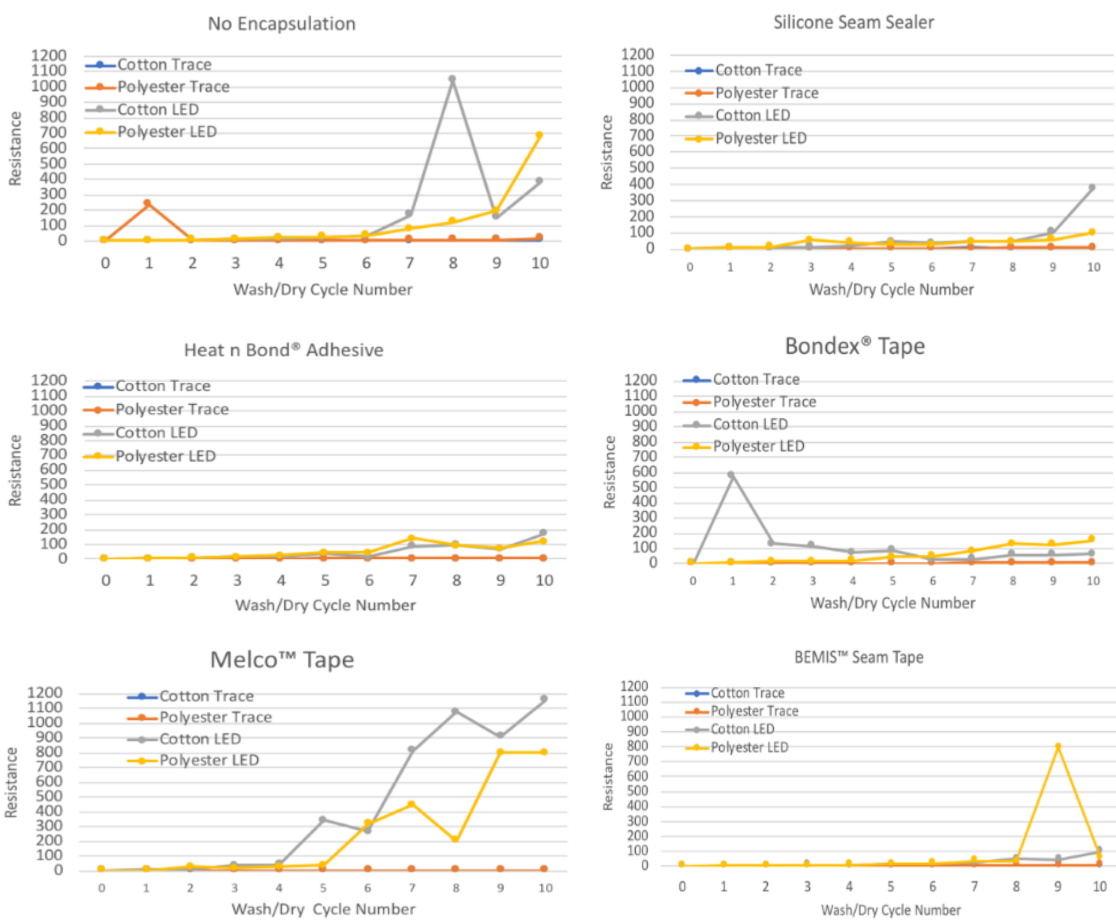


Figure 33: Effects of protection method on trace resistance

When no protective material was used, the increase of resistance was higher for traces with LEDs compared to traces with no LEDs (Figure 33). All five materials worked well to protect traces without LEDs compared to traces with LEDs. For all materials except

Melco™ Seam Tape, the average resistances of the traces across all 120 samples (240 traces) were lower than the samples with no protective material. Heat n Bond® Iron-on Adhesive provided the lowest average resistance value for all traces (27.25 Ω/m) followed by Sil-Net™ Silicone Seam Sealer (28.26 Ω/m), BEMIS tape (30.70 Ω/m), and Bondex® Fabric Mending Tape (45.4 Ω/m). The Melco™ Seam Tape samples had higher average resistance (168.35 Ω/m) than the unprotected samples (76.98 Ω/m). Overall, protected samples had lower average resistance (59.92 Ω/m) compared to unprotected samples. Protection helped more for the trace-only samples compared to LED samples (the changes in the maximum average resistance values were much lower for trace-only samples compared to LED samples.)

Influence of the various materials used here on trace and solder joint durability was mixed. The results showed that Bondex® Fabric Mending Tape (E3) and Melco™ Seam Tape (E4) performed well while protecting the cotton traces with no electronics from degrading whereas BEMIS tape (E1), Heat n Bond® Iron-on Adhesive (E2) and Sil-Net™ Silicone Seam Sealer (E5) performed well when electronics were attached. For polyester fabric, all materials helped to reduce the resistance change of the traces, but Melco™ Seam Tape (E4) provided the best results when no electronics were used and Sil-Net™ Silicone Seam Sealer (E5), followed by Heat n Bond® Iron-on Adhesive (E2), Melco™ Seam Tape (E4) and even BEMIS tape (E1) (excluding one outlier) provided similarly strong performance for traces with soldered components. In summary, Melco™ Seam Tape (E4) provided the best results for protecting traces with no components. BEMIS tape (E1) and Sil-Net™ Silicone Seam Sealer (E5) provided the best results for protecting cotton-LED traces and polyester-LED traces respectively. Interestingly, while Melco seam sealer provided the best results to limit the increase of the resistance of the traces with no electronics, it also provided the worst results for both cotton-LED and polyester-LED samples.

Overall, insulation did help the traces to remain constant. Resistance values of the traces were higher when no encapsulation was used (Figure 33). All insulation materials but Malco tape across all 120 samples had a lower average trace resistance than samples with no protective material. Heat n Band Adhesive provided the lowest average resistance value for all traces followed by Silicone Seam Sealer, BEMIS tape, and Bondex tape. Melco tape showed the highest average resistance value.

Overall, Melcro Seam Tape provided the best results for protecting trace-only conditions. Interestingly, Melcro Seam Tape provided the worst results for trace + LED conditions. BEMIS tape and Silicone Seam Sealer provided the best results for protecting cotton-LED traces and polyester-LED traces respectively.

Limitations

While measuring the resistance values using the digital multimeter (DMM), we applied force using the DMM probes to provide a consistent measurement context. This repeated force may have contributed to thread breakages but was experienced in the same way by all samples. Due to the same repeated force, some of the small beads of solder we used on each trace end to get consistent resistance measurements came off from the threads after few washing and drying cycles. Subsequent measurements were taken in the same locations without the benefit of the stable surface, which may have affected some measurements.

Stiffness and Material Properties

Averages were calculated for each sample condition tested across all stiffness test trials. Results are listed in Figure 34.

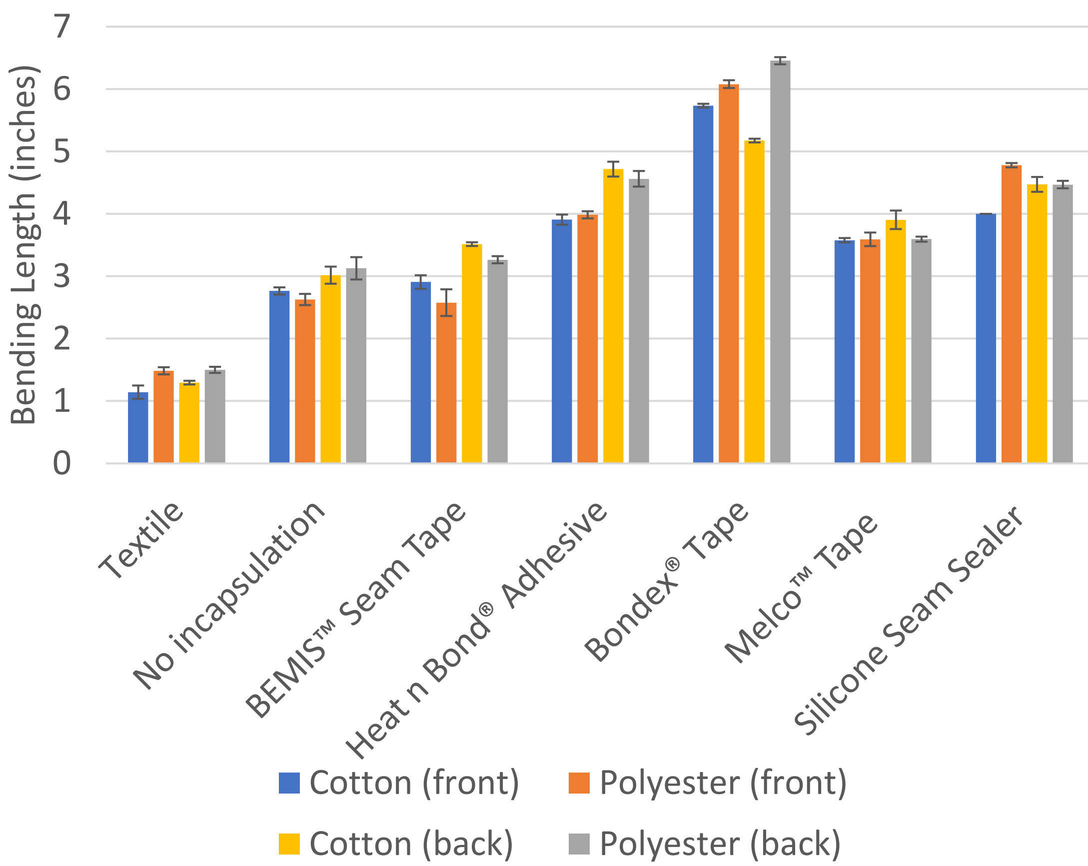


Figure 34. Average and standard deviation of bend length for each sample material: face- and back-side.

In general, the cotton fabric is less stiff than the polyester fabric. However, cotton fabric shrinks more after washing and drying than polyester fabric which could put more stress on the traces. Of all the protective materials, the BEMIS™ Seam Tape samples were the most flexible. The BEMIS™ Seam Tape was also water-resistant and translucent. Melco™ Seam Tape added little more stiffness than BEMIS™ Seam Tape, but was more flexible than both Heat n Bond® Iron-on Adhesive and Sil-Net™ Silicone Seam Sealer. Finally, Bondex® Fabric Mending Tape was the stiffest material used.

While there were benefits to the BEMIS™ Seam Tape, some delamination was observed during wash and dry cycles, occasionally exposing LEDs and solder joints (Figure 35). This delamination clearly affected the protective properties that the material provided to traces and components. BEMIS™ Seam Tape has a thermoplastic adhesive layer on both sides, therefore when heated in the dryer it can fuse to itself or other samples

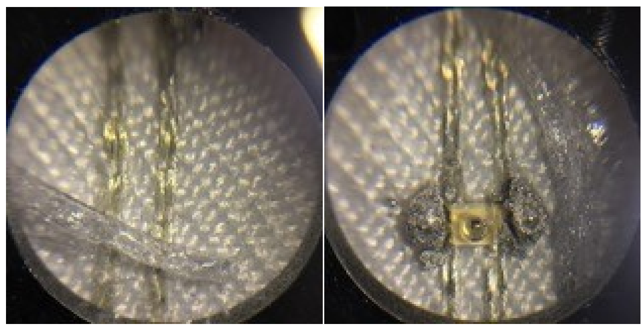


Figure 35. E1 delaminating after wash/dry cycles.

(Figure 36). This material fusing occurred during the beginning cycles and was not observed after the second cycle. It should be noted that specialist materials exist with thermoplastic adhesive on only one side of the tape: these were unfortunately not available to us, but would likely improve the performance of this material. Similarly, the sheer synthetic fabric used with the Heat n Bond showed durability effects in terms of delamination over the cycle period.

Figure 36. E1 bonding after wash/dry cycles.

3.3.3 Summary

This study evaluated the durability of stitched traces and surface-mount components during home laundering, under two different textile substrate conditions, and six different protective material conditions. Results showed that protective materials can effectively protect stitched circuits by maintaining trace resistance (best-case increase in resistance from 0.24 to 0.58 Ω/m) and preventing breakage of solder joints (best-case 0% failure rate).

However, differences were seen in the relative performance of protective materials on trace resistance vs. solder joint durability. The material that was the most effective in protecting solder joints (silicone sealant) was also effective in maintaining polyester-LED trace conductivity. Conflicting results were seen for combinations of variables within the tape-type materials: Melco™ Seam Tape provided best results for protecting traces with no electronics whereas BEMIS tape provided best results for protecting cotton-LED traces. Similarly, the material that was the least effective in protecting solder joints was the most effective in most cases while protecting stitched traces (seam tape film). Fusible tape-based products are more feasible to implement in cut-and-sew factory environments, and several fusible tapes measured here added negligible stiffness to the stitched circuit.

However, overall the best-case approaches to protecting traces and circuits in each textile condition showed strong washability results. For polyester samples, 0% joint failure was observed for samples protected with Silicone Seam Sealer, and 143% (0.24 Ω/m to 0.58 Ω/m) maximum change in resistance was observed for Melco™ Iron-on Seam Tape. For cotton samples, 0% joint failure was observed for Silicone Seam Sealer and 171.78% (0.22 Ω/m to 0.60 Ω/m) resistance increase for Melco™ Iron-on Seam Tape. These results showed an expectedly higher LED joint failure rate for un-protected samples (8%) during water-based laundering compared to our previous study (6%) evaluating un-protected samples in dry tumble testing [51]. However, here our results show that the use of the right protection material could improve durability for wet-laundered circuits above that of dry-tumbled unprotected circuits.

These results support the feasibility of tape-based approaches for protecting stitched circuit elements in textiles during washing.

Acknowledgement: This work was a collaboration with Crystal Compton and Dr. Lucy Dunne. Crystal primarily helped me by stitching conductive traces on the samples and performing stiffness testing. The rest of the work including sample development, data collection, and results analysis was done by me.

3.4 TRANSLATION OF THE FABRICATION METHOD FOR MORE COMPLEX STRUCTURES

Since we have developed and validated a method for e-textiles fabrication, the next step is to extend that method to garment-scale fabrication. With my next research questions and sub-questions, I will try to answer these questions.

Research Question 4: Is it feasible to use the method to produce garment-scale e-textile products?

Sub-question 4.1:What new fabrication and manufacturing variables must be addressed when deploying the stitched-based surface-mount method to produce more complex circuits?

Sub-question 4.2: What are the implications of electronics integration for apparel manufacturing workflows?

To identify the fabrication and manufacturing variables for a typical e-textile garment, we developed several e-textile prototypes of increasing complexity, which range from a swatch to a complete garment using the methods previously described as well as novel methods required by these more complex structures. The development of these prototypes served as an exploratory investigation to discover the major challenges of fabricating garment-scale e-textile products. In this section, I will describe the prototypes we have developed to explore the feasibility of the method for garment-scale products and mass production, and the manufacturing processes and variables identified in each iteration. Similar to the previous section, I will mention individuals who have provided a significant intellectual contribution to the project after the end of each project.

3.4.1 LED Display Swatch

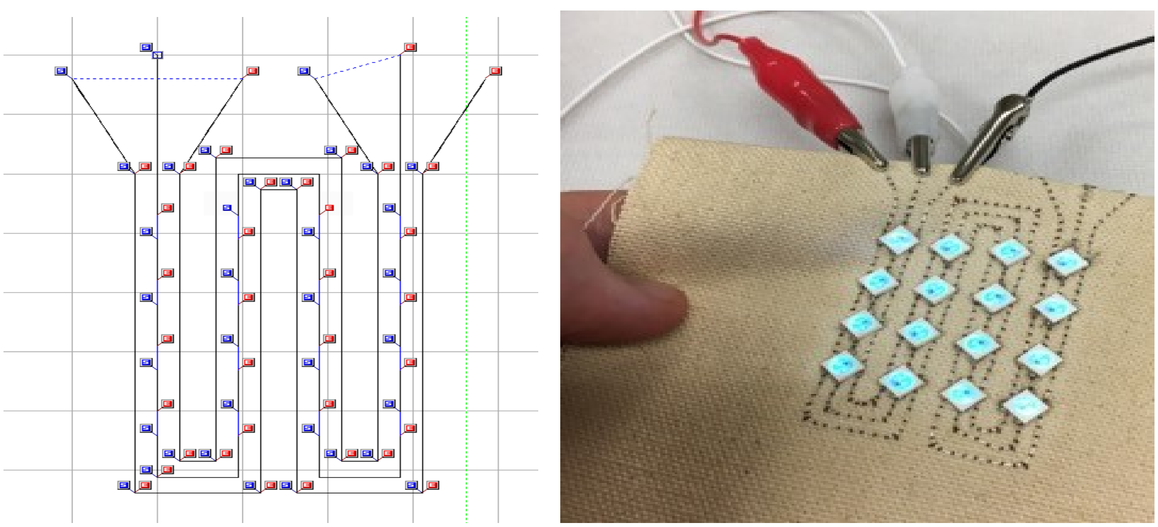


Figure 37. LED matrix display implementation: stitch layout (left) and functional swatch (right).

In the previous studies, we made very simple designs with the pattern stitcher where parallel LED circuits were created in two basic trace layouts: "a parallel" trace layout where the connecting traces meet the LED package parallel with its axis, and a "perpendicular" trace layout where traces meet the package perpendicular to its axis (see Figure 18). For this study, a more complex circuit in the form of an LED matrix display was developed using controllable RGB LED ICs (SK6812 Shenzhen LED Color Optoelectronic Co) [51]. A custom-designed stitch layout (Figure 37) was used to connect an array of 16 LEDs to an external Arduino microcontroller. An inertial sensing unit provided the input to the display, which changes color depending on the motion and orientation of the sensor. For this example, only the LED matrix was fabricated using the e-textile method: the remaining circuit components were assembled in breadboard form, and attached to the swatch for testing via alligator clips.

Fabrication

The operations involved in producing the LED matrix are described in Figure 38. The RGB LED ICs used in this study were packaged in a 5mm square 4-PLCC package. These LED packages are 4-pin ICs that require power, ground, and input/output connections. Because they can be "chained" by connecting one LED's output to the input of the next LED, they were set in an offset pattern so that traces could be routed in a serpentine manner to avoid trace crossings.

The input/output pins of each package need to be connected serially, in a "daisy-chain" structure. Therefore, although traces didn't need to cross within the circuit, input and output traces needed to be isolated. Isolation of traces within a circuit was a new variable that had not been addressed in prior work. To allow traces to be isolated in

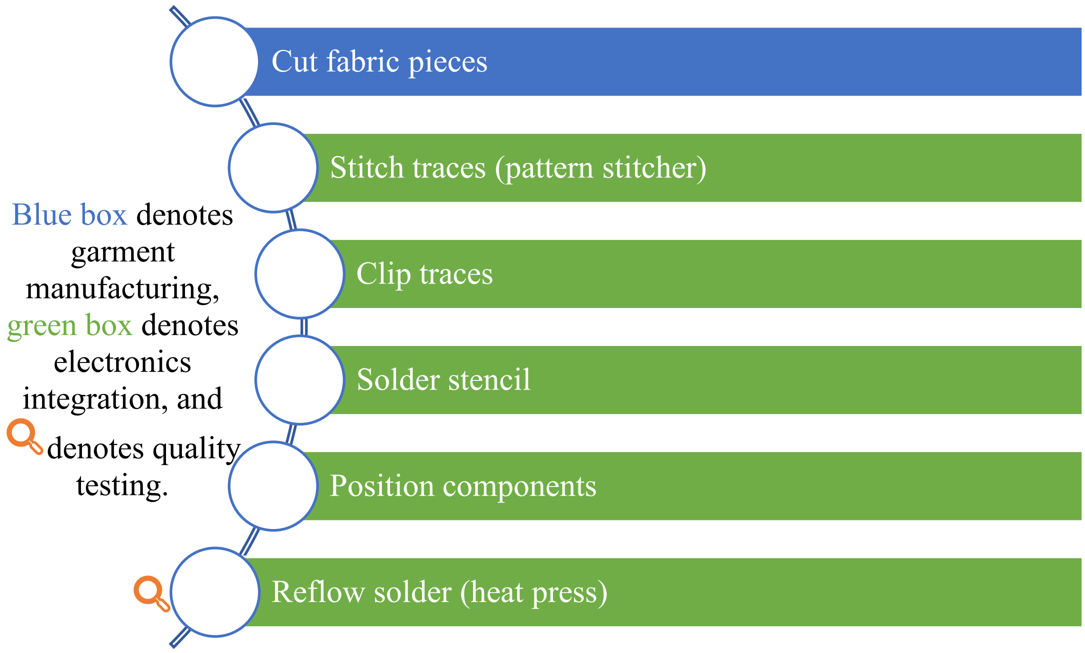


Figure 38: Operation sequence of the LED matrix

the stitched pattern, beneath each chip package location, a stitch "float" was placed, that was clipped after the swatch was stitched to isolate the input and output of the chip package (Figure 39).

This example demonstrates that programmable 4-pin IC packages can be soldered using the method. However, we realized that it is slightly more complicated to solder ICs having 4 isolated pins compared to the regular surface-mount LEDs we used in our previous studies (5mm 6-PLCC LED, 3mm 1206 LED, etc.). The gap between the pins in programmable 4-pin ICs is 2.5mm smaller than the regular surface-mount LEDs (5mm) which makes them more difficult to solder. Due to the narrow spacing between pins, a slight displacement of the IC package can create a "short" in the circuit. Displacement can be caused due to manual handling of the IC packages or the movement of the bed of the heat press.

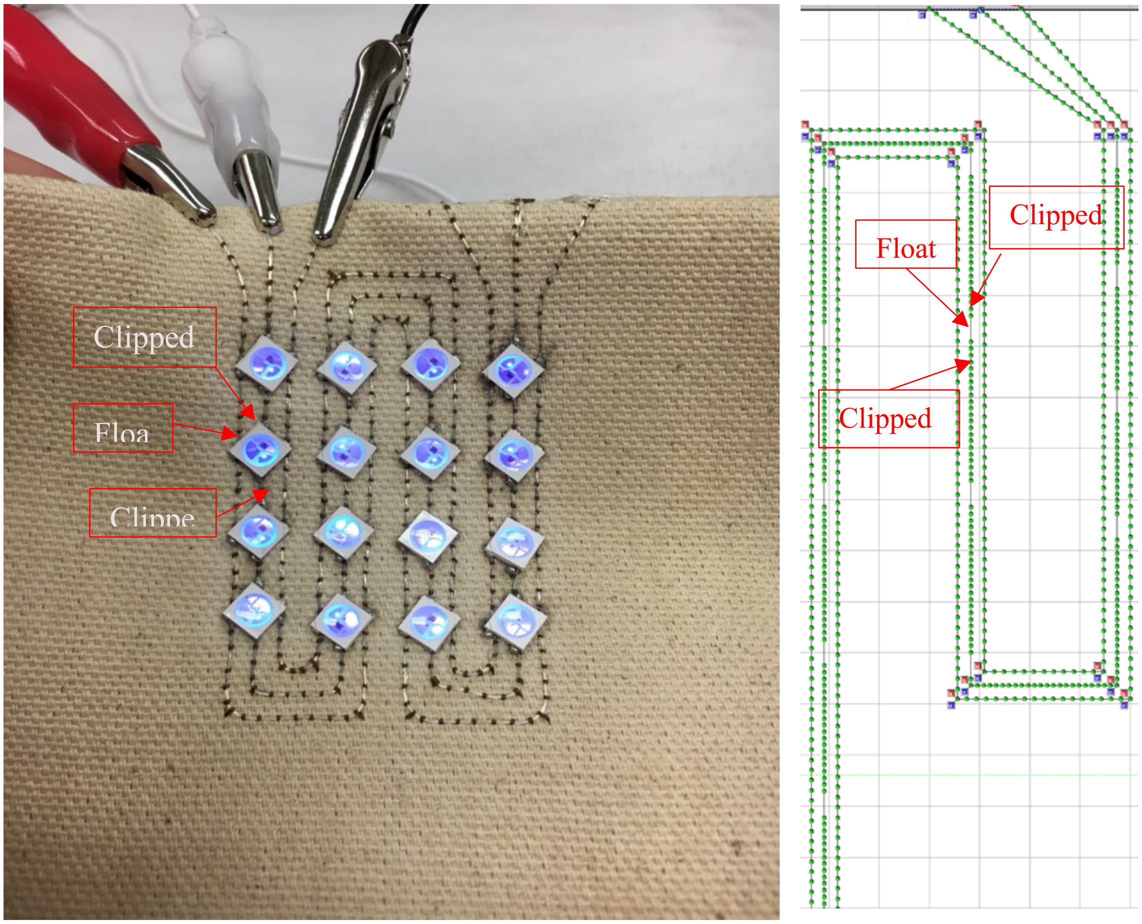


Figure 39: "Float" in the stitched layout

The clipped float technique was done manually, but it would be more difficult to automate. The pattern stitching machine can be programmed to insert thread trims at specific locations, but these trims require a backtack or other method of securing the thread tail otherwise they might easily come off from the seamline (Figure 40). Further studies should be done to investigate backtack and trim operations in more depth. In addition, 2-layer trace crossings would expand the functional scope of this technique dramatically. Prior work has demonstrated the feasibility of 2-layer stitched circuit layout techniques [16], which may be adapted to this method.

Quality Check and Troubleshooting

Each LED was first checked visually to see if there were any broken connections or cold solder joints, a process that relies on human intelligence and worker skill. Rework was performed if any problem was noticed during visual inspection. Later, a power source was used to check the functionality of LEDs. Once we found any problems in any of the LEDs, the LED was resoldered and checked again. We kept repeating the process until all the LEDs lit up. For this demonstration, we used 16 programmable LEDs to create a LED matrix. We noticed adding more LEDs increased the possibility of failures. A hardware setup using a prototype board and Arduino code were used to test the functionality of the LED matrix. Similar to the LED matrix, we used a different prototype board/Arduino set up for testing the accelerometer. However, the accelerometer was temporarily connected with the prototype board, not integrated into the fabric similar to LEDs. Three different types of codes were used to test the LED matrix (whether the LEDs change their color on command), accelerometer (to test whether the accelerometer is functional or not), and LED matrix-accelerometer (to test whether LEDs change color based on the orientation of the accelerometer). If there was any problem in the hardware system i.e. a broken connection or short, the Arduino code gave an error message or show invalid numbers which meant there was a problem in the connections and needed further troubleshooting and rework.

Figure 40: Thread trims: Thread tail come off (left) and using backtack to secure the tail

In summary, we performed a quality test at different stages of LED matrix fabrication. Each connection was first tested visually which was followed by testing with a power source, and subsequently by testing with the hardware setup using a prototype board and Arduino code. We performed an in-process quality test using a power source for each LED separately during the LED matrix fabrication and a final test of the completed circuit with the prototype board/Arduino set up as shown in Figure 41.

We found that using the prototype board/Arduino set up was extremely useful for troubleshooting the LED matrix rather than testing individual LEDs using a power source. However, since all of the programmable LEDs were "chained" (where the output of one LED was connected with the input of another LED), their connections were also dependent on each other. So, when a LED didn't light up, we had to check the connection of both the LED with a broken connection and the LED immediately ahead of that one.

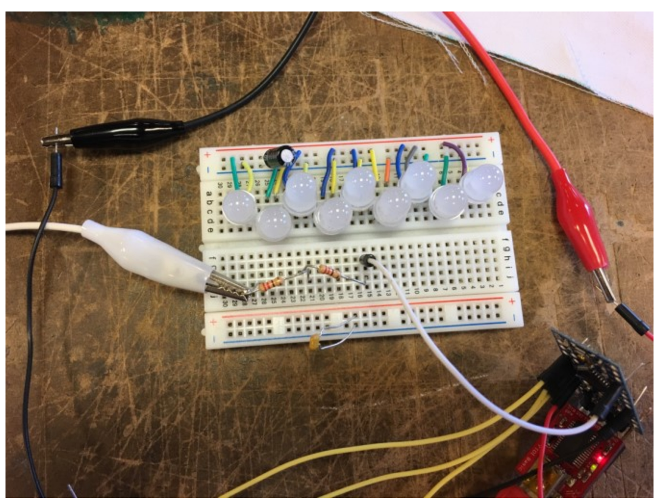


Figure 41: Hardware set up

Therefore, it made the troubleshooting more complicated and time-consuming. We also noticed that sometimes the connections between LEDs were not always stable, especially when the fabric is laying loosely onto a flat surface which impacts threads conductivity. The resistance values of the traces increased when they sat more loosely on the fabric. Stretching the fabric (to make it stable on a flat surface) and pressing the LEDs by hand made stable connections among them. Further development is needed in this area. Rework using the heat press method was also a challenge. While the heat press is an efficient way to solder a large number of LEDs all at once, it also limits the ability to isolate the problematic LED in a LED matrix for rework. Therefore, if there is a problem in one LED in the array, the whole LED matrix need to be pressed under the heat press which often created additional problems. The heat gun and soldering iron have more advantages over the heat press in terms of isolating individual LEDs in a LED matrix. However, the heat gun has several issues too. There is always a chance of burning the fabric if the heat gun is placed too close to the fabric. The hot air also can displace the LED from its original position and may create faulty connections. Also, as mentioned before, the heat press produces more durable connections than the heat gun, which is one of the main reasons the heat press was used over the heat gun.

Acknowledgement: I along with Steven Goodman, Nicholas Schleif, Cade Zacharias, Crystal Compton, and Dr. Lucy Dunne were primarily involved in various stages of this work. Steven Goodman and I together developed the stitched LED sample. Cade was responsible for the prototyping of the electronic systems. Nicholas and Crystal provided insightful suggestions at various stages of the project.

3.4.2 A Motion Responsive Visual Display Garment

After successfully developing a LED display with RGB LEDs, the LED display was integrated into a motion responsive visual display garment (Figure 42), to explore garment-level integration variables when the fabrication technique is combined with a multi-piece garment design that also integrates peripheral PCBs, a microcontroller, and a power source [47–49]. The design presented here is a sensor-controlled smart shirt, with embedded inertial sensing, microcontroller, power source, and LED display. While it was important to design and build a functional prototype to demonstrate the potential, special focus was placed on garment construction using traditional apparel manufacturing technologies to enable comfortable wearable technologies.

Figure 42: A motion responsive visual display garment

Garment System

A system diagram of our garment is shown in Figure 43. It consists of a 3G Analog 16LFCSP PCB-microcontroller with a PKCELL LP503562 3.7v LEDs. The movement of the accelerometer is used to control colors and patterns of the LEDs.

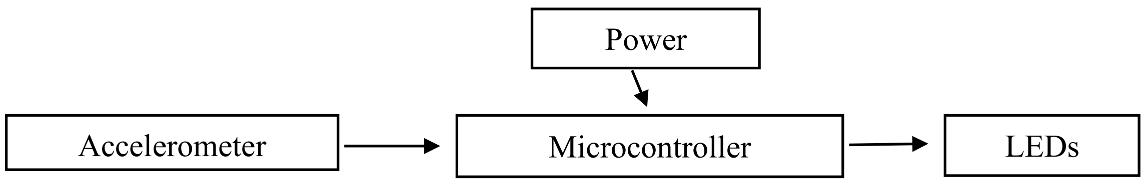


Figure 43: System diagram for the motion responsive visual display garment.

Garment Design

The electronic system was integrated into a white button-down dress shirt, shown in Figure 44. The LED display is controlled by a wearer's wrist/hand and arm movement through an accelerometer. The LED display is integrated onto the left- and right-side of the front of the shirt.

Figure 44: Electronic system on back shirt piece. (NB: blue lines are water-soluble ink, silver threads are stitched traces).

The main body textile used for the shirt is an 80% Polyester, 20% Cotton twill woven fabric. This fabric was chosen 1) for its medium-weight, which affords uniformity in stitching the conductive traces due to its sturdy structure, as well as 2) its high synthetic fiber content, which minimizes textile discoloration when heated for soldering of the LEDs.

Production process

We used the same method described in Section 3.4.1 for manufacturing the shirt's LED display. The small, localized microcontroller and inertial sensors were PCB-mounted and attached using stitched through-hole techniques (Figure 45). Trace connections between parts of the system (e.g. between the LED display and the microcontroller, and between the inertial sensor and the microcontroller) were made using a lockstitch machine during the garment assembly process.

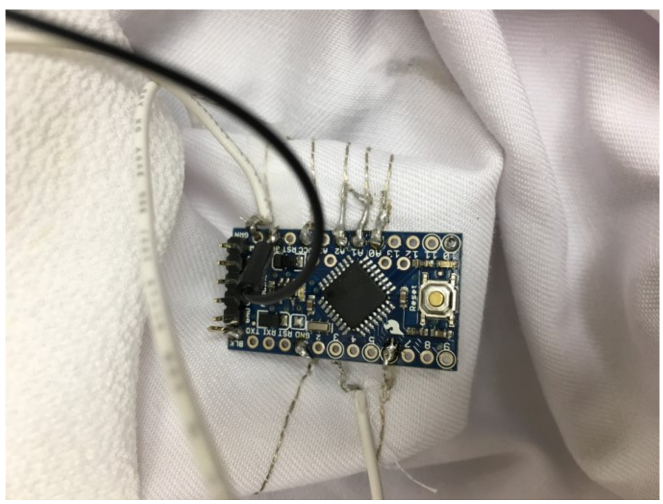


Figure 45: Through hole integration technique for microcontroller

In our previous study, the stitched layout developed for the LED display swatch contained 16 LEDs. This prototype required a bigger stitch pattern containing a larger number of LEDs.

However, here it was necessary to design this stitch pattern relative to the pattern layout for the whole garment. Therefore, we had to consider two new garment-level manufacturing constraints: mechanics of stitching (stitch a cut piece vs. stitch a piece of fabric with the piece outline drawn on it), the size of the garment, and the machine bed size. For this project, we decided to stitch a cut piece due to convenience. Since the garment design required an LED display on each side of the front part of a button-down shirt, the length of the stitched layout should be smaller than the original length of the shirt, and width should be smaller than the half-width measurement of the shirt. The same thing is also true for the pattern stitcher bed size. The length and width of the stitched layout should be smaller than the length and width of the machine bed respectively (11” x 7”). The stitch layout should also keep some distance from the seam line and the buttons so that it doesn't create any problem during stitching and button attachment, leaving about 13” of width for the LED display. Using the Brother software, a layout was made based on all these considerations. For the stitched layout, fabric was cut based on pattern layout. A placement mark was placed using a washable marker into the front parts of the garment so that the stitched layout remains inside the desired area. Later, the pattern stitcher was used to stitch the LED layout. A picture of the layout is shown in Figure 46.

An approach similar to that used for the LED display swatch was used to design the LED display stitch layout on the shirt. Due to the number of LEDs used in each swatch, we decided to use a consistent stitch length of 2mm for both the side traces (VCC and Ground) and a stitch length of 1.3mm for the middle trace (Data-In and Data-Out). The shorter stitch length minimized the negative impact of using clipped “floats” at the trace area and to make a stable seamline, since conductive threads become loose and unstable when they are cut in the middle, especially for threads with longer stitch length. This makes it difficult to deposit solder. Smaller stitches are more compact, help to stabilize the seamline, and improve solder deposition. This is a new variable that we learned from the shirt development.

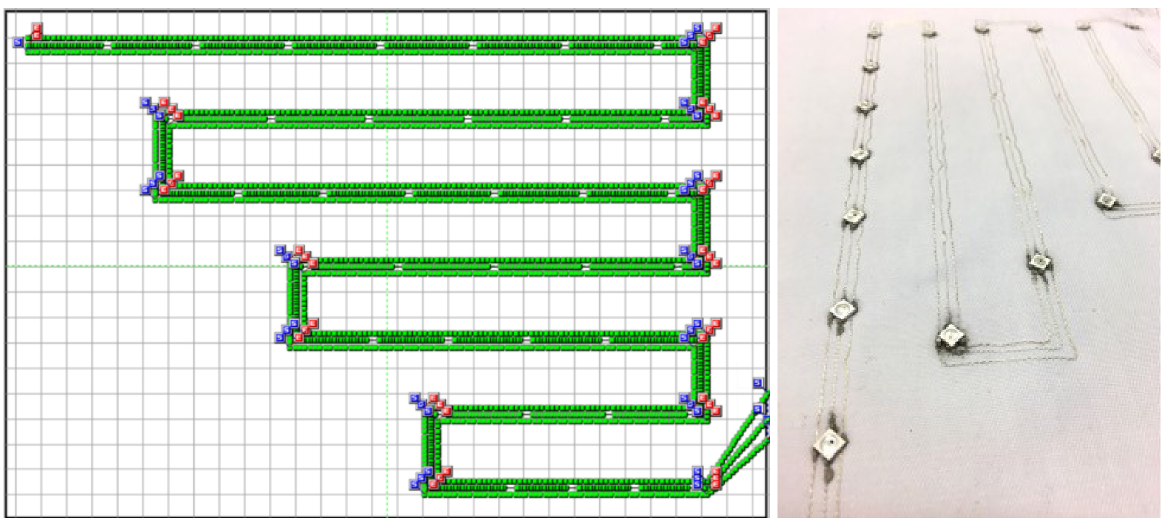


Figure 46: Traces and layout for LED display

As mentioned earlier, the final shirt design used PCB-mounted inertial sensors, attached using through-hole techniques as shown in Figure 47. However, we initially tried to implement the surface-mount manufacturing method for the inertial sensor too. The largest integrated inertial measurement unit (IMU) sensing package we found was a 3G Analog 16LFCSP (ADXL335BCPZ-RL7CT-ND) package type, which uses an array of flat, integrated pins on the bottom of the package. The 16-Lead flip-chip inertial sensor

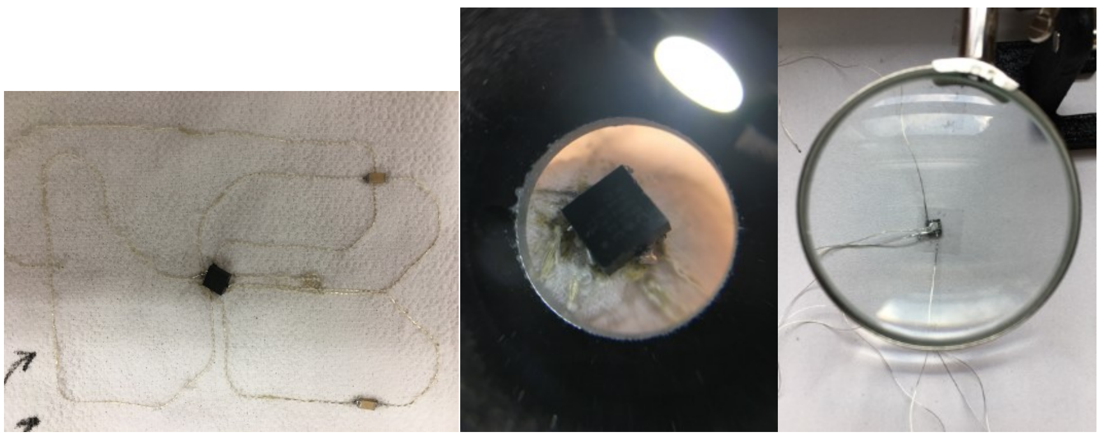


Figure 47: An attempt to integrate the 16-Lead flip-chip inertial sensor into the garment

was extremely difficult to solder using both reflow and hand soldering techniques due to the extremely small size of its leads (pin size 0.30 mm, and space between pins 0.65 mm) (Figure 47). The dimensions of the sensor were 4 mm x 4mm x 1.45 mm which is very small for our advanced manufacturing method. The diameter of the conductive threads (0.18 mm) used in the stitched circuit was thicker than the diameter of the leads of the inertial sensor and therefore, there was always a chance of creating short between adjacent leads. So, we had to rule out the surface mount IC for our manufacturing method and instead, use a through-hole accelerometer breakout board which was comparatively easier to integrate into textiles, as discussed in the previous section.

In e-textiles, to make an e-textile product aesthetically beautiful, it is often necessary to conceal electronics so that they don't interfere the visual appeal of the garment. One way to conceal electronics is to hide them between fabric layers. For this prototype, an additional layer of textile was overlaid to conceal the LED packages and diffuse the light emitted from the LEDs. This was done for aesthetic reasons, to create a more subtle and organic visual display, while also having the illusion of the shirt being a "traditional" dress shirt without electronics. A textured 96% Polyester, 4% Silk crepe woven textile has been used as the diffusing layer. This textile is semi-translucent and semi-opaque with a medium texture, which obscures the ability to easily see the hardware underneath but still lets light through. Inside the shirt, only the regular polyester sewing thread is visible, creating only the slightest visible effect of the electronics.

Trace routing pattern/layout

Since the system design for this shirt was much more complex than the LED matrix swatch, (including the LED matrix as well as Arduino microcontroller, and IMU PCB), many more traces needed to be made to connect components. While determining the trace routing layout, we tried to minimize the need to cross traces over each other, to minimize the chance of short. In a PCB, trace crossing is typically enabled by adding multiple layers and allowing traces to pass from one layer to another. However, in garments adding multiple layers increases the thickness and bulkiness of the garment which is not often desired, unless these extra layers add some aesthetic or functional value to the original garment. So, in fabric, the goal is to avoid trace crossing whenever it is possible. For this garment, multiple iterations were made manually (Figure 48) and a final design was selected that ensured minimum numbers of trace crossings to avoid shorts. However, it is possible that this layout could be made using an automated routing software.

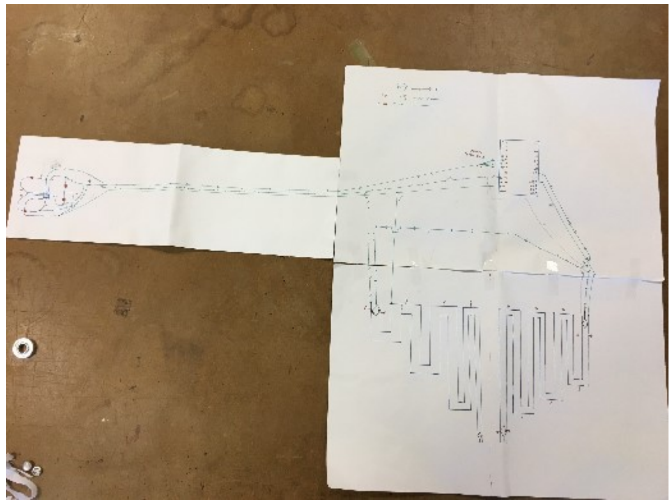


Figure 48: Trace layout of the garment

We placed two large LED arrays in the front part of the garment. The accelerometer was placed in the right cuff, and the Arduino, Bluetooth, and battery were placed at the center back of the shirt. Conductive thread was used to make connections among all the components.

Constructing the trace layout using the combination of pattern stitcher and lockstitch machines also introduced new fabrication variables. Some of the variables that emerged in the process of constructing the trace layout were:

- Thread/machine tension can be too loose or too tight. If the tension is too tight, there is a greater likelihood of thread/traces breaking.
- There are few occasions where traces had to cover a long distance i.e. a connection between the cuff and back of the body, which makes them vulnerable for thread breakage. The longer the length of the trace, the greater the potential for breaking of thread.

- In the case where multiple components are connected to a single trace (e.g. power and ground), a broken thread can cause all components to not work.
- The fabric needed to be held very taut when stitching lengthwise and crosswise to avoid any faulty seamlines due to higher strength of the conductive thread.
- Backstitches are often needed at the beginning of a stitch when connecting to already stitched traces, at corners or transition points, going over seams (e.g. armscye) to strengthen the connections during trace crossing by adding more conductive surface area.

Trace crossing

Although trace crossings were minimized, there were some instances where traces needed to be crossed, and the crossed traces were needed to be insulated to isolate the

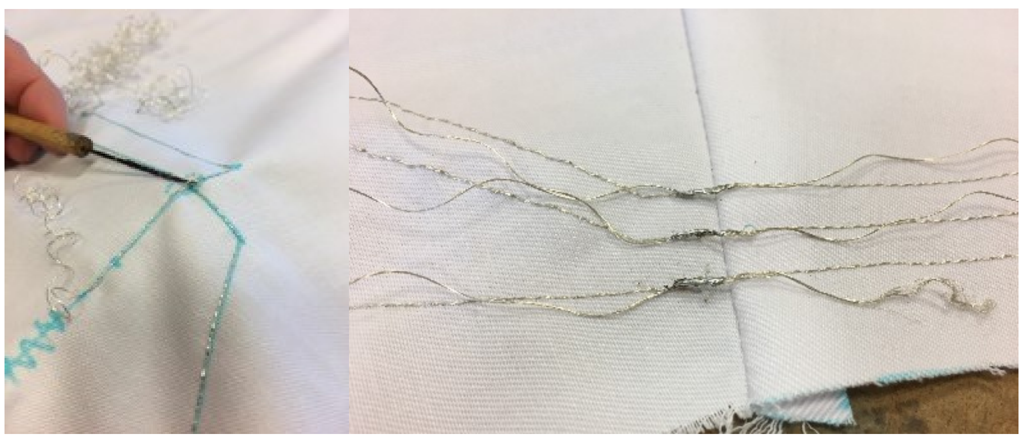


Figure 49: Examples of trace crossing and seam crossing: Float stitch example for trace crossing (left) and trace connections in the garment (right)

crossing threads from each other and prevent a short circuit. A float stitch was used to allow traces to be separated, by floating one trace over another already stitched trace. A small amount of fabric paint was then applied to the bottom trace (while lifting the float stitch) to insulate the trace crossing (see Figure 49-left). This method was effective, but time-consuming. Further development is needed to identify more scalable trace-crossing techniques.

Seam crossing

While stitching traces, the LED display traces were stitched using the pattern stitcher, while a regular lock stitch machine was used to stitch traces on the sleeves and the back of the shirt, and finally, the same lock stitch machine was used to connect traces over seamlines. As previously mentioned, although the LED display traces were stitched using the pattern stitching machine, the total garment surface area exceeds the bed size for the pattern stitching machine. Therefore, for trace connections outside of the LED matrix, we used a regular lock stitch machine where the conductive thread was used as a bobbin thread and a polyester thread was used as a needle thread, and stitch placement was controlled by the operator. The stitches produced by the two machines are identical (only one side of the fabric has conductive traces). The manually-controlled lock stitch machine was more suitable and convenient for creating some conductive traces compared to the pattern stitcher because it can apply stitch lines to 3-dimensional garment pieces (through manual handling of the garment). However, the manually-controlled lock stitch machine was also slower, less precise and less scalable compared to the pattern stitcher machine.

There were instances where some of the traces had to cross over seams (like the armscye) (Figure 49-right). As previously discussed, several methods can be used to join traces together. In this situation, the seam-crossing technique we used was to sew the traces to a visually-estimated point on each piece, and then sew the seam, and then join the traces across the seam by soldering the threads together manually. Again, while this technique was adequate for this prototype, it is labor-intensive. Future research should address scalable methods for joining traces across seams.

Microcontroller and Battery

A three-axis accelerometer (3G Analog 16LFCSP) breakout board is placed on the right cuff of the shirt. The breakout board had through-holes that was stitched around manually and later soldered with the conductive threads and hidden inside the two layers of fabrics in the right cuff. The Arduino was also soldered using the through-hole fabrication technique with the trace layout as shown in Figure 50. A 9v lithium-ion polymer battery was used to power the system. This was our first attempt to directly integrate the hardware into the garment, as opposed to the small LED matrix where the system was powered by an external device.

Figure 50: Microcontroller attachment on the garment

Operation sequence for production

Several operations were involved in the manufacturing of the shirt. Table 5 describes the operations involved in the manufacturing of the shirt as well as the equipment/tools necessary to perform the operation. The operation sequence of the manufacturing of the shirt is described in Figure 51.

Sl No.	Operation	Machine Used
1	Create 2D pattern pieces	Manually
2	Place the pattern pieces onto the fabric and draw the shape of all the pattern pieces onto the fabric	Manually
3	Cut fabric Pieces	Scissors
4	Stiched the circuit for the large-area LED array onto the front-left and front-right part of the garment	Pattern Stitcher
5	Cut the satin 'float" stitch to isolate Data-In and Data-Out traces	Scissors
6	Deposit solder at the 4-lead PLCC packages	Mask and squeegee, Soldering Iron
7	Mount LEDs on top of the stitched circuit with the help of a tweezer	Manually
8	Put the fabric with the surface-mounted LEDs onto the bed of the t-shirt press, covered using a light fabric, and pressed at 240 degree Celsius for 10 seconds	Heat Press

9	Remove the LED circuit from the t-shirt press after its cool down and test the electrical performance of the circuit	Digital Multimeter
10	Look for any weak and faulty connection and resolder it again if needed	Visually, Digital Multimeter, Soldering iron
11	Test the circuit until all the LEDs function as expected	Digital Multimeter
12	Mount the accelerometer on the right-hand wrist and Arduino at the back part	Manually
13	Create conductive traces in front parts, back parts, and sleeve that will connect the motion sensor and the Arduino	Lock Stitch Machine
14	Stitch an additional layer of textile on the front parts of the garment to conceal the LED packages	Lock Stitch Machine
15	Assemble all the fabric pieces	Lock Stitch Machine
16	Connect traces using stitching and soldering at different joining points of the garment	Lock Stitch Machine, Soldering Iron
17	Insulate traces where needed	Fabric Paint
18	Solder a battery with the Arduino that will power the system	Soldering Iron

19	Test the complete circuit	Digital Multimeter
20	Troubleshoot the circuit	Digital Multimeter
21	Final assembling the garment	Lock Stitch Machine

Table 5: List of operations involved in the fabrication of the shirt

Several tools/machines are identified for the fabrication of this garment. A list of the machines and tools used in the fabrication process along with their operations are provided below in Table 6.

Machine Used	Operation
Pattern Stitcher	Stitching circuit layout for the LED array
Lock Stitch Machine	Creating both regular and conductive traces; assemble the garment
Soldering Iron	To make electrical connections among components and traces
Mask and squeegee	To ensure even and accurate distribution of solder into the LED joints
Heat Press	Reflow soldering
Digital Multimeter	Troubleshooting the connections and circuits

Table 6: Tools/machines used for production

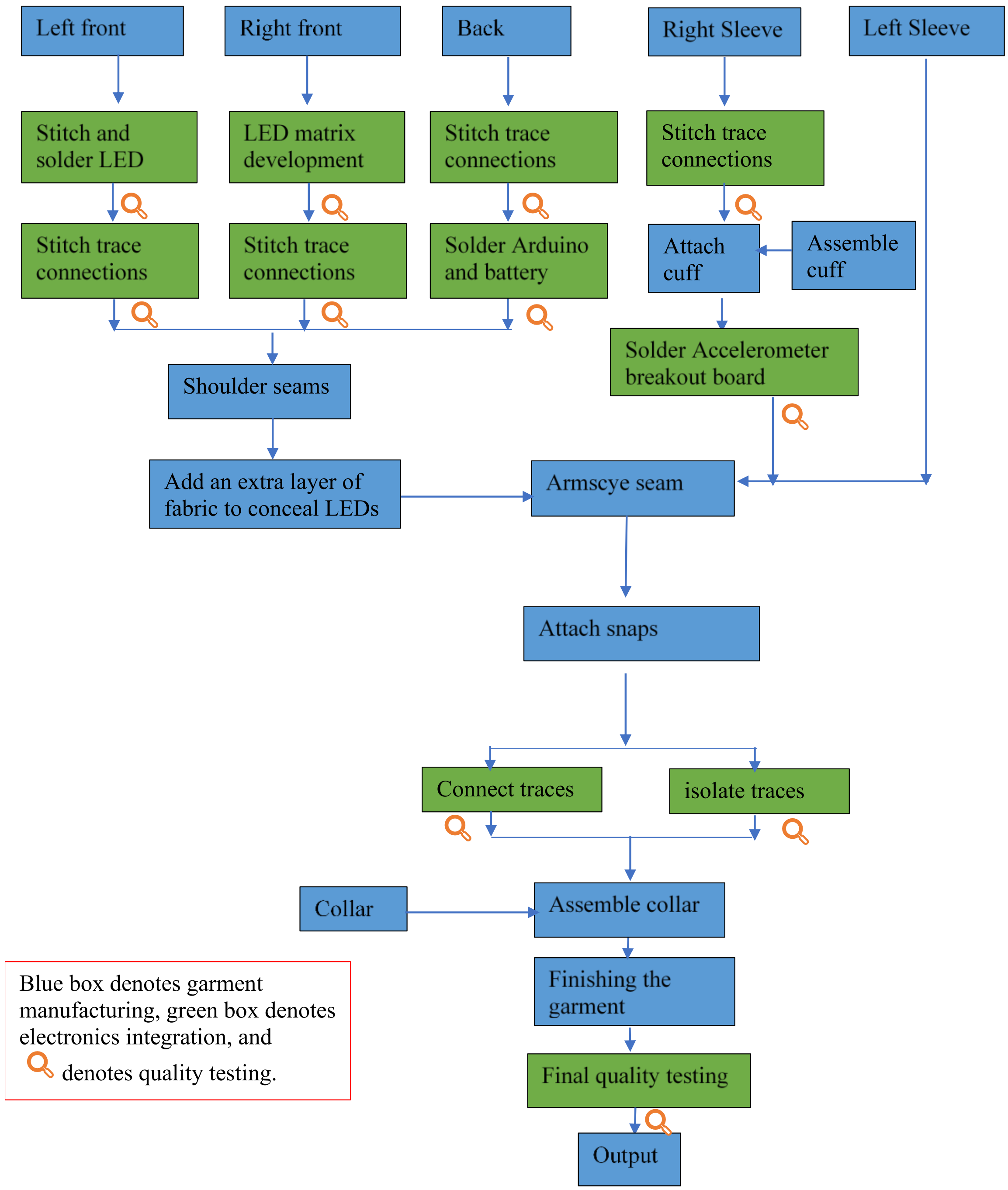


Figure 51: Operation sequence of the manufacturing process

Quality Check and Troubleshooting

For quality checking and troubleshooting purposes, we were able to use many of the same techniques that we used for the LED matrix. However, this time there were two major differences: the LED display was integrated into a more complex garment, with lockstitched traces connecting components across the garment surface (including trace crossings and seam crossing), and the supporting hardware system (accelerometer, Arduino, power supply) was also integrated directly into the garment. Quality testing was performed for both the hardware components (e.g. accelerometer and Arduino breakout board) and the garment integrated electronic components (e.g. accelerometer and Arduino breakout board integrated into the garment).

The tools involved in quality testing and troubleshooting of the e-textile shirt are listed below. They are described in the following section.

- **Visual inspection of the individual LED connection**
- **Inspection using Microscope**
- **Testing using a power source**
- **Testing using a hardware set up with a prototype board and Arduino code**

While selecting the quality assessment tools and techniques, we tried to use the tools and techniques that are commonly used for e-textile prototyping. Special attention was placed on selecting tools and techniques that were readily available in the lab at the time of the study. All tools used here are very common for testing simple electrical circuits. For instance, Arduino prototyping boards are very popular among hobbyists and practitioners in the e-textile community since these boards use a simple, easy to use plug-and-play technique to assemble and can be easily used for prototyping and testing purposes. Hence, for this project, we have used an Arduino prototype board to test the e-textile components of the finished garment. Using a power supply and the Arduino set up, we tested the functionality of the e-textile components and the finished shirt, continuity of the wires between components, and the attachment of the components. We used the hobbyist approach where we started testing and troubleshooting with the finished shirt and moved down to individual component levels until all the e-textile components were working as expected. More complicated circuits would require more rigorous testing of the individual e-textile components. Since the primary objective of this project was to seamlessly integrate the e-textile components into the garment and create a reliable connection between components, use of more sophisticated and automatic quality assessment tools and machines were out of scope of this project.

Stages of quality control and troubleshooting are described below:

- **Development of QA tools**
    - **Develop a hardware set up for testing electronics using prototype board and Arduino**
- **Primary QA check**
    - **Visual inspection of solder joints (LEDs, trace crossings, seam crossings, through-hole joints)**
    - **Test individual LED connection in a LED matrix using a power source**
    - **Test the completed LED matrix using the hardware set up**
    - **Test the LED display using the external hardware set up (to see if color changes based on the orientation of Accelerometer)**
    - **Rework any faulty joints**
- **Garment-level QA check**
    - **Test the LED matrix after sewing the garment**

- **Test the accelerometer after integrating it into the right cuff**
- **Test the accelerometer after attaching the cuff to the garment**
- **Test the Arduino after integrating it into the garment**
- **Inspection on a regular interval during the final garment assembly using visual inspection, a power source, and a hardware set up.**

- **Final QA check**
    - **Inspection after final assembly using visual inspection, a power source, and a hardware set up.**

Since the same LED display was integrated into this prototype garment, many of the same techniques (described in Section 3.4.1) were used for quality testing of the LED display and accelerometer system development. Again, we used the same hardware setup using a prototype board and Arduino code to test the LEDs and the accelerometer once they were integrated into the shirt. Similar to the LED matrix, each LED was tested in different stages of fabrication from soldering them onto the fabric pieces to integrating them into the garment to after final assembly of the garment. The LEDs were first inspected visually to see if there was any obvious joint failure and later tested with a power source. Once the LED display was fabricated, it was tested separately using the prototype board/Arduino hardware set up to ensure all the LEDs were functioning properly. A power source was used to check if there were any weak connections or cold solder joints. Re-soldering was done using the heat press when there was any weak connection.

Primary QA Check

As with the LED matrix swatch, faulty LEDs in the display were a significant quality assurance challenge. Since the shirt had 35 LEDs (as compared to 16 in the swatch), this challenge was even greater in the shirt. However, LED faults were similar to those experienced in the swatch and troubleshooting strategies were also substantially the same.

Due to their uneven and twisted structures, conductive threads often caused unstable connections. All electronics components (LED array panels, accelerometer, Arduino, etc.) were individually tested after stitching to a garment piece but before the piece was integrated into the garment. Later, we tested them again once they were integrated into the garment. We observed more faults after integrating the electronics into the garment compared to before integration. Again, the uneven and twisted structures of conductive threads were primarily responsible for that.

Solder Joint Rework

Due to the added complexity of the shirt display, excessive re-work caused irreversible failure of the stitched traces in some cases. This required re-construction of the stitched layout on a new piece. Ultimately, we fabricated redundant display pieces to ensure we had at least two LED array panels with fully functional LEDs.

Garment-level QA

While assembling the garment, some of the connections became weak or even broke due to the handling of the garment. We performed in-line system testing using visual inspection, a power source, and a hardware set up whenever we integrated a new electronic component and after performing a major process. Troubleshooting was done whenever we found a problem and the rework was performed before moving to the next operation.

Final QA

We also had some connection issues after the final assembly. Once everything was integrated into the shirt, we found it extremely difficult to troubleshoot the electronic system. For instance, there was one occasion where we had to remove the additional layer of textile (used to conceal the LEDs) to resolder some of the connections. Therefore, we had to spend a lot of time on the troubleshooting of the garment which we didn't anticipate at first. Further research needs to address all these challenges to increase the scalability and reliability of the e-textiles garment.

Limitations of the study and future work

Future development of the shirt should include extending the fully-integrated method to replace the microcontroller and inertial sensor unit (maybe with bigger package size, or by refining the method so that it can be used for smaller components). An intensive durability test of the shirt using a washing machine and tumble dryer is necessary to ensure that the produced e-textile is durable enough to withstand the conditions of everyday wear and tear. Further, using smaller size component packages for the LEDs will improve the drape and aesthetics of the garment (however, addressable LEDs are not currently readily available in smaller packages, so this may limit the design to single-color responses or require more extensive circuit design). Finally, repair and replacement of components in the fully-assembled garment is important for long-term usability. More sophisticated hardware and software, machines and tools could be used for testing and troubleshooting of the circuits which were not available during the time of the study. The summary of the study is shown in Table 7.

New Technique Developed in this shirt	Feasible/ deployable for mass production	What further development could be done
Use of the advanced assembly technique for the LED arrays	Feasible. Can be used for integrating similar PCBs into textiles	Try with smaller size LEDs or other types of PCBs. An automated pick and place machine could be used.
Use of the advanced assembly technique for the accelerometer	Not feasible for the same size packages or similar flip-chip packages.	Refine the method so that small components (less than 1mm) can be used too or try with a bigger package size e.g. components with smaller pin spacing and/or components pins having smaller diameter than conductive threads should be soldered easily.
Troubleshooting	Feasible	More in-depth in-process and after production

		troubleshooting need to be performed. Automated inspection systems could be used.
Reparability of the system by the users	Not feasible with the existing system design	Could be used replaceable parts or software debugging system so that user can fix the garment at home
Durability of the circuit	No durability test has been performed yet.	Durability test (i.e. washing and tumble dryer test) of the completed garment could be performed
Replacement of the components in the fully-assembled garment	Not feasible.	Could use replaceable electronic components in the garment assembly if that's a desired feature from consumer ends. The method would need to be refined to use replaceable electronic components.

Table 7: Summary of the techniques developed in the shirt

This work is the result of collaborative work among me, Steven Goodman, Crystal Compton, Cade Zacharias, and Dr. Lucy Dunne. Crystal was responsible for patterning and assembling the garment, I and Steven developed the stitched LED array, and Cade was involved with the prototyping of the electronic systems. The trace layout was developed by Crystal Compton and I.

3.4.3 A Controllable, Color Changing Dynamic Costume

The method was subsequently implemented to develop a child's costume with color-changing capabilities inspired by the Disney classic 'Sleeping Beauty' dress [7]. The color-changing capabilities on the dress are controlled based on input from a garment-embedded color sensor, based on a stimulus from a separate colored LED embedded in a wand. For this design, the surface-mount method was used to develop the top part of the garment.

We used the same NeoPixel 5050 RGB SMD LEDs here too. As previously mentioned, re-work was one of the significant constraints of our assembly and troubleshooting process in the LED display shirt presented in the last section. For this garment, we explored a modification of the stitched surface-mount technique to facilitate easier re-work. Specifically, with a large number of components and the relative inexperience of our team (relative to an industrial or highly skilled process), we found that more accessible re-work capabilities were needed to avoid scorching the base fabric during plate-press or heat-gun re-work. The fabrication method requires LED pad connections to be surface-mounted to the stitched traces on the textile surface. Once soldered, the pads are no longer accessible (they are beneath the component body, flush against the fabric), which can cause complications if troubleshooting is necessary. Therefore, as an extension of the previous method, small holes for each LED were cut in the base textile using a laser cutter before stitching the traces, to expose the LED pads from the base (Figure 52). A sacrificial layer of embroidery tear-away stabilizer was used to support the holes while stitching. The stabilizer was removed once the traces were stitched. Fusible interfacing was added to the back after troubleshooting was complete to fill the holes and maintain the mechanical stability of the component.

Figure 52: Laser cut holes exposing the underside of daisy-chained LEDs for ease of troubleshooting

This is the first time we used as many as 129 RGB LEDs in the garment without any significant manufacturing issues. Our technique for exposing the soldering surface of PLCC component packages for easier re-work helped translate an industrial method for craft and artistic processes. However, the process is labor-intensive and time-consuming and may not be suitable for large-scale application of the method. While the method modification presented here was successful in facilitating re-work capabilities, future development that minimizes the need for re-work (such as by using a precise, mechanized approach to placing components on the fabric) would further streamline the process. We have realized that the troubleshooting and re-working technique used here is quite time-consuming and arduous and need major refinement before using it for large-scale development of e-textile garments. Hence, this technique was not used in the latter part of this dissertation.

Acknowledgement: This work was jointly performed by Mary Ellen Berglund and Esther Foo, Md. Tahmidul Islam Molla, Smitha Muthya Sudheendra, Crystal Compton, and Lucy E. Dunne. Mary and I developed the top part of the garment which contains the LEDs developed by the surface-mount technique. The cutout approach to facilitating re-work was a concept generated by Mary Berglund, who also was responsible for developing the laser cutting and trace stitching methods. Dr. Dunne supervised the work and the work was supported by the University of Minnesota Imagine Fund.

3.5 Design for manufacturing for e-textiles products

Product Development for E-Textile Garments

From the studies described above, a framework has been developed for the product development process of e-textile garments, with a focus on development for manufacture [88]. From our preliminary study, we found the following major stages are involved in developing e-textile garments (Figure 53). Stages 1 to 5 are the product development phase and stages 6 to 8 are the transition to manufacturing or production. In this section, we will briefly describe the major steps involved in product development. The next chapter deals with translation for manufacture. Here the product development steps will be guided by what we have done before and will serve to develop a prototype from design concept to manufacturing.

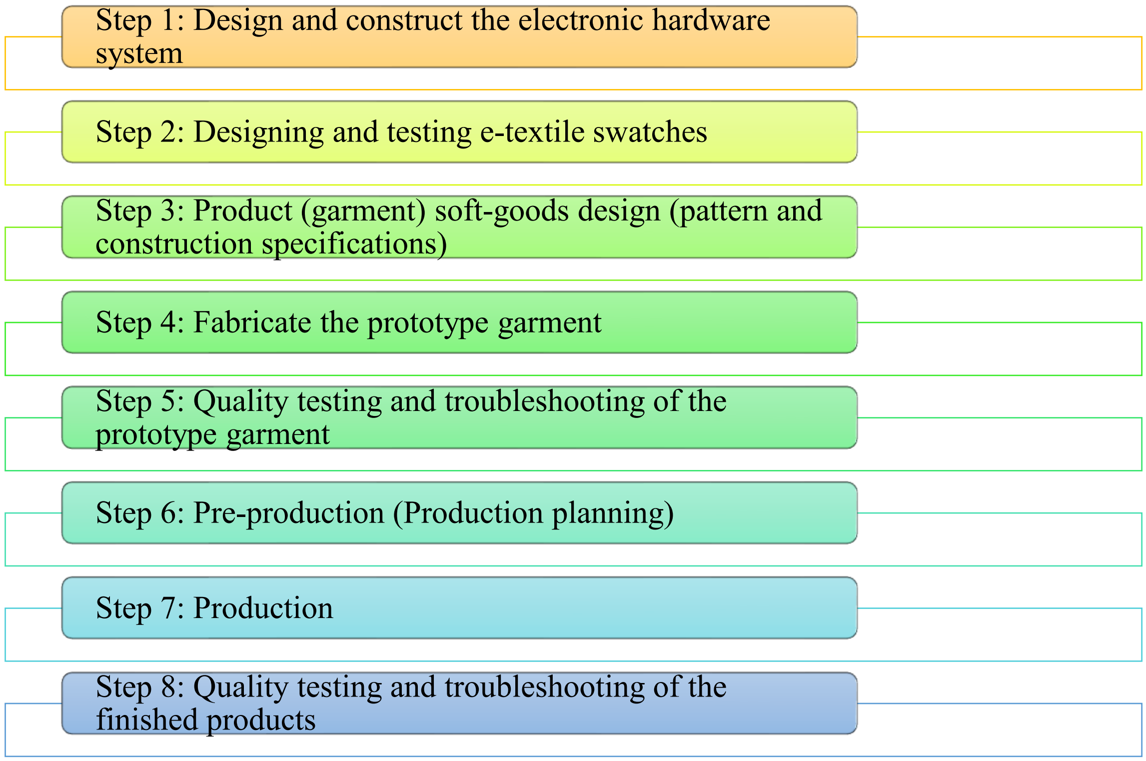


Figure 53: Stages of product development for e-textile garments

Figure 54 describes the workflow of an e-textile product development process prior to manufacturing. The process presumes that the overall garment concept (what it will look like, what it will do) has already been established. The blue boxes denote the steps involved in garment development and the green boxes denote the steps involved in electronic integration. Some of these steps may be modified or changed based on the product requirements.

Step 1: Construct the electronic hardware system

The first step of the e-textile product development stage is designing and constructing the electronic hardware system for the garment. Before developing an e-textile product, a hardware system needs to be developed to show the feasibility of the electronic system for e-textile applications which may be later translated into an e-textile. The

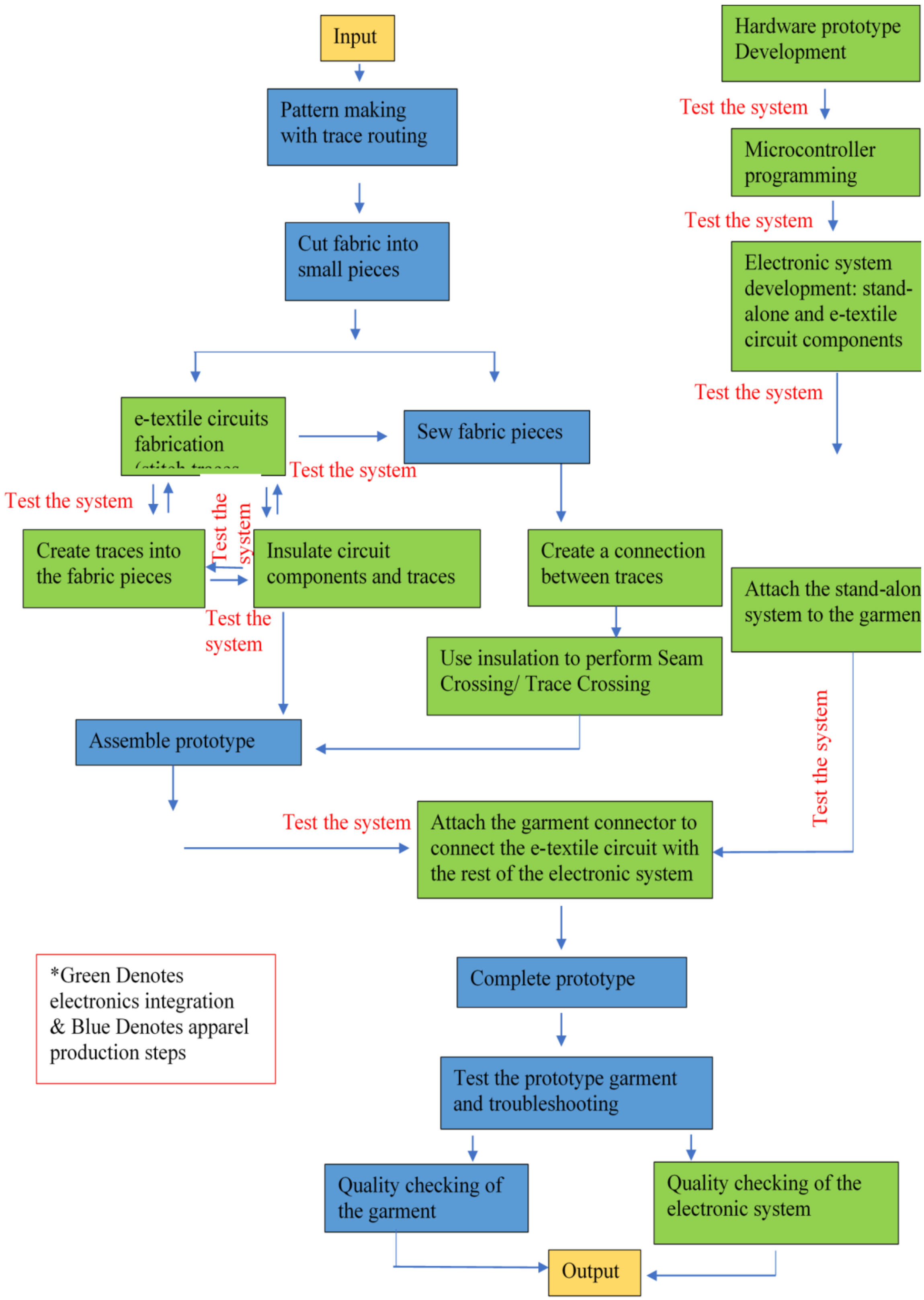


Figure 54: Workflow of an e-textile product development

hardware system helps to determine the electronic components and system architecture. The hardware system contains all the necessary components to make the system work which may include a microcontroller, sensors, actuators, battery, etc. A prototype board may be used to develop the system circuit since they are easy to work with. Once the hardware system is developed, the next step would be programming the microcontroller.

Step 2: Designing and testing e-textile swatches

Designing and testing e-textile circuit

In this stage, the electronic circuit will be converted into an e-textile circuit. Similar to the regular electronic circuit, the e-textile circuit consists of connectors, wires, and sensors which need to be integrated onto the textile platform. A method of integrating conductors and components into the textile is selected and implemented. In addition, an insulation material should be used to protect the circuit from regular wear, and tear and moisture. Functionality of the e-textile circuit needs to be tested first in textile form before translating it for product development. As described in section 3.4.2, the following techniques can be used to evaluate the functionality of e-textile circuits.

- **Visual inspection**
- **Microscopic inspection**
- **Testing using a hardware set up consisting of a prototype board and an Arduino code**

Steps involved in the integration of the electronic system into the product are described below.

Selecting an Integration Technique

The first stage of e-textile garment prototyping is selecting a suitable method for electronics integration. As mentioned earlier, the manufacturing process largely varies depending on the level of integration of electronics into textiles. Electronics can be integrated directly into fibers, yarns, or fabrics; or off-the-shelf electronic components can be attached to the surface of the textiles; or the complete electronic system can be attached directly onto the textiles. Each of these techniques will bring unique challenges for the mass production of e-textiles. For instance, when electronics are integrated into fiber level or yarn level, a significant portion of the manufacturing process will be involved with how the fibers, yarns, or fabric are made in a textile machine. On the other hand, when off-the-shelf electronics are affixed onto the surface of the textiles, most manufacturing process related to e-textile manufacturing are involved after the fabrics are made or before the garment assembly. Therefore, selection of the integration technique plays an important role in determining the most important variables for e-textile manufacturing. An existing manufacturing technique can be used for mass production of e-textiles. If needed, additional research needs to be performed for improving existing integration technique as well as looking for new integration techniques. The manufacturing method described earlier presents an alternative to traditional hard-goods electronics manufacturing for smart clothing and textile-integrated wearable technologies. The successful implementation of the technique for several prototypes indicate that the method can be used for developing a scalable and durable e-textile test prototype garments. In this thesis, that method is the focus of manufacturing efforts conducted. However, other methods are also feasible and may follow a similar product development process.

Material Selection

The next step is to understand the aesthetic and functional requirements of the garment and the embedded system. Once the concept is finalized, materials such as fabric, microprocessor (e.g. Arduino) and other system components (e.g. sensors, actuators, etc.) are selected at this stage. Since the focus of this study is on stitching conductive traces on the fabric, the selection of fabric largely depends on what the machine can handle. For example, our previous studies showed that stretchy fabric (especially knit fabrics) is not suitable for the pattern stitcher. We found the sturdy structure of the medium-weight cotton fabric allows uniformity in stitching the strong conductive traces. In terms of conductive thread, silver-coated Vectran conductive thread is suitable for our method since to our knowledge this is the only conductive thread that can be soldered and has minimum resistance values per unit length. We found that using the silver coated Vectron thread as a bobbin thread and regular polyester thread as a needle thread ensures only one side of the fabric is conductive and reduce the short on the other side of the fabric.

Once fabric and conductors are selected, the next step would be determining the system requirements and selecting system components accordingly. This stage involves balancing system design requirements and wearability requirements of the garment. Hardware and connectors required for the garment design are selected in this stage. Placement of components that require specific body locations as well as other system components and connectors is determined in this stage. The size and type of system components and protection of the components need to be considered while selecting the electronic components for the garment:

As illustrated in previous sections, the conductor/trace integration technique selected in the previous phase will dictate to some extent the package types and sizes that are feasible for garment fabrication. In addition to individually-integrated components, other system components must also be selected, taking into account their size and shape as well as functional capabilities. This includes a central processor (such as a microcontroller), any communication or networking hardware (such as multiplexers or wireless capability), and the system power source. So far, the battery is the most commonly used power source for wearable products. A lightweight battery such as Lithium-ion or Lithium-polymer battery might be suitable for e-textile projects, but must provide adequate run time between charges. Additional system components might be necessary depending on the design and complexity of the system

In our previous studies, we have explored several insulation materials and methods to protect circuit structures. Tradeoffs between level of protection, wearability or hand feel, and production requirements exist for all methods explored. Therefore, the designer must balance these requirements when selecting a method to protect embedded components in the e-textile garment.

E-Textile swatch development

Once we find the right components for this project, our next step will be creating a circuit design. The stitched method of fabricating surface-mount components presented in the previous section can be implemented for the e-textile prototype development. While creating the e-textile circuit design, several other design variables such as stitch length, satin floats (to create isolate connections), and backtacks (to strengthen the trace ends) need to be further explored.

Step 3: Product (garment) soft-goods design (pattern and construction specifications)

The design of the soft-good is developed in this stage. The desired garment design, garment patterns, placing marks, darts, etc. for electronics placement, fabric cutting, etc. are developed for the prototype development.

Placement of Components

The location of components with specific spatial requirements as well as other system components needs to be determined at this stage. These requirements depend on the system design, the base fabric substrate and trace/insulation materials, and the wearability requirements of the garment. Further, component placement may take into account other factors like avoiding high-flex or high-impact body areas.

Trace routing

Since electronic components are placed in different locations of the garment, many traces will be made to connect them. There will be instances where traces need to cross each other, and instances where traces need to isolate from each other. Several iterations of the trace layout are made to ensure minimum trace crossing in the garment.

Fabric cutting

Fabric is cut based on the size and shape of the pattern pieces. All the placement marks, darts, etc. are retained in the fabric pieces.

Step 4: Fabricate the e-textile prototype garment

Finally, physical samples are made in this stage. Prototyping the garment involves surface-mount component integration, PCB assembly, electronics integration, and garment construction. Fabric pieces are sewn together. Based on the position and alignment of the traces, a method may be needed to ensure effective trace crossing and seam crossing in the garment. This might be the use of a satin stitch and fabric paint as an insulator (as done in the previous examples), use of a different insulation material such as silicone or a thermoplastic tape, addition of a fabric layer on top of the conductive traces, or a more advanced multilayer circuit technique. Finally, an insulation material is used to protect the components and traces of the electronic system.

Step 5: Quality Testing and Troubleshooting of the Product

Similar to the testing of the electronic circuit, the final product needs to be tested. The following testing can be performed to ensure prototype garments are working perfectly.

- **Test the electronic system of the prototype**
- **When testing reveals system faults, troubleshoot and resolve the fault**
- **User study to evaluate the user comfort and convenience**

Quality testing and troubleshooting must happen repeatedly at different stages of product development as described in section 3.4.2. Two main types of quality testing and troubleshooting are performed: in-line quality testing and quality testing after final product development. The functionality of the prototype is tested, and troubleshooting is performed if there is any connection and/or system issue found in any stage of the product development. Necessary rework of the product also performed to ensure the e-textile system is functional, and fabrication processes are modified if needed to prevent future faults.

Decision-making variables for e-textile product development

Several manufacturing variables that are particularly important for the decision-making of e-textile product development are identified throughout the process and described below in figure 55.

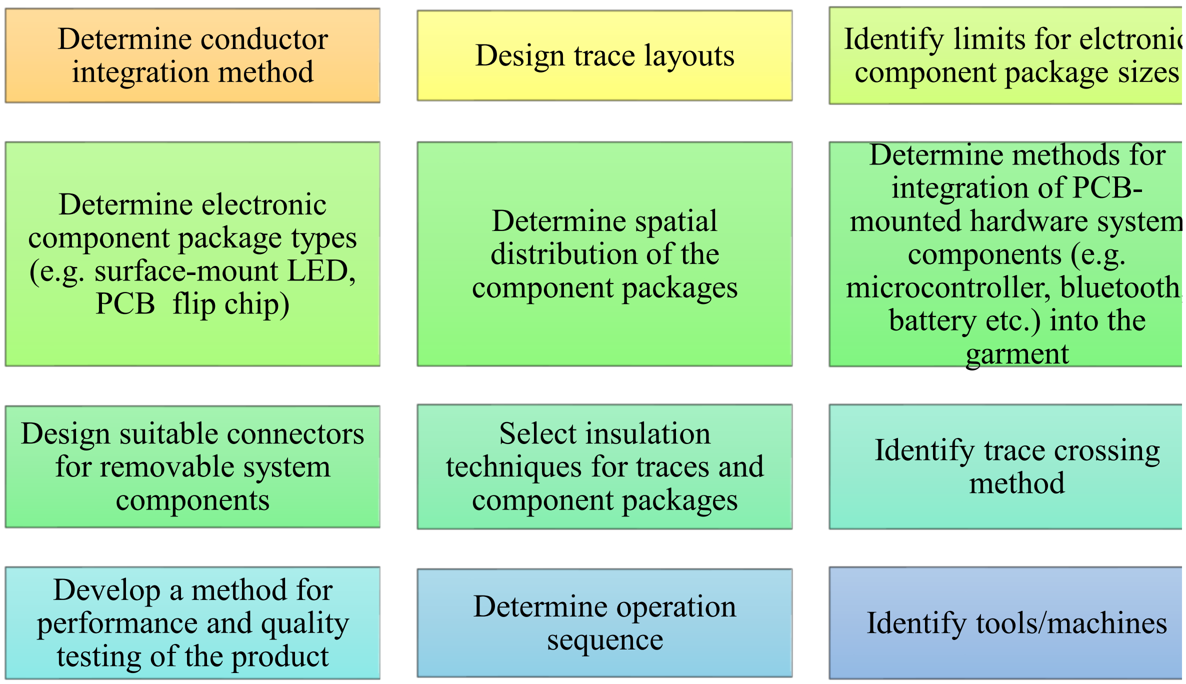


Figure 55: A summary of list of manufacturing variables for e-textile product development

Summary

We have developed a surface-mount fabrication method which uses an embroidery machine industrial pattern stitching machine to stitch conductive traces onto a fabric surface in a 2D pattern and a reflow soldering technique to affix standard electronic components. The method was rigorously tested to ensure the method can produce efficient, durable, and reliable e-textile circuitry that can withstand regular wear and tear and washing. Durability of this method was evaluated for circuit architecture variables of component size, trace width, and trace orientation, as well as for methodological variables of solder deposition technique and reflow process. A 14-hour wear test shows a 3% failure rate for the best manufacturing conditions. Next, we performed a durability test based on machine washing and drying while varying the textile substrate, component size, and intensity of the laundering cycle. We measured a 1.5% failure rate for component solder joints after around 17 hours of rigorous washing and drying. We extended the launderability test with alternative surface insulation materials, textile substrate properties, and soldered component joints. After around 16.67 hours of rigorous washing and drying, we measured a best-case 0% failure rate for component solder joints, and a best-case 0.38 ohm/m maximum increase in trace resistance. Where silicone seam sealer shows best results protecting e-textile components, we found that film-based insulations such as Bemis seam tape could be used to protect the e-textile circuitry during home laundering. All these results show the effectiveness of the method for e-textile applications. Later, the method was extended to develop more complex circuitry to a complete garment. To demonstrate the manufacturing method with a slightly more complex circuit, a custom-designed stitch layout was used to connect an array of RGB LEDs to an Arduino microcontroller which was later translated to a motion responsive visual display garment. The development of these prototypes served as an exploratory investigation to discover the major challenges of fabricating garment-scale e-textile products. A design framework was developed for the product development process of e-textile garments, with a focus on development for manufacture. Finally, a list of manufacturing variables is described which are crucial for the general e-textiles product development process.

CHAPTER 4: DEVELOPMENT OF A CASE STUDY MANUFACTURING PROCESS

So far, we have used the stitched surface-mount fabrication methods to develop more complex multi-component e-textile circuits, and a few e-textile garment prototypes. But we do not know yet how the method translates to the production of e-textile garments at a larger scale. Manufacturing e-textiles in mass likely involves additional processes and variables not addressed when developing a prototype or individual sample. There should be some common variables that are important for both prototyping and mass production, and some unknown manufacturing variables between them as well. Furthermore, the tools and machines we used in the laboratory setting to develop a single prototype might be different from a CMT factory setting used for bulk production. Therefore, new challenges may emerge when these methods are deployed in a CMT factory setting. The next step of this thesis aims to identify and explore these potential new factors. Therefore, I proposed the following research question:

Research Question 5: What are the tasks involved in transitioning from prototype development stage to the deployment stage in a factory setting? What additional manufacturing variables emerge during the deployment of the e-textiles manufacturing process?

To answer the above question, we developed an example e-textile prototype garment which was later produced in higher-volume production in a CMT factory case study scenario. As shown in the previous chapter, there are many options for e-textile integration strategies. Within each, there are many different integration processes and sub-steps of e-textile production, each of which can be individually developed and optimized.

The scope of the deployment of the manufacturing process is directly related to the choice of e-textile integration strategy. For instance, when electronics are directly integrated into textiles (e.g. fiber, yarn, and fabric), the deployment should be primarily focused on integrating electronics by manipulating textile machines such as knitting, weaving, and/or braiding machines. On the other hand, when electronic systems and apparel are developed as a separate process so that they can be later combined together, the deployment would be primarily focused on seamless integration of fully fabricated electronic systems into textiles. Similarly, when a hybrid integration process is implemented where small PCB components are integrated into textiles, the whole deployment is designed based on the implementation of tools and machines that are used in both apparel and electronics industry. As in previous chapters, this work focused on using the stitched surface-mount fabrication process. All of the durability and functionality testing was performed to validate that the method can be implemented for the deployment of the study in a factory setting. The methods and tools used for the implementation of the method could be used with minimum or no modifications for producing e-textile garments in bulk.

However, optimizing all operations and sub-processes is out of the scope of this dissertation. Here, my goal is to identify the more abstract challenges involved in transitioning from one-off production to a larger-scale context in a CMT factory setting, somewhat independently of the operations used. Therefore, I developed a case-study manufacturing process and later deployed in a CMT factory setting. The main advantage of the case study method is that it is narrowly focused, provides a high level of detail, and can combine both subjective and objective data to obtain an in-depth understanding. Furthermore, case studies often shed new light on an established theory that ends in further exploration. Since the manufacturing of e-textiles is a very new area and has not yet been the focus of substantial attention in academic research, a thorough and in-depth analysis of the area is required. The case study method is a useful way to identify challenges in mass manufacturing which can later be used as a reference for general e-textiles manufacturing in a factory setting. I believe the proposed case study will help provide a better understanding of the manufacturing challenges related to e-textiles manufacturing.

To answer the above questions, we developed an example e-textile prototype garment which was later produced in higher-volume production in a CMT factory case study scenario. As discussed in chapter 3, there are three major stages involved in the production of e-textiles in mass that are the primary focus of this study. These are: product development, production planning, and production. In this chapter, I will briefly describe the product development and the production planning steps and explain how I implemented them in a factory setting. This Chapter addresses Research Question 6. I will discuss the production study in Chapter 5.

4.1 E-Textile Prototype for the Study

For this study, I designed and manufactured a temperature-sensing firefighter turnout coat liner. An example of the firefighter turnout coat liner is shown in Figure 56. Firefighter suits have multiple layers, and the primary purpose of the suit is to protect the user from extreme heat and moisture conditions. Currently available firefighter suits do not have the facility to detect the change in temperature inside the garment and between the layers, which is related to how comfortable the user feels and how safe they are in hazardous environments.

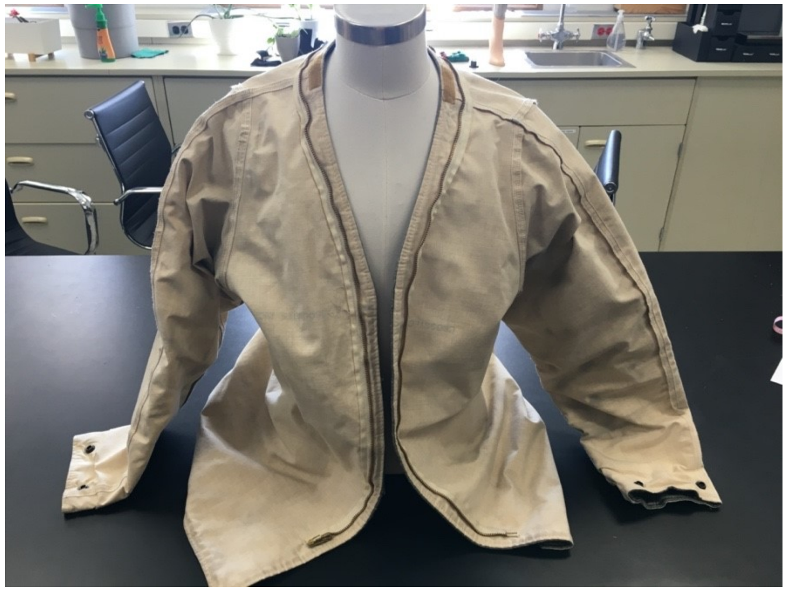


Figure 56: A fire-fighter coat liner

To measure the impact of technology integration into a garment (as compared to a standard garment) in a manufacturing scenario, forty pieces each of e-textile thermal liners and regular thermal liner garments were developed. The integration of technology was considered in-line with a regular apparel manufacturing process. The manufacturing case study was used to identify abstract manufacturing variables introduced by electronics-integration processes.

4.2 Developing the Manufacturing Process

Developing the manufacturing process for e-textiles involved three major stages as described earlier: product development, production planning, and production. The following section will discuss about the development of a regular and a sensor-integrated thermal liner garment which will be followed by a detailed description of the production planning for the manufacturing of forty regular and forty sensor-integrated thermal liner garments in a CMT factory setting. The production planning steps will address all the additional tasks and new variables emerged in transitioning from prototype development stage to the deployment stage in a factory setting.

4.2.1. Prototype Development

For the design and development of the sensor-integrated thermal liner, we bought a medium size fire-fighter suit and used the thermal liner as a reference for our final product development. The thermal liner was used to develop new patterns for the prototype garment. For the development of the fire-fighter turnout coat liner, I used the framework that I outlined in chapter 3 section 3.5. The following sections will provide specific details of the prototype garment following the steps developed in Chapter 3.

Step 1: Construct the electronic hardware system for the sensor-integrated thermal liner

A hardware set up for testing the electronic system of the garment was developed in breadboard form with through-hole components, based on an Arduino microcontroller, using the technique described earlier. The electronic system reads the temperature from an array of 6 sensors over an Arduino serial monitor and was also used in in-line and post-process quality assessment of the e-textile garment. Figure 57 describes the system design of the garment.

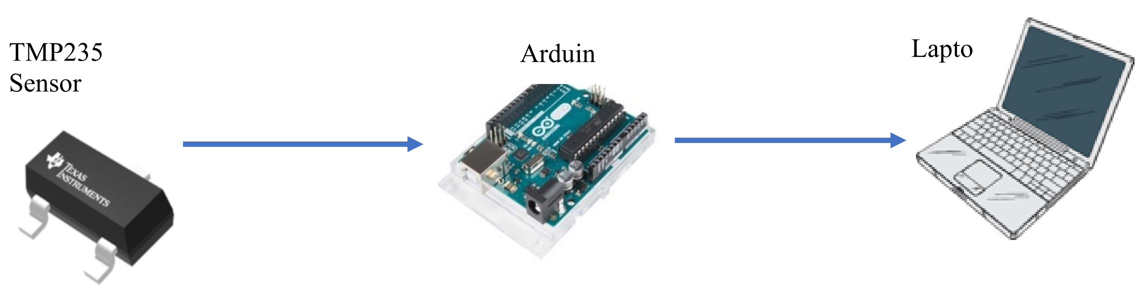


Figure 57: System Diagram of the Garment System

As shown in Figure 58, each sensor has 3 leads: V_{DD}, V_{OUT}, and GND which need to be connected with 3 pins of a microcontroller. Power and Ground pins from each sensor can be routed to power/ground rails within the trace layout, but each V_{OUT} pin must connect to an individual microcontroller input. Later, an e-textile circuit was developed using surface-mount components. Figure 59 describes an Arduino Uno microcontroller set up that was developed for e-textile testing purposes.

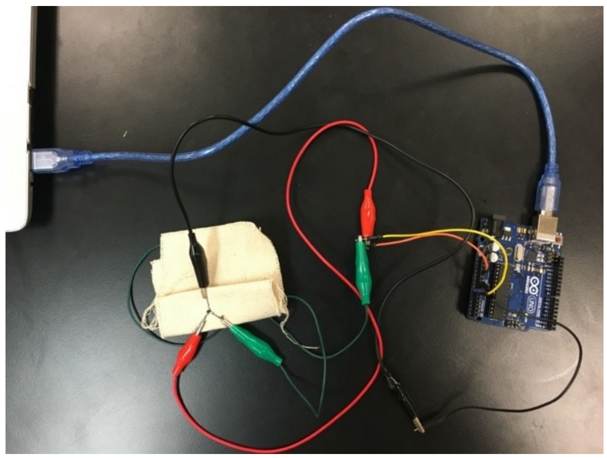


Figure 58: Arduino set up for testing e-textile swatch

Step 2: Design variables involved in e-textile prototype development

The surface-mount method described in Chapter 3 was implemented here for a new component package. The following sub-sections describe details on the implementation of the fabrication method for this specific garment design.

Electronic components

Since the garment design requires a temperature sensor, I explored several surface-mount temperature sensors. Finally, I decided to use the Texas Instruments TMP235 analog temperature sensor as shown in Figure 59. The sensor has an output voltage proportional to the temperature and can measure temperature ranging from -40^{0}C to +150^{0}C. The package has a dimension of 1.4mm x 3.04mm. It has 3 leads and the distance between the two closest leads is 1.9mm.

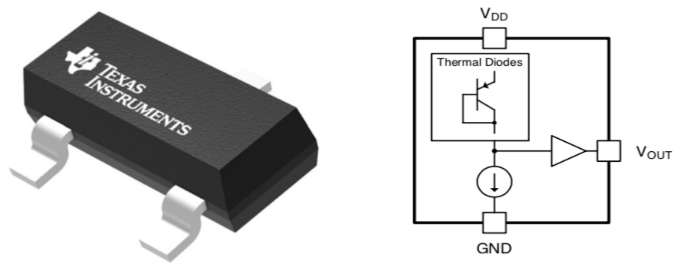


Figure 59: TMP235 Sensor: Outside view (left) and functional block diagram (right)

A feasibility study was done to make sure that the package is solderable using the surface-mount reflow method (Figure 60). The test showed that a sensor of this size and shape can be adequately soldered to stitched traces using our method, and hence it was selected for this study. Similar to previous prototypes, silver-coated vectran thread was used as a conductive thread in the bobbin and 100% polyester thread was used as a needle thread.

Figure 60: Stitched surface-mount sensor circuit: Stitched circuit (left) and microscopic view (right)

System design for e-textiles

As described in Step 1, sensors need to be connected to a microcontroller to collect and process the sensor data, and to communicate data to an external computing system. While an Arduino Uno was used for testing the individual sensor, an Arduino Nano microcontroller was used to handle processing and control for this garment. The Arduino Nano has 6 analog pins that read the input from 6 temperature sensors and also has a very small form factor. Arduino Nano was not directly attached to the e-textile circuit, rather it was attached to the e-textile circuit via a fastener. The fastener development process will be described later.

Step 3: Product (garment) soft-goods design (pattern and construction specifications)

Location of the system components

For this study, I have decided to use six sensors in six different locations of the body: front right chest, front left abdomen, back left waist, back right armpit, left wrist and right wrist. The Arduino Nano system component was placed in a small compartment at the front right abdomen of the garment. Figure 61 describes the location of the system components in the liner garment.

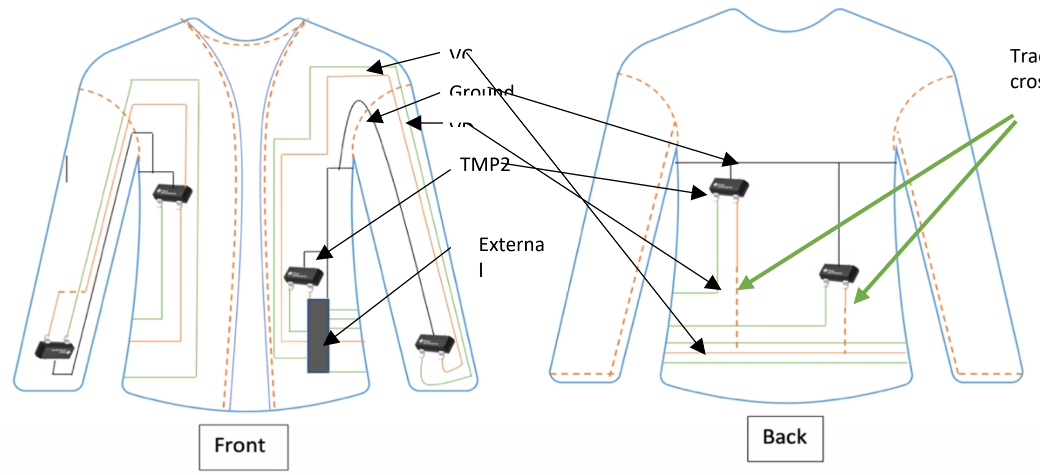


Figure 61: Location of the system components

Step 4: Fabricate the e-textile garment

The next step is the development of the e-textile garment. The following steps were mainly involved in the fabrication of the e-textile garment.

Pattern making and Fabric Cutting

The measurements of the thermal fire-fighter liner garment of a medium-size firefighter suit were considered for preparing the sample garment and a pattern was created based on these measurements. Placement marks and notches were made to indicate the alignment of the pieces and the position of the electronics on the garment when necessary. Patterns were created for front, back, and sleeves of the garment.

Textile Components

In real-life applications, Kevlar and Nomex fibers are generally used in most firefighter gears. Since these materials are expensive and more difficult to procure, to simplify the process a medium weight 100% cotton canvas twill fabric was used for the production of fire-fighter thermal liner garment. The sturdy structure of the medium-weight cotton fabric allows uniformity in stitching the strong conductive traces. To be consistent with the traditional firefighter thermal liners, a zipper and velcro straps were used in the liner. The zipper and Velcro straps allow the user to attach the liner to the outer garment. The liner prototype also includes a pocket that holds and hides the external hardware unit as described below.

Developing the trace layout for sensor attachment

The next step is to develop the component attachment layouts using the pattern stitch machine, according to the method described in Chapter 3. I decided to use six sensors on the outside of the firefighter thermal liner and therefore, six sensor trace layouts were made to attach components in six different locations of the garment pieces (1 on the right sleeve, 1 on the left sleeve, and 4 on the body). Several automated stitch layouts were explored while changing trace orientation, trace density, and stitch length to determine the layout for component attachment that would produce the most reliable solder attachment of the component. Each sensor has 3 pads and the gap between two nearest pads (power and output) was 1.4 mm. Therefore, I had to design the stitch layout in such a way that the traces were far away from each other not to short, but close enough to the leads to be still solderable. As shown in Figure 62, at first, I stitched two parallel lines for attaching power and output pads on the traces. While I was able to solder the components, there was a higher chance of sorts between traces. Later, I decided to use a Y-shape layout which leaves the two pads further away from each other, but still in a range where they could be solderable. Due to the smaller size of the sensor, I tried to put all three trace lines as close as possible while making sure they did not touch with each other. As described in chapter 3, I used two different types of threads to create the trace layout-regular 100% polyester thread in the needle and silver-coated vectran conductive thread in the bobbin which ensures that only one side of the fabric has conductive threads on it. The silver-coated vectran conductive thread is much stronger than the needle thread and therefore, it shows some reluctance against machine tension while stitching compared to the polyester thread. Within the same stitching length, the conductive thread covers less distance than the needle thread when the stitching direction is reversed (doubles back on itself). I used this feature to manipulate the trace layout. In my design, I designed the traces in such a way that polyester thread traces touched each other, but since the conductive thread stopped short of the last needle position, it avoided contact between conductive threads. Several iterations were made to find the best trace layout which allowed trace ends to stay as close as possible without touching. For the trace density, I evaluated a single stitch line, two stitch lines, and four stitch lines in each trace and found that two-stitch traces were the most suitable for this particular design. While more stitches increase the conductivity of the trace layout, it gives a messy and crowded surface which makes the soldering more difficult. On the other hand, the two-stitch layout provides more stability than the one-stitch layout. I made different trace layouts with stitch lengths of 2mm, 3mm, and 4mm. While larger stitch length provides more conductive thread exposure which makes soldering easier, it also makes the thread less stable on the fabric surface. My study results showed that 3mm stitch length provided a better balance between conductive thread exposure and sturdy trace layout and hence, was selected in the trace layout. After considering all the above factors, finally two identical stitch patterns (one for the left hand, one for the right hand, and four sensors for the body) for the TMP235 temperature sensor were developed.

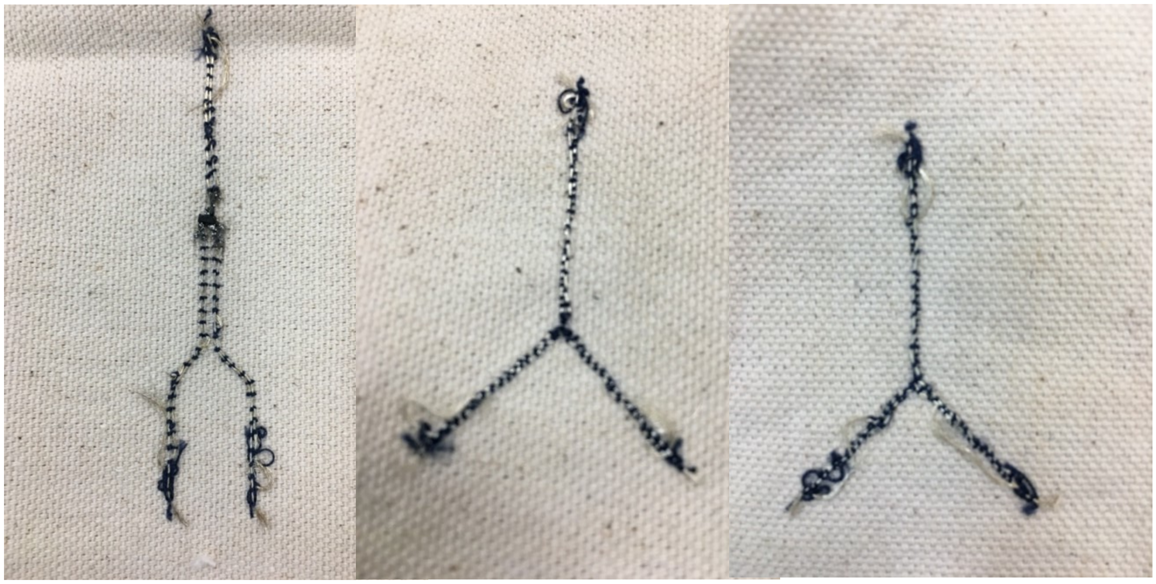


Figure 62: Several iterations of the trace layout for the sensor attachment

The TMP235 temperature sensor attachment was developed using the method described in chapter 3. Figure 63 describes the steps involved in fabricating the sensor attchment. Each sensor was tested individually to ensure the functionality of the sensor joints.

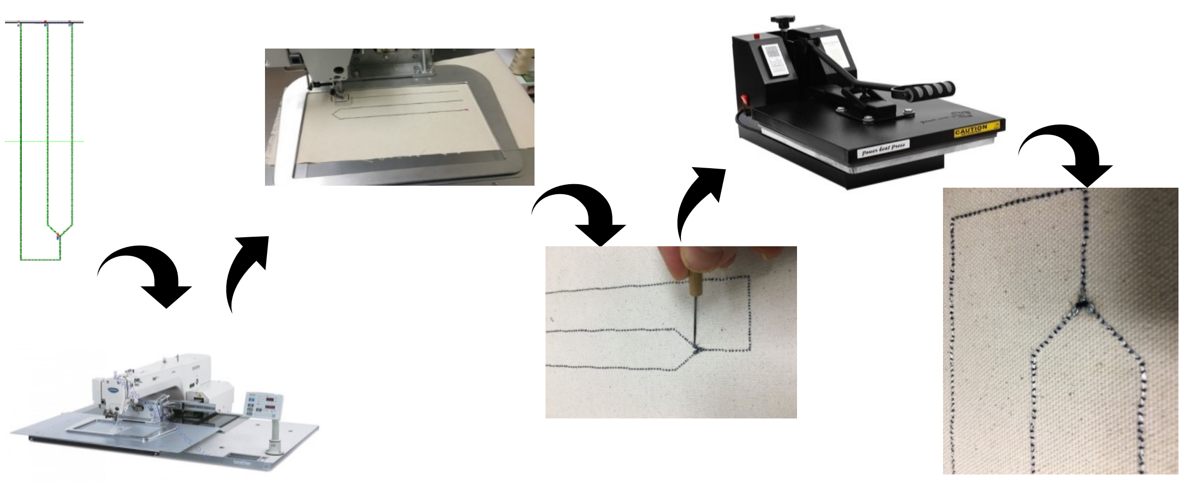


Figure 63: Surface-mount fabrication of the TMP235 sensor

- **Trace connections**

Similar to an electrical circuit, trace connections were made to connect the automatically stitched sensor layouts with the rest of the electronic system on the garment (e.g., other sensors, Arduino, etc.). Since the six sensors were distributed all over the body, a trace layout was developed to allow traces to travel from sensor locations to the removable hardware system. The trace layout was developed following the method described in Section 3.5. While designing the trace layout, primary attention was paid in developing a simple trace layout which will allow less connection joints and crossing points. Several iterations were made before selecting the final design of the trace layout as described in Figure 64.

In the sensor-integrated thermal liner garment, traces were created using a lock stitch machine. Connections between traces were made by stitching traces on top of each other. Traces were stitched according to a trace layout described below. Similar to the pattern stitcher, I used conductive thread in the bobbin and 100% polyester thread in the needle, and the fabric was stitched upside down. I left a 1inch edge on shoulder seams to give some allowance while connecting traces over seamlines during the final assembly of the prototype garment.

However, while testing the finished prototype garment, I noticed a weak connection often existed between the connection points of two different stitched traces (e.g. between the pattern stitched traces and lockstitch traces). Therefore, additional enforcement was required to create connections between the sensor circuit layout sewn with the pattern stitcher and the joining traces applied using a lockstitch machine. I found backtacking, a sewing technique where multiple stitches are stitched in a small area, could be used to increase the conductive surface area which eventually helps to solidify the connections between two different trace layouts. Hence, backtacking was used for stable electrical connections among traces. Backtacking was also used as reinforcement at corners, transition points, and crossing garment seams (e.g. armscye). In addition, a soldering iron along and solder was used to solidify the connection between traces if needed.

- **Trace crossing and seam crossing**

As shown in the trace layout (Figure 64), there are certain situations where a connection needed to be made between traces (e.g., two power lines should join each other without touching the ground or sensor output), but were interrupted by a different trace line (e.g., sensor output). In an electrical circuit, trace crossing is typically done by using additional layers. The same technique can be implemented for e-textiles as well where additional fabric layers can be used for trace crossing and seam crossing purposes. However, adding additional fabric layers make the garments bulkier which is not a desirable property for clothing. In the Motion Responsive Visual Display Garment described in Section 3.4.2, a float stitch was used to allow traces to be separated, by floating one trace over another already stitched trace. A small amount of fabric paint was then applied to the bottom trace (while lifting the float stitch) to insulate the trace crossing. That method was effective but time-consuming. In addition, the fabric tape might come off anytime exposing the electronic system for a short circuit. Since our method uses conductive thread only one side of the fabric that allows us to use the fabric surface as a two-layer circuit where the fabric is used as an insulation material between layers. Therefore, when a trace crossing is needed, a connection can be made on the other side of the fabric. This technique was originally developed by Dunne et al. [16] and applied in this project for developing the sensor-integrated prototype garment. For situations where traces should not cross each other (i.e., a situation where power and ground cross each other), trace crossing was performed using four steps: first a needle was used to take the thread to the opposite side (wrong side) of the fabric, second, stitching was performed on the wrong side of the fabric and third, a hand sewing needle was used to move the conductive trace to the right side of the fabric and fourth, tie the traces together to make a connection. There was a total of 5 instances where a trace crossing was needed as showed in the red markings on Figure 64.

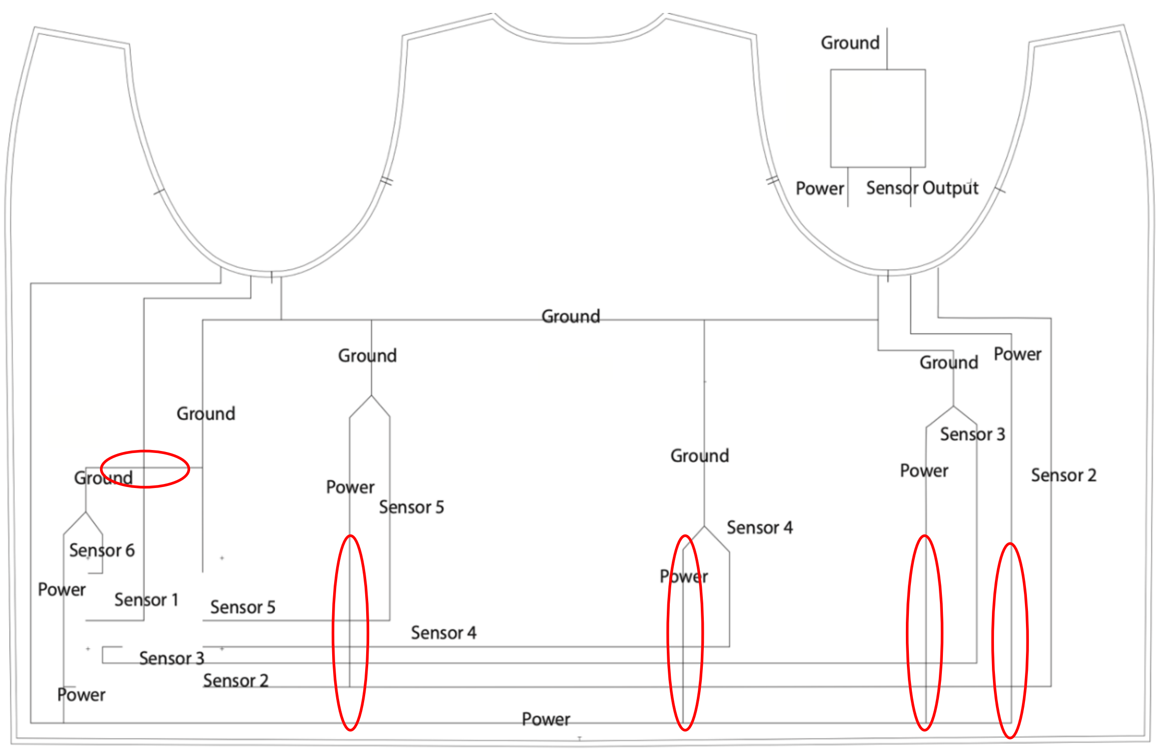


Figure 64: Draft Trace layout for the fire-fighter thermal liner garment

- **Removable hardware development**

The control unit (Arduino) was developed as a removable device in a non-textile housing. Within the housing, wires were soldered using a soldering iron to create permanent durable connections between components and connectors embedded in the housing. The whole removable system was developed and tested separately from the e-textile garment. Steps involved in the development of the external hardware system are described in Figure 65.

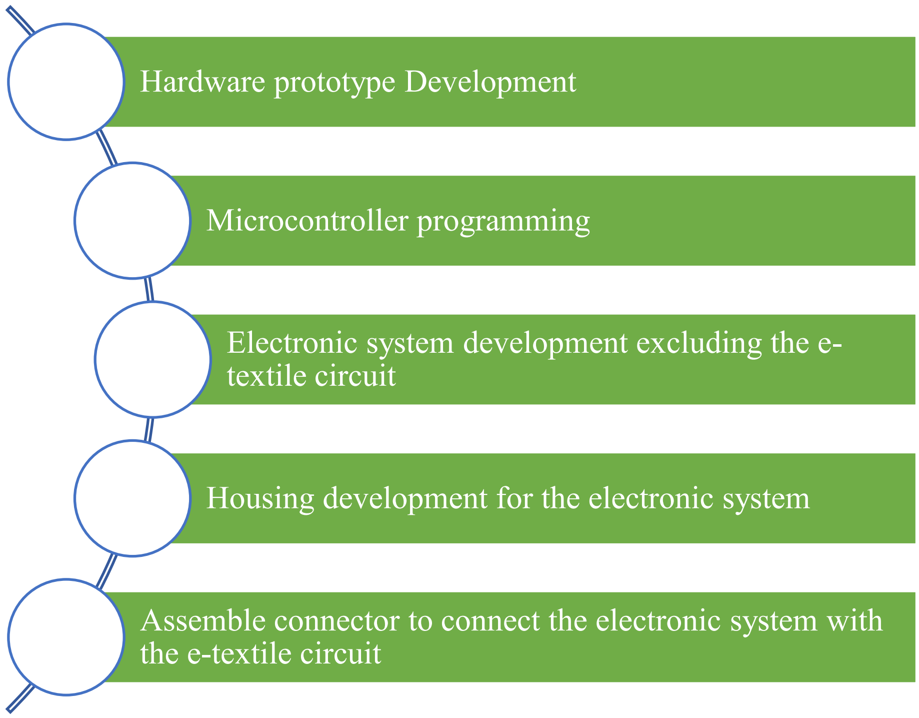


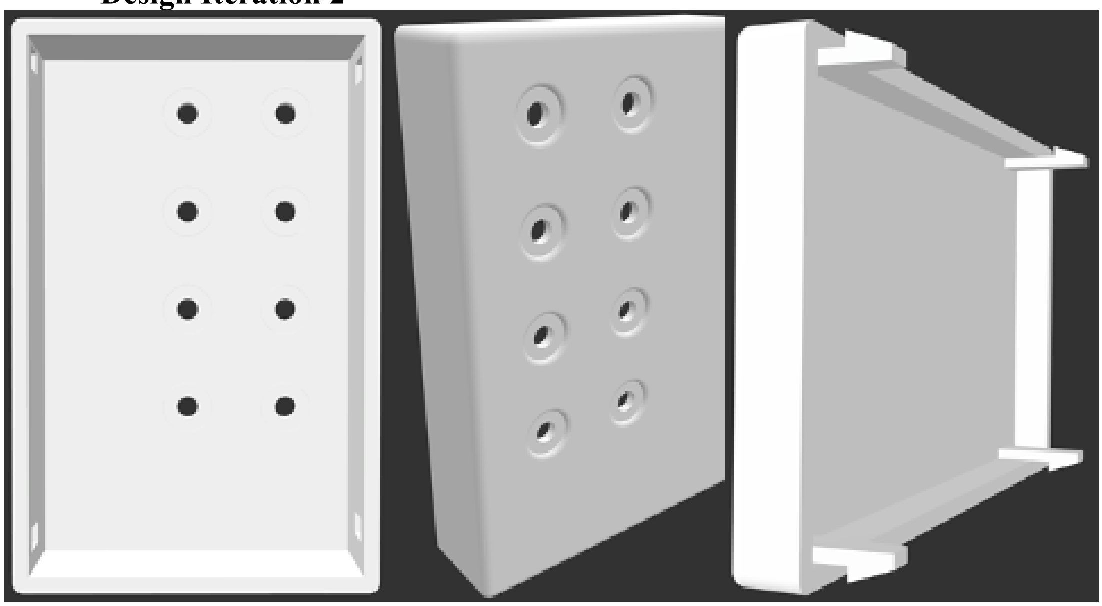
Figure 65: Removable hardware development flowchart

A 3D printed housing was made to enclose the Arduino and wires and was placed in a pocket on the front part of the garment. The housing consists of two parts: body and lid. Several iterations were made for both body and lid of the body as shown in Figure 66. In iteration 1, the case body was too big for the pocket and the snap holes were made on the side of the body. Since the pocket can be only accessed from the top, I realized that it would be more convenient for the user to snap the housing inside the pocket if the snap holes are placed on the underside of the housing body. Hence, for iteration 2, I put the snap holes on the underside of the housing body. For the housing lid design, I initially made a cantilever snap joint that allows semi-flexible cantilevering hooks to make a mechanical bond once the hook passes the edges of the housing body. When printing the housing lid with the 3D printer, I realized that the hooks were not flexible enough and could easily break if too much pressure was put on the lid while putting inside the housing body. Later, I designed a sliding snap joint where the housing lid was a little bit bigger than the housing body and the housing body could easily fit under the lid once it slides into the lid. A few adjustments were made to make sure the snap joint worked perfectly between the lid and the body. The final design was selected based on the form factor of the case, ease of printing, and the size of the pocket. Three different materials (PLA, Ninjaflex, and PETG) were used to test the housing and I found PLA provided the most rigid and stable printed structure and hence, it was used for the housing.

A temporary connector is needed to connect the removable hardware system with the e-textile garment. Here, I used metal snaps as the temporary connector. Flexible wires were used to connect the snaps with the hardware system. This sub-system was developed and tested following the process described in Section 3.4.2. Figure 67 describes different parts of the final removable hardware. As you can see in Figure 67, the housing was way bigger than it needed to be and not optimized for the thermal liner garment. The case was initially designed to contain few other system components such as battery, Bluetooth, etc., which were not included in the final prototype garment since it was not the primary focus of this project. However, these components should be considered for future design improvements.

Design Iteration 1

Design Iteration 2



Design Iteration 3 (Final Design)

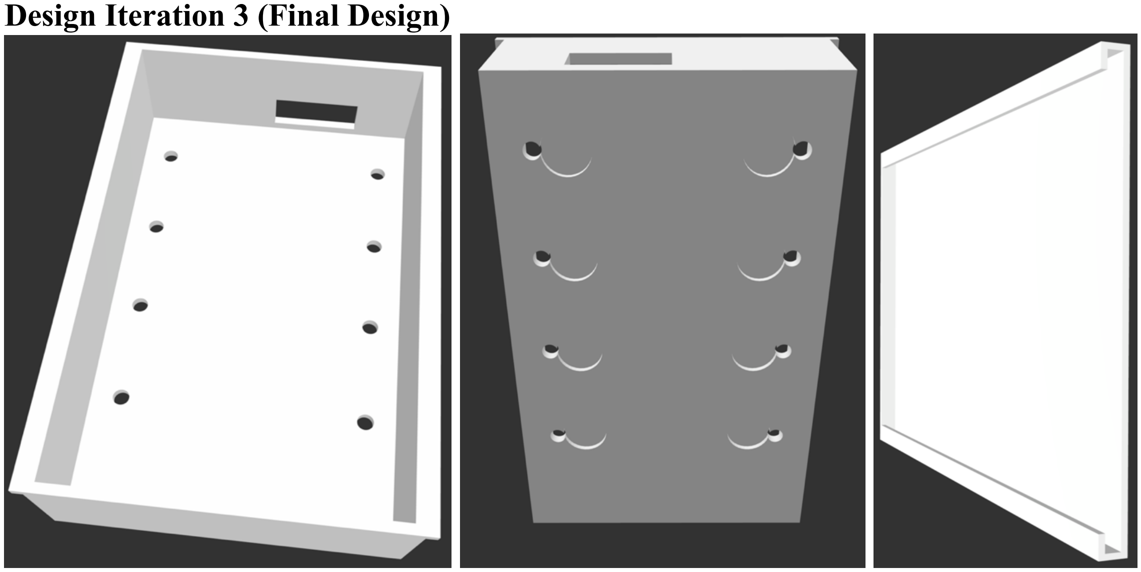


Figure 66: Design iteration for the 3D-printed: design iteration 1 (top), design iteration 2 (middle), and design iteration 3 (bottom)

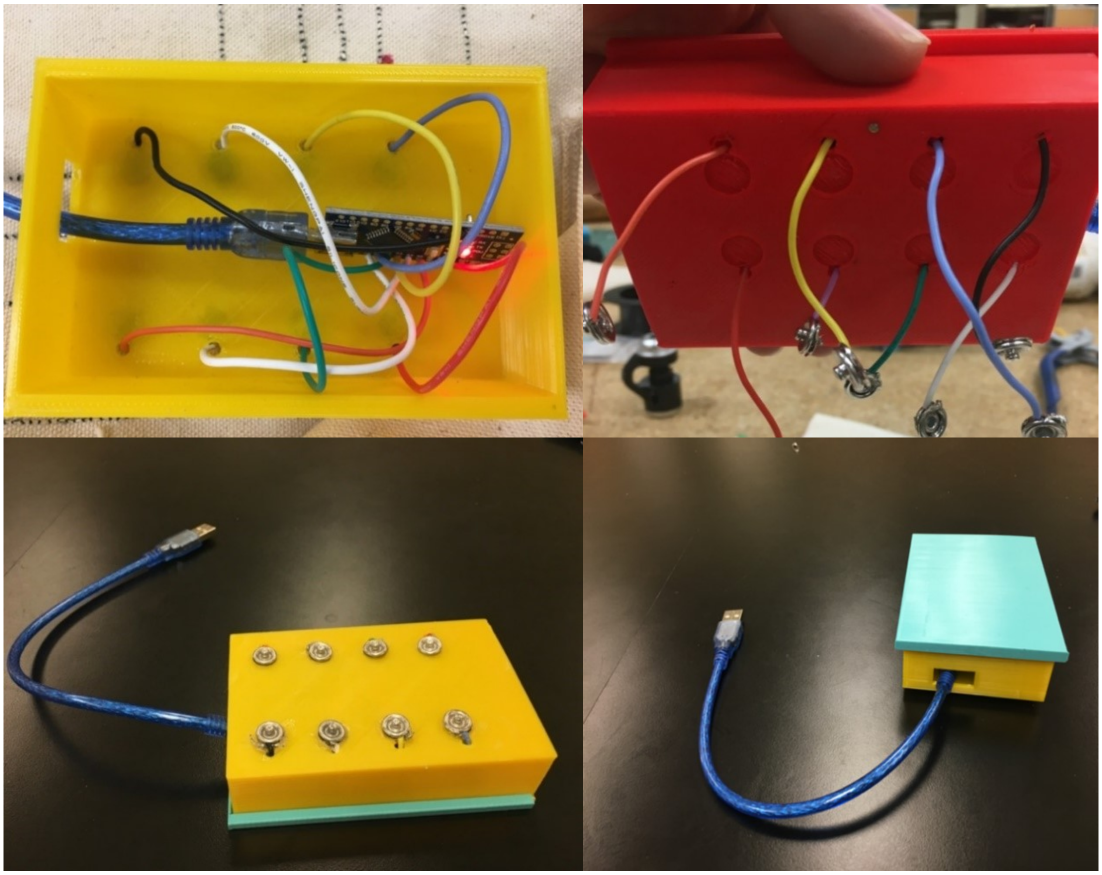


Figure 67: Final housing for external hardware

- **Assembling the garment**

For the e-textile prototype garment, once all the sensors were soldered onto the garment pieces and functionality was tested, the garment pieces were stitched together to give the shape of the thermal liner garment. At the beginning of the assembly, the sleeves and the body pieces were serged together using a serger machine. Later, a lockstitch machine (with conductive thread) was used to connect traces over seams. Finally, the same lockstitch machine (with non-conductive thread) was used to assemble the zipper, the velcro straps, and the pocket. Figure 68 describes the finished garment. The steps involved in assembling both regular and e-textile thermal liners are described in Figure 69.

- **Designing the Workflow**

The operations were sequenced based on the design requirements and the electronic system requirements. Figure 70 describes the operation sequence process for the product development phase of the thermal fire-fighter liner garment which is modified from Figure 54. Here, the main difference is the development of the removable electronics for the sensor-integrated thermal liner garment. An operation-level workflow (similar to the workflow described for the LED display shirt in Figure 54) was developed once the product development process below was completed. The production plan was developed based on that workflow.

Figure 68: Fire-fighter thermal liner garment prototype

Figure 69: Steps involved in assembling both regular and e-textile thermal liners

Step 5: Quality Testing and Troubleshooting of the Product

Quality testing and troubleshooting of the garment were performed following the process described in section 3.4.2. As described in the previous sections, the primary goal of this dissertation was to develop a manufacturing technique for standard e-textile garments. Hence, the primary emphasis was on designing and developing a manufacturing system rather than improving and optimizing the individual segments of the manufacturing system. Therefore, the standard prototyping tools and techniques were used for testing, troubleshooting, and reworking of the fire-fighter liner garment prototype. For the fire-fighter thermal liner garment prototype, a visual inspection followed by an Arduino-PC set up was used to test the functionality of the electronic system of the garment. Sensor data was monitored by sending data over a serial monitor in Arduino. Re-soldering was performed where needed. Sensors were tested until all sensors worked as expected. The prototype was tested at different stages of the development from the integration of individual sensors to the finished garment as described in Figure 70. While we have tested the attachment of the solder joints, and continuity of the connections between components and sensor responses to ensure the functionality of the prototype garment, a more rigorous system level testing (in-circuit test, accuracy of the sensor responses, etc.) could be performed using automated sophisticated tools and machines which weren't readily available at the time of the study and were out of the scope of this dissertation. Future studies should include a more comprehensive quality testing and troubleshooting techniques to ensure that the reliability, durability, and functionality of the produced e-textile garments are comparable to that of traditional electronic devices.

- **Production Planning**

Once I was done with the production study, the next step was to determine the tasks involved in transitioning from prototype development to the factory setting. I have found that even though most of the steps mentioned above are perfectly suitable for fabricating a sample prototype sensor-integrated thermal liner garment in a laboratory setting, a few of them might not be applied in the same way for the deployment in a production setting, while considering scalability, efficiency, cost-effectiveness, ease of use, etc. Additionally, as a research case study it was necessary to better understand the generalizable challenges of integrating of electronics into clothing and the overall manufacturing process of the example prototype garment in order to be able to design an efficient and scalable manufacturing process. To perform a more in-depth analysis of the individual operations and other abstract challenges associated with them, I performed a pre-production study. A final production plan was developed in parallel, based on the outcome of the pre-production study results. In the next few sections, I briefly describe the pre-production study results followed by a final production plan.

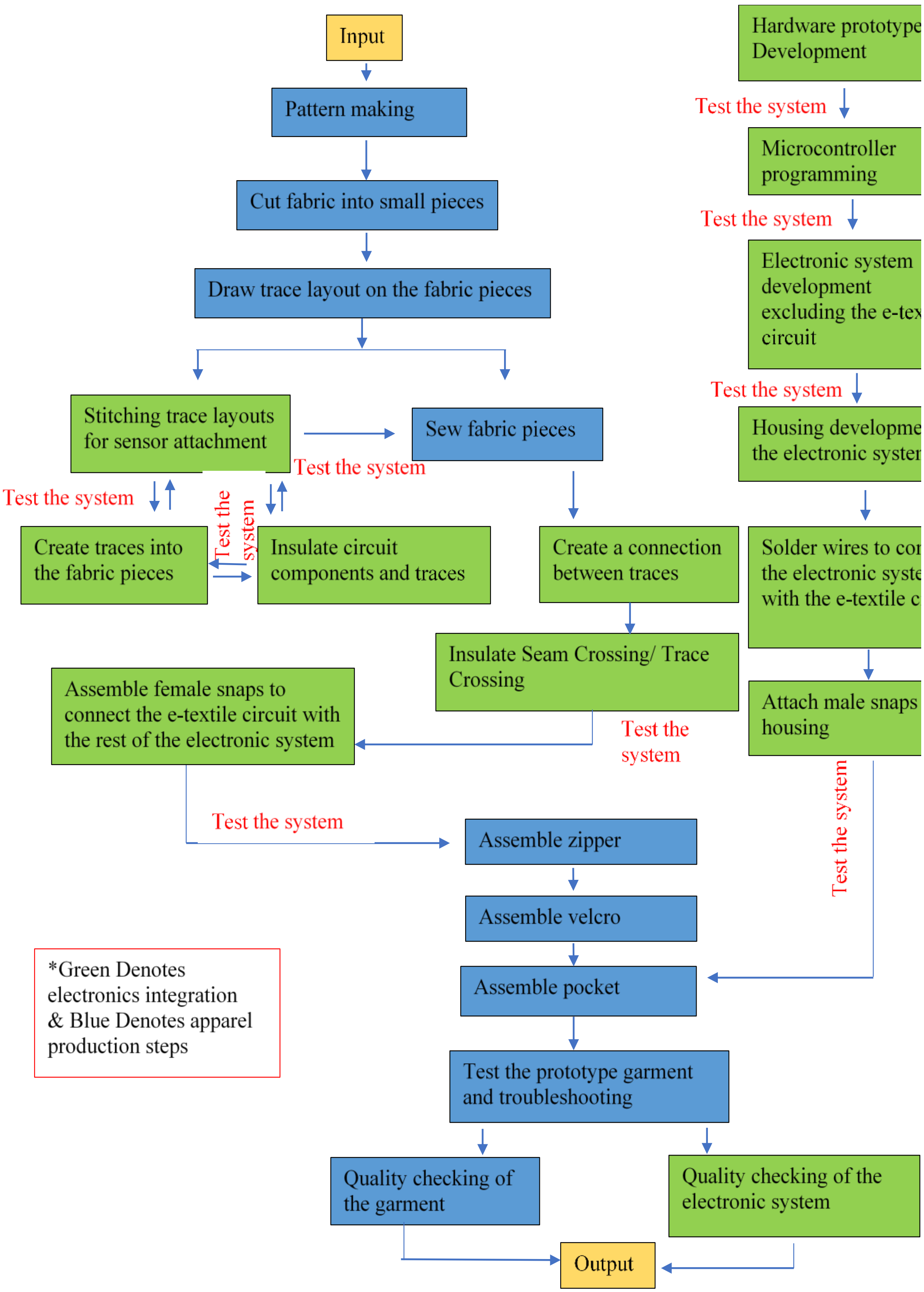


Figure 70: Operation sequence of the product development

4.2.2.1 Pre-production Study

A pre-production study was performed in parallel with the production plan, and included both in-line QA checkpoints and summative QA checkpoints. The objective of the pre-production study was to identify the approximate time needed to perform each operation which would help me plan for labor, machines, and materials required for the production study. In addition, the study was performed to understand the abstract manufacturing challenges for this process due to human involvement and what could be done to minimize these challenges. An in-depth analysis was performed to determine machines and tools necessary for quality testing during production and to determine when and exactly how quality testing should be performed for this particular production process. To answer all the above questions, a pre-production study was performed at the Wearable Technology Lab from September 2019 to December 2019. A total of five sensor-integrated thermal liner garments and one regular thermal liner garment were developed by three undergraduate students of apparel design. It was expected that the participants working in a laboratory setting would never be able to have the same level of efficiency similar to industry standard, therefore, a different comparison was needed in order to understand the relative impact of the electronics. Hence, a non-electronic garment was developed in parallel to the electronic-textile. Two out of the three had never worked with e-textiles and the third had previous experience working with e-textiles. Participants were selected to reflect the skill range of the participants in the actual production study. The participants were given detailed instructions on how to manufacture the example prototype garment. During the study, participants were asked to record the time needed to perform each individual operation. They were also asked to write down anything confusing they noticed while working with the pre-production samples and their suggestions to improve the efficiency of the production workflow and the data collection process. This helped ensure that functional products were produced and allowed for measurement of the exact locations where faults actually happened.

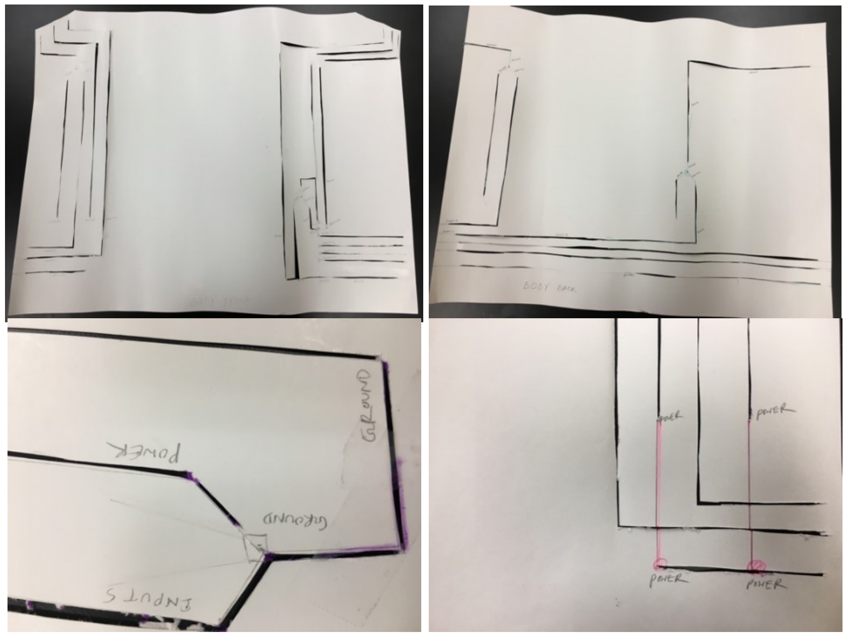


Figure 71: Paper templates for drawing traces onto fabric pieces

The workflow of the pre-production study samples was similar to the workflow of the prototype sample development as described in Figure 69 with a few exceptions. The main difference was in the use of a tracing template to draw the traces reliably on the garment (which was done using visual approximation in the prototype development stage). One of the major challenges I discovered from my e-textile prototype garment study was stitching the e-textile circuit traces properly on the garment. Stitching regular stitch lines on top of each other doesn't cause problems but stitching conductive traces does. Unintended trace connections can create major problems for e-textile garments such as failure or short inside the circuit. Short circuits can result in the burning of the circuit which may make the circuit malfunction. Since my goal is to create the garment in a regular apparel factory with people who have no prior experience of working with electronic circuits, I had to come up with a method which would allow operators to sew conductive traces with no errors. After some brainstorming, I decided to use a template which could be used later to draw traces on the fabric pieces, a method that is commonly used in the industry to do decorative or mid-piece stitching. For this purpose, I drew the whole trace layout in paper patterns using a marker and used a knife to cut the trace layout. Later, I placed the paper patterns on top of the fabric pieces and used the pattern templates to draw lines onto the fabric using a washable ink. I drew red lines on the other side of the fabric to indicate that the operator needs to connect the traces on the other side of the fabric. Figure 71 shows the paper templates for drawing traces onto fabric pieces. The conductive threads were stitched following the trace layout on the garment.

During the pre-production study, a time study was performed for the five sensor-integrated thermal liner garment prototypes. No time study was performed for the regular thermal liner prototype. A pre-production time study was performed for the first sensor-integrated thermal liner prototype garment to collect time for individual operations. Later, I iteratively changed the process following each participant's garment assembly. In the following section, I will describe the time-study data collected from the first sensor-integrated thermal liner prototype garment (Table 8) followed by highlights of the results and process improvement of the rest of the iterations. The results and process improvement techniques were mostly derived from participants' feedback and personal observations. In the end, I will present the best time-study data out of all the iterations for each individual operation which would be used for final production study planning.

Department	Job No	Activity	Assembly Time (minutes)- Prototype 1
Cutting	Job 1	Cut pattern pieces out of fabric	12:54
	Job 2	QA (Testing, Troubleshooting, and rework)	4
Sensor Development	Job 1	Draw traces onto fabric pieces and check faulty trace layout	7
	Job 2	Stitch traces using pattern stitcher	6:10
	Job 3	QA (Testing, Troubleshooting, and rework)	0:20
	Job 4	Solder sensors onto traces	45
	Job 5	QA (Testing, Troubleshooting, and rework)	84
	Job 7	Sew traces using a lockstitch	7:40
	Job 8	Attach snaps	6:30
Sewing	Job 1	Serge	39:30
	Job 2	Connect traces over seams	78
	Job 3	Zipper	30
	Job 4	Pocket	23
	Job 5	QA(Testing, Troubleshooting, and rework)	10:37

	Job 6	Troubleshooting and rework	17:35
Post-production Quality Assessment	Job 1	QA for garments ((Testing, Troubleshooting, and rework)	7
	Job 2	QA for Electronic system	N/A
	Job 2	Troubleshooting and rework	
Total			381 ~ 6hr 20min

Table 8: Time study data for the first prototype garment during pre-production study

Participants feedbacks and personal observations for process improvements from the pre-production study

Cutting: The first step of the manufacturing sensor-integrated thermal liner garment is cutting. It took 12:54 minutes on an average to cut pattern pieces out of the fabric. For cutting, individual pattern pieces were used for cutting fabric. However, the time for cutting individual pieces would be very different from the time for cutting pieces in bulk. During apparel production, multiple plies of fabrics can be cut together using a paper marker and an industrial knife. Which means, within the same time frame, more pieces could be cut during production.

Sensor attachment:

Draw trace layout: It took 7 minutes to draw traces onto fabric using the tracing template. One of the participants found the trace layout on the current stencil to be confusing and suggested to using points of reference to anchor the placement of it, either through notches or by any other suitable methods. He also suggested to include a way to differentiate traces that need a long thread hanging off of as well as traces that are supposed to be on the wrong side of the fabric.

In addition, the participant had to re-draw most part of the trace layout, since the ink faded after a few days and was not visible on some parts of the garment. It took another 7:40 minutes approximately to re-draw the trace layout on the fabric. In the future, a more permanent marker such as a washable marker should be used to avoid redrawing of the traces on the fabric.

Stitch traces using pattern stitcher: It took approximately 6:10 minutes to stitch 6 stitch circuits using the pattern stitcher. Participants spent 20 additional seconds to inspect the trace layout. Here, participants used two small stitched trace layouts described in the product development stage. Since participants only used two small designs, there was less possibility of errors in the process and did not observe during the pre-production study.

Solder sensors onto traces: It took 45 minutes in total to solder and heat press all six sensors. The soldering of sensors took more time than I anticipated. The main reason behind the longer soldering time was one participant's inexperience with soldering. It was the first time when the participant learned how to do soldering and hence, it took some time for him to familiarize himself with the process. The small shape of the sensor also made things more time-consuming and complicated for someone who had less experience with electronics.

Quality assessment (testing, troubleshooting, and rework): After initial soldering, there were some broken connections which needed to be fixed before testing the circuits. It took approximately 5 minutes to re-solder the broken connections. The sensors were later tested using an Arduino hardware setup and a power supply for 46:30 minutes (Sleeves: 6:30 minutes and Body: 22:41 minutes). After the initial testing, 4 out of 6 sensors worked. Participants later spent around 30:27 minutes (sleeves: 7:46 minutes and body: 22:41 minutes) to fix the other two sensors which include re-soldering, heat pressing, and testing the sensors. Similar to soldering, quality assessment also took a lot of time due to participant inexperience while dealing with electronics. This gave me some insight on how participants' inexperience would play a vital role in the efficiency of the method during production.

Stitch trace layout on the garment pieces: Once participants were done with the soldering, the next step was to run the conductive thread through lockstitch machine over marked lines to form traces. It took them 3 minutes to stitch traces on two sleeves and 40 minutes to stitch the conductive traces on the body. However, participants reported some trouble with the conductive thread while working with the body. The higher strength of conductive thread created some unbalance in tension between regular and conductive threads and required some additional adjustments in the machine set up that probably partly accounted for higher assembly time. Moreover, part of this process was stitching traces on the wrong side of the fabric and pulling the thread through to other end and manually tying knots to intended connection points which took them 35 minutes.

Quality assessment of the stitched layout (testing, troubleshooting, and rework): After stitching the trace layout on the garment, the trace connections were visually inspected to ensure if all the traces were properly stitched. In addition, a digital multimeter was used to test the electrical connectivity of the traces. It took 10:37 minutes to test all the traces. There were 4 occasions where a faulty trace connection where the fault happened due to human errors. Participants removed the faulty traces and re-stitched the traces again. It took 15 minutes to remove the faulty traces and 2:25 minutes to re-stitch them. It is obvious from the study that removing stitched traces took more time than re-stitching and a faulty trace layout can significantly increase the manufacturing time.

Final garment assembly:

Serging: The next step was to serge the garment together. Serging was done in body hem, sleeves bottom seam, sleeves to armscye seam, and shoulder-top sleeve seam. It took around 39:30 minutes to serge the complete garment (hems: 11 minutes, both sleeves bottom seam: 3 minutes, sleeves to armscye 20 minutes, shoulder-top sleeve seam: 5:30 minutes).

Assemble zipper: It took 22 minutes to sew the zipper on the garment (10 minutes for preparing such as cutting, affixing zipper stops, marking the location of the zipper, and 12 minutes for actually sewing the zipper on the garment). However, participants wrongly stitched a part of the zipper which was later fixed and re-stitched which took around 8 minutes. Participants reported that they felt the necessity of some additional guidance including references for exactly where the zipper goes (how far away from the edge of the garment, how long, the orientation of the zipper head, etc.). Participants ran into some issues with the zipper stops as well. They reported that the zipper stops were not easy to figure out and even less easy to make sure that they would stay in place. These steps may need some additional attention during the final production study.

Assemble snaps: The sensor-integrated thermal liner garment has 8 snaps that connected the external hardware with the main garment. Assembling these snaps took 6:30

minutes without any issues. However, participants ran into a single snap misplacement which was later removed and assembled that added about 9 more minutes.

Assemble pocket: It took 23 minutes to sew the pocket on the garment. Participants reported that the pocket piece given to them had errors, with a cut segment and a single corner already sewn. They had to figure out the construction method for attaching the pocket themselves which vastly increased the time it took to sew. The takeaway from this study was to add a detailed pocket construction diagram.

Quality assessment of the finished garment: Once the garment was completed, it went through a quality assessment process. It was performed in a similar way as in a regular CMT factory. Participants tested the size and constructions of the garment using a measurement tape. It took approximately 7 minutes to do the quality check. The study results showed in Table 9 for the first pre-production study sample. From the quality assessment results of the finished garment, we can see slight differences between expected and actual dimension measurements. Since sizing of the garment wasn't the primary focus of this study, dimensions weren't fixed at this stage. A higher tolerance limit would help in this case. The final production study should try to address this issue to minimize the gap between these two measurements. At the time of this study, the external hardware was not completed and hence, the quality assessment for the electrical circuit was not performed.

	Expected	**Allowance +/-**	**Measured**
Body Length	31 1/4	1/2	30 3/8
Body Width	28 1/4	1/2	27
Sleeve Length Outer Seam	27 3/4	1/2	27

Sleeve Length Inner Seam	24	1/2	23 1/4
Sleeve Width	6 3/4	1/2	7 1/4
Zipper Length	64	1/2	64

Table 9: Measurement chart for the QA of the finished garment

Summary: The initial production study results showed that it took approximately 6 hours 20 minutes in total to assemble the sensor-integrated thermal liner garment. It was on the higher end compared to the industry standard of assembling a regular thermal liner garment which is less than an hour. From my personal observation and a deeper look into the participants' notes, I realized that the participant's unfamiliarity with the manufacturing process of the sensor-integrated thermal liner garment may primarily be responsible for the longer assembly time. In addition, some complexities in the design itself and unclear instructions on some of the steps also contributed to this additional time. For instance, the paper templates I used for drawing trace layout were taking a lot of time and the templates were made out of light paper which was not suitable for tracing markings.

Therefore, my next step was to make necessary changes in the manufacturing processes to make these simpler and to change the instructions to be more detailed where necessary. In addition, I looked into individual operations and tried to see which operations need additional attention to cut down the extra processing and troubleshooting time and thus would make the whole process more efficient and cost-effective. One of the major changes I made was modifying the "stitching conductive traces" operation of the manufacturing process. For the pre-production prototype 1, a small segment of conductive trace layout was stitched using the pattern stitcher and the majority of the stitched layout was made using an industrial lock stitch machine. To improve the scalability of the process, significant changes were made in the conductive trace layout design so that most of the conductive stitched layout could be stitched using automatic pattern stitcher and a small part of the stitched layout was performed using an industrial lock stitch machine. For the regular sewing operations, some of the process were simplified (e.g., pocket and zipper) so that those operations could be performed within a shorter period of time. Eventually, I made four more garments with the help of the participants and analyzed each operation to have an effective, efficient, and cost-effective manufacturing process. Time for each operation was also recorded. Table 10 describes the pre-production assembly time for prototype 1 as compared to the best-case time study data collected across all five garments made by all three participants' to represent the best possible manufacturing time in a standard CMT factory setting. My final pre-production study results showed, it took approximately 212 minutes or 3 hours 32 minutes (172 minutes for electronics integration and 40 minutes for regular garment sewing operations) to assemble one sensor-integrated thermal liner garment from start to end. Which means, manufacturing of one e-textile garment took approximately 2 hours 48 minutes longer than manufacturing the same garment with no added electronics. In addition, with the modified stitch layout (stitching most part of the stitched layout using pattern stitcher), it took longer to stitch conductive trace layout using pattern stitcher for the final pre-production prototype (25 minutes) than the pre-production assembly time for prototype 1 (6:10 minutes). On the contrary, it took less time to perform "sewing traces using a lock stitch" operation compared to prototype 1 (78 minutes). By simplifying the process, zipper assembly time was reduced to 8 minutes from 30 minutes and pocket assembly time was reduced to 5 minutes from 23 minutes for the final pre-production prototype. The final production study was designed based on these results.

Department A: Cutting

Department	Job No	Activity	Pre-production Assembly Time	Final Pre-production	Target assembly [illegible]	Total hours	Machine Needed	Operators
Cutting	Job 1	Cut fabric into small pieces using the marker	12:54	12:54	180		Cutting Knife	3
		Cut zipper & remove two teeth using scissors					Scissors	1
	Job 2	QA (Notes: change to cut length)	4	4	60		Tape	1
Total					240 mins	11		3

					~4 hours			

Department B: Sensor Development

Department	Job No	Activity	Pre-production Assembly Time	Final Pre-production	Target assembly time	Machine Needed	Operators
		Part 1					
Sensor Developm-ent	Job 1	Draw traces onto fabric pieces	7	7	200 (5mins/ pc)	Pencil	1
	Job 2	Stitch traces using pattern stitcher	6:10	25	1000	Pattern stitcher	1
	Job 3	QA	:20	0:20	60	Tape	
	Job 4	Solder sensors onto traces	45	45	1800	Solder, awl, heat press	3
		Part 2					

	Job 5	Troubleshooting and rework	84	30	1200	Multimeter, Arduino, power supply	3
	Job 6	Sew traces using a lockstitch	7:40	7:40	320	Lock Stitch	1
	Job 7	Attach snaps	6:30	6:30	240	Snapping machine	1
	Job 8	Insulate traces and sensor components					
	Job 9	QA and rework					
Total					4820 mins ~ 80hours		

Department C: Sewing

Department	Job No	Activity	Pre-production Assembly Time for	Final Pre-production Assembly Time	Target assembly time (80) (minutes)	Machine Needed	Operators Needed
Sewing	Job 1	Serge	39:30	10	640 (80pc)	Serge (2)	2
	Job 2	Connect traces over seams	78	20	800 (20/pc)	Lock Stitch (2)	2
	Job 3	Zipper	30	8	640 (10/pc)	Lock stitch (1)	2
	Job 4	Pocket	23	5	400	Lock stitch (1)	1
	Job 5	QA	10:37	10:37	800	Tape, hardware (1)	1
	Job 6	Troubleshooting and rework	17:35	17:35	800	Soldering tools	1

						(1), comp uter	
Final					4080 mins ~68 hours	5	

Department	Hours	Operators Needed	Cost/hour ($12/hour)	25% allowance (199 hours)
Cutting	11	5	$132	$165
Sensor Development	80	5	$960	$1200
Sewing	68	5	$816	$1020
Total labor cost			$1908	$2385

Table 10: Time study data for the pre-production study

4.2.2.2 Final production planning

One of the main objectives of the study was to deploy the method in a regular apparel factory setting with people having no prior experience with electronics or electronic textiles. Therefore, some of the processes were modified and simplified based on the pre-production study results so that they could be easily implemented in the industry with minimum or no instructions. While performing the production planning for both the regular and the sensor-integrated thermal liner garments, I took the existing steps involved in a typical CMT manufacturing process and modified and added additional processes, tools, and materials wherever needed. Some of the modifications were necessary for mass production, and some of them needed for simplification of the process. For instance, it made more sense to use a paper marker to cut fabric pieces in bulk since it could significantly cut down the time for cutting. Similarly, a change was needed to make in the trace layout so that most of the trace layout could be stitched using the pattern stitcher which minimizes the use of an industrial lock stitch machine. Even though my pre-production study results showed it was quicker to stitch most of the trace layout for the sensor integration using an industrial lockstitch machine compared to the pattern stitcher, it took longer to connect traces over seams using a lockstitch machine than the pattern stitcher. Hence, the actual time to make the garment was less for the pattern stitcher compared to the lock stitch machine. Furthermore, stitching conductive traces using lock stitch machine added a few other complexities in the process such as the requirement of drawing the whole trace layout on the garment, which made it more time consuming and less scalable compared to stitching using an industrial pattern stitcher. Similar changes were made throughout the process. A list of steps that were involved in transitioning from prototype development to the factory setting is described below. Here, I mostly talk about the steps that one needs to consider while transitioning from fabricating a single e-textile garment to the mass manufacturing of e-textile garments. Though marker development is not specific to e-textile garments but common for any bulk manufacturing process, I have included this here as a general step of transitioning from prototype development to mass manufacturing for both regular and sensor-integrated thermal liner garment.

4.2.2.2.1 Marker development

For the production of apparel, a paper marker is commonly used for cutting fabric pieces in bulk. The production marker contains all the pieces of the pattern that would be required to produce the liner garments. Since the pieces were the same for the production

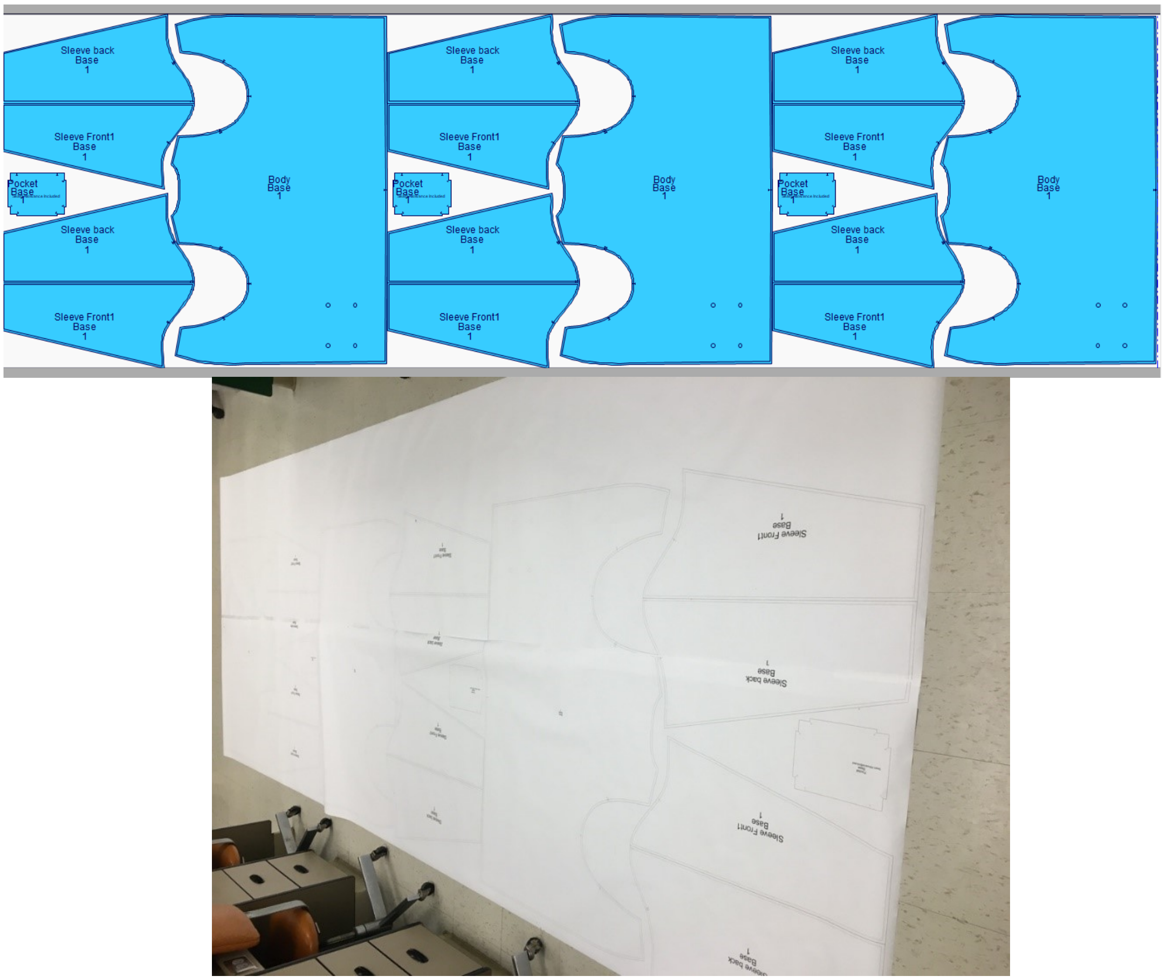


Figure 72: Marker development for the production study

of both the e-textile fire-fighter thermal liner garment and the regular fire-fighter liner garment, one set of markers was developed (Figure 72). At the beginning of marker development, Optitex 3D CAD software was used to design the patterns for the body, front sleeve, back sleeve, and pocket. The pattern pieces contain notches and other relevant markings which are identical for both regular and e-textile garments. Later, the patterns were used to create a marker.

Patterns were placed in the marker following the grain line. The length and width of the cutting tables and the width of the plotter printing machine was considered while designing the marker. Optitex Marker software was used for creating the production marker. Several markers were made and eventually I picked the one with the highest efficiency. The final marker had a width of 54 inches and a length of 72 inches and the efficiency of the marker was 83% which is pretty good compared to the industry standard. Once the marker was designed, a plotter was used to print the paper marker. The plotter I used for production has the capacity of printing a maximum 36-inch width paper. Therefore, the marker was printed in two parts, and later it was taped together. A total of three markers were printed for cutting fabric pieces of 96 liner garments. A total number of fabric pieces needed to cut is described in Table 11.

Garment Piece	Quantity/Garment	Quantity/80 garments	Allowance (20%)	Total	Total Marker
Body	1	80	16	96	3 Marker and 32 pieces of fabric lay
Front Sleeve	2	160	32	192	
Back Sleeve	2	160	32	192	

Pocket	1	80	16	96	
Press cloth	1/12 press	20	2 (10%)	22	
Zipper	1	80	8 (10%)	88	

Table 11: Total number of fabric pieces needed to be cut for the final production

4.2.2.2.2 Developing stitch patterns using the pattern stitcher

One of the primary goals of this project is to emphasize the use of scalable and automatic tools and/or machines that already exist in the CMT industry and are ready to be used for mass production. Therefore, I tried to maximize the use of pattern stitcher for stitching the conductive traces. As discussed in Chapter 3, the pattern stitcher has a limited bed size (stitching area) and the size of the design is largely dictated by the machine bed size. The prototype garment design requires that sensors be placed all over the garment including the sleeves and the body, and hence, the traces need to travel from the sleeves to the front and back to the external hardware area. I would have needed a larger bed area to stitch the complete trace layout on the garment, and the fully-assembled garment would not have been flat enough for the pattern stitcher bed. Therefore, I broke down the trace layout into segments and designed a total of 10 pattern layouts using the Brother software. After stitching 10 pattern layouts on the garments, some gaps still existed between traces that need to be connected. However, all of these gaps were smaller and composed of largely straight lines, so it was easier for operators to eyeball. An image of the trace layout was used as a reference to provide detailed information on the trace layout including information regarding trace connections and trace crossings. An industrial lock stitch machine was used to make connections among patterns.

Several factors were considered while designing the stitch patterns. First, the orientation of the fabric pieces needed to be considered while designing the pattern layout. I have used conductive thread as a bobbin thread and polyester or non-conductive thread as a needle thread. While stitching the pattern, the wrong side (back side) of the fabric needs to be at the top of the machine bed so that the conductive thread can be at the right side (face side) of the fabric. Therefore, I flipped/mirrored the design in the Brother software so that in the original design conductive threads were stitched on the right side of the fabric (Figure 73).

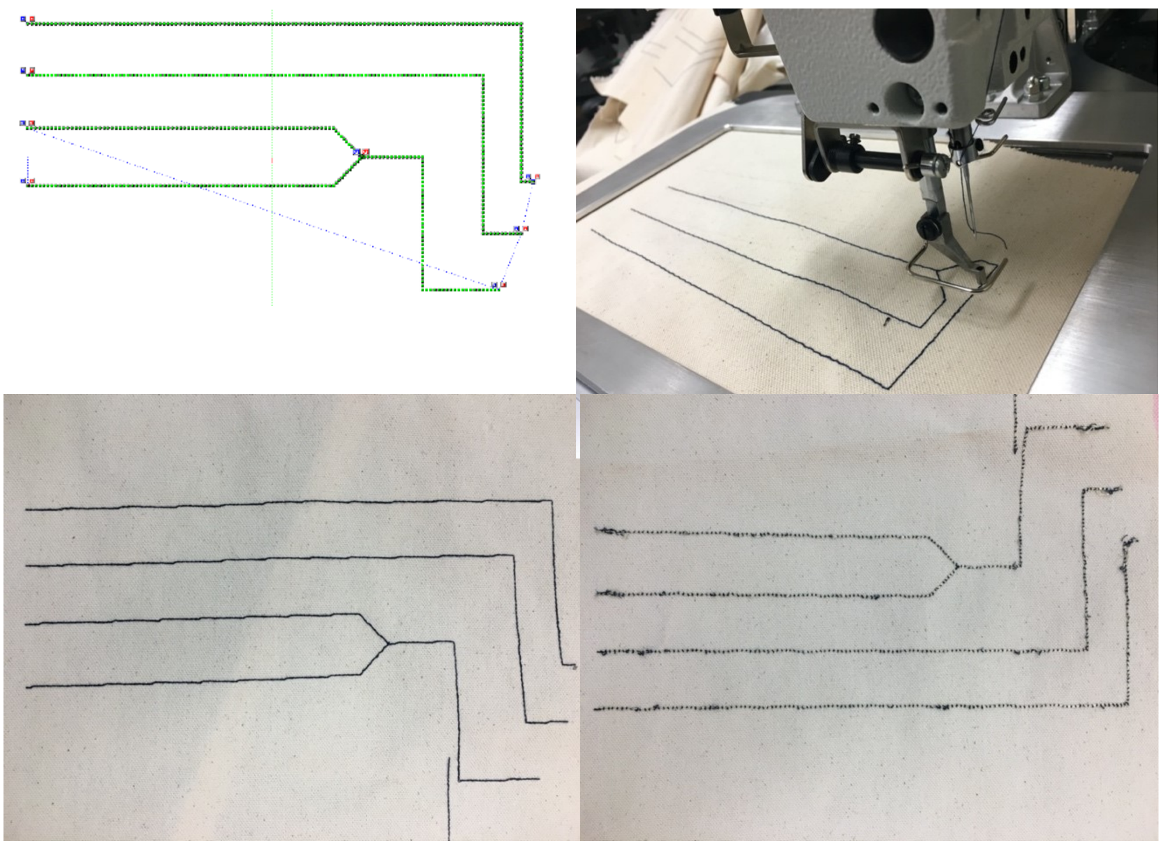


Figure 73: Development of the stitch patterns: designing the patterns using Brother software (top left), stitching using pattern stitcher (top right), stitched pattern on the wrong side of the fabric (bottom left), and stitched pattern on the right side of the fabric (bottom right)

Second, the design should fit into the desired shape of the garment. I took the actual measurements of the trace layout from the prototype garment and divided the whole design into 10 segments and later, made 10 different pattern layouts based on the actual measurements. I also made some adjustments in the design to fulfill all the requirements of the machine bed size and the actual garment.

Third, the design of the patterns needs to align with each other so that one can see where each trace should line up with no or minimum instructions. To ensure this, I again used the original measurement from the prototype garment, and made multiple iterations of the design to ensure that the traces from different patterns lined up properly (Figure 74).

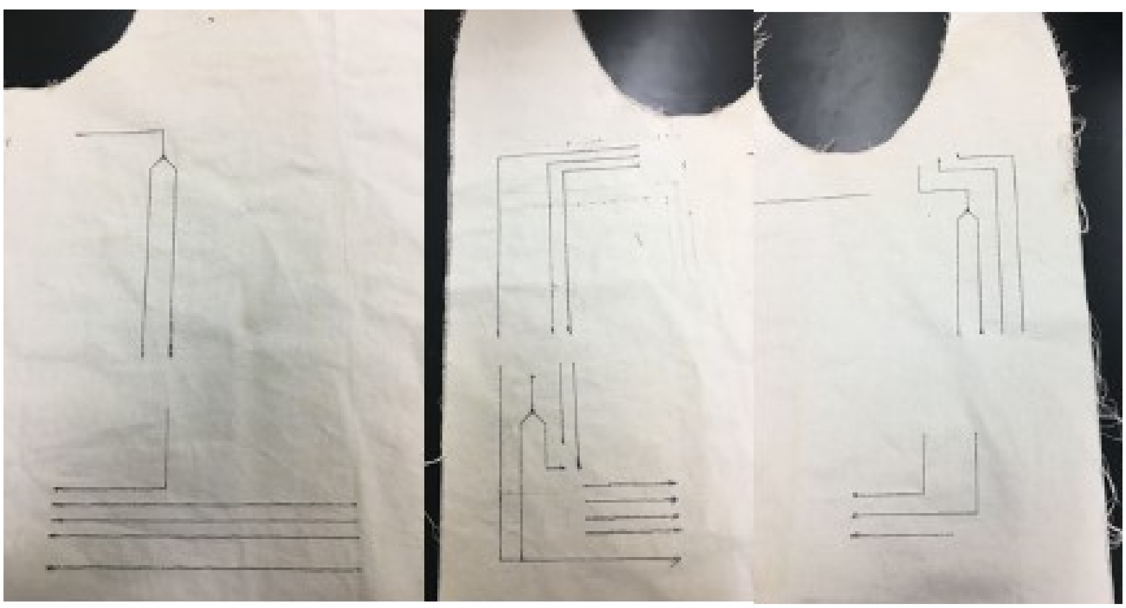


Figure 74: Alignment of the pattern layouts

Fourth, the position of the needle is also important. The position where the machine starts stitching determines where the design will end up so that it can provide enough space for the next design and line up properly with the actual design. I used the first prototype as a reference to determine the exact position (x and y coordinates) of each design layout. Later, with a few trials and errors, I determined the starting point for each design layout and ensured they lined up properly (Figure 75).

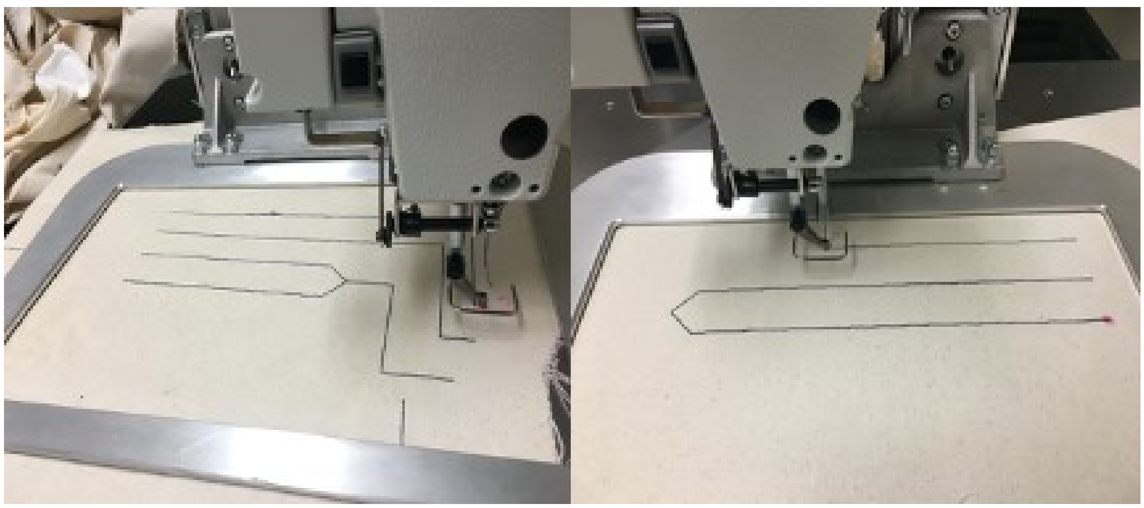


Figure 75: Alignment of the needle with the starting point

During the prototype development stage, I developed paper patterns with the complete trace layout, and I realized that the process takes a lot of time since individual lines need to be drawn separately on the garment. In the modified version, I made the same paper templates with the shape of the actual body and sleeves (Figure 76). But in this case, I made 10 holes (instead of the whole trace layout) to determine the starting points of the 10 designs. These points were derived from the layout described in the previous paragraph. Later, the paper pattern was placed on top of the wrong side of the fabric and I marked the location using a permanent marker.

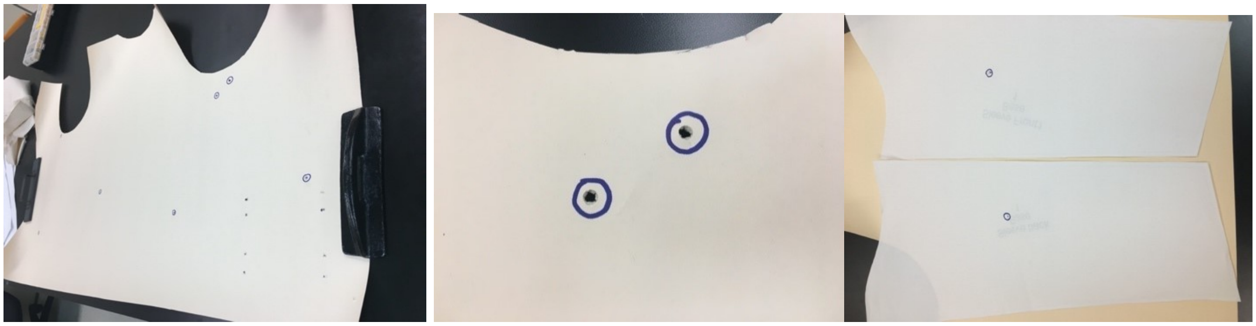
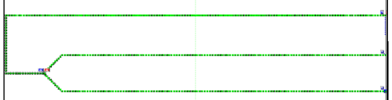
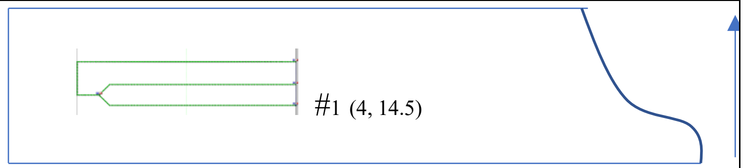
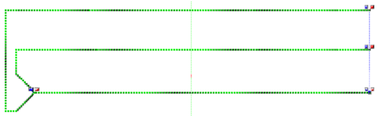
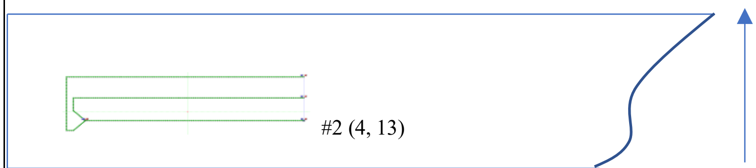
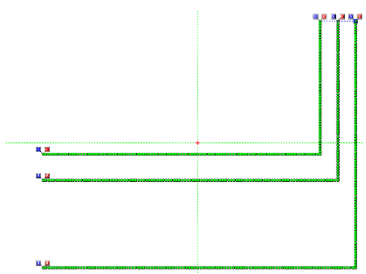
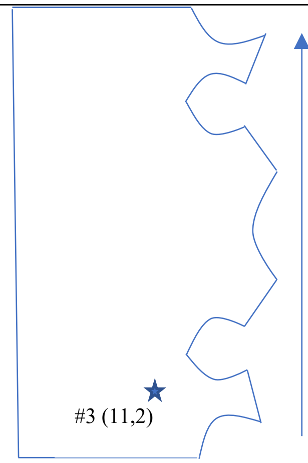
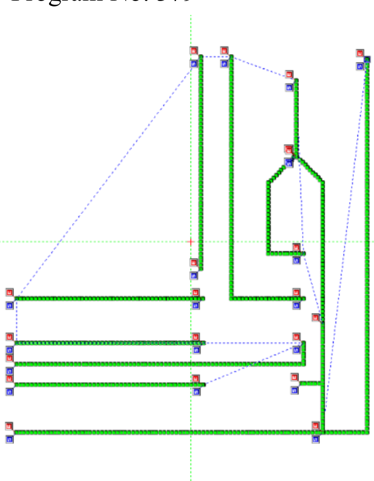
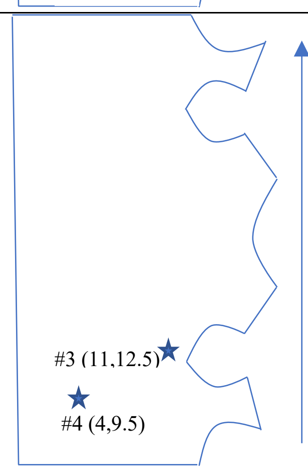


Figure 76: Modified trace layouts for marking the starting point

Fifth, the orientation of the fabric also needed to be determined. The design can only be sewn in one direction on the pattern stitcher. It is not possible to flip the stitch design itself or change the stitch design in the software because the machine has physical constraints. The dimension of the stitch should be inside the clamps of the machine and hence, the orientation of the fabric should be fixed for each design. To overcome this problem, I made some adjustments both in the original design and in the fabric orientation so that the design is consistent throughout the process. Final trace templates were made while considering all the design variables and machine constraints. Later, some adjustments were made on the original trace layout designs based on personal observations and participants' notes. Figure 77 shows the final trace layout designs selected for the final production. Here, the left column denotes the actual design and the right column denotes the location (x and y coordination) of the design layout on the garment pieces and the correct orientation of the garment pieces on the machine bed. This would ensure that all the design layouts line up properly throughout the finished garment.

Actual Design	Location of the design and orientation of the garment pieces

1. Right Hand Program No: 376 	
2. Left Hand Program No: 377 	
3. Front_Left Side Top Program No: 378 	
4. Front_Left Side Bottom Program No: 379 	

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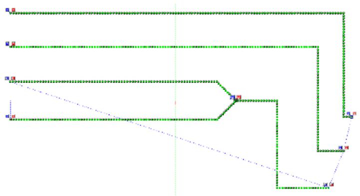

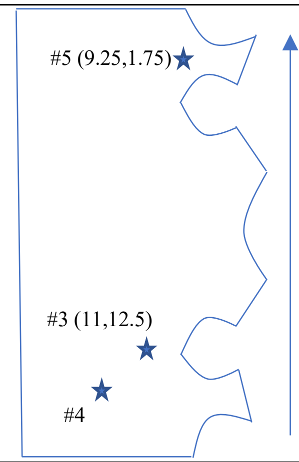

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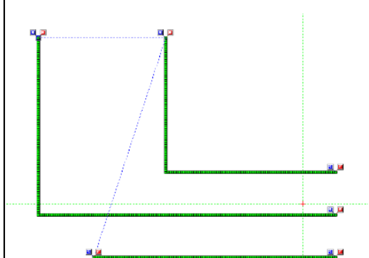
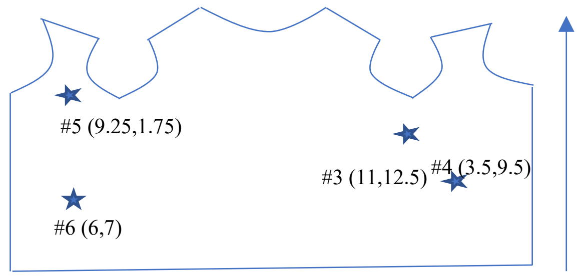
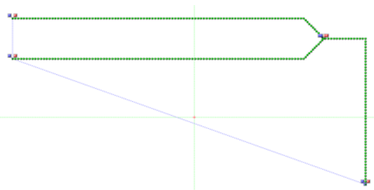
Program No: 381

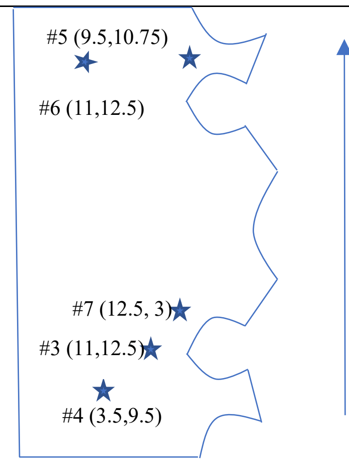


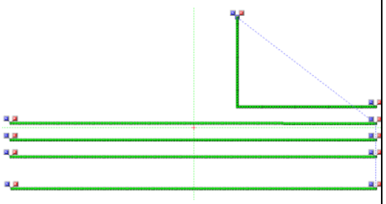
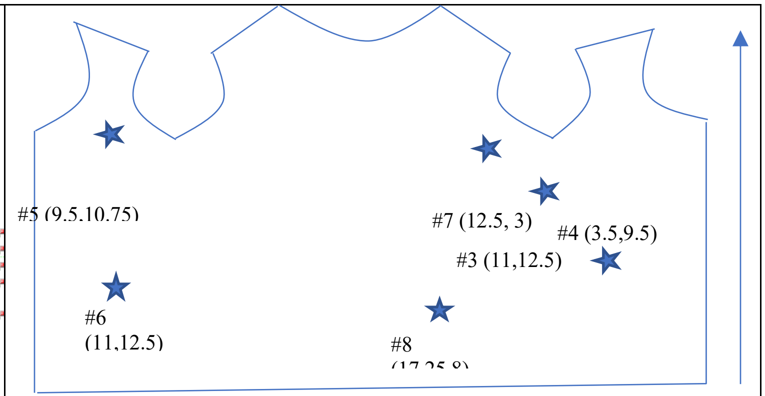
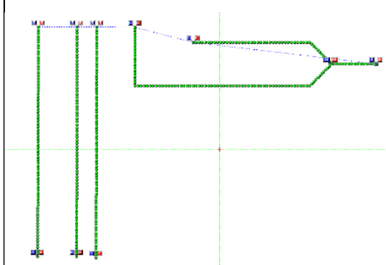
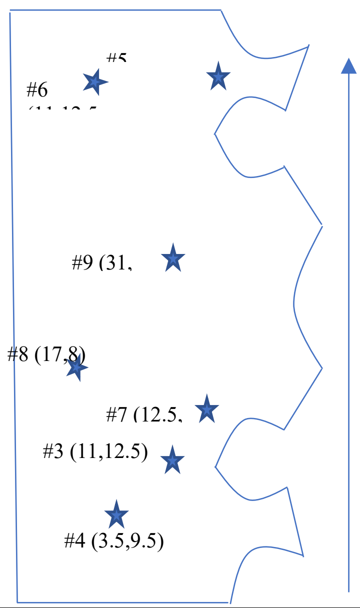
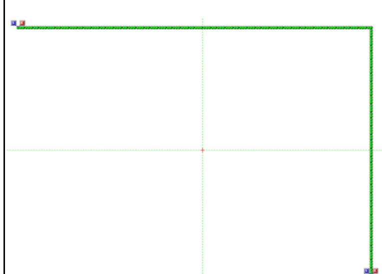
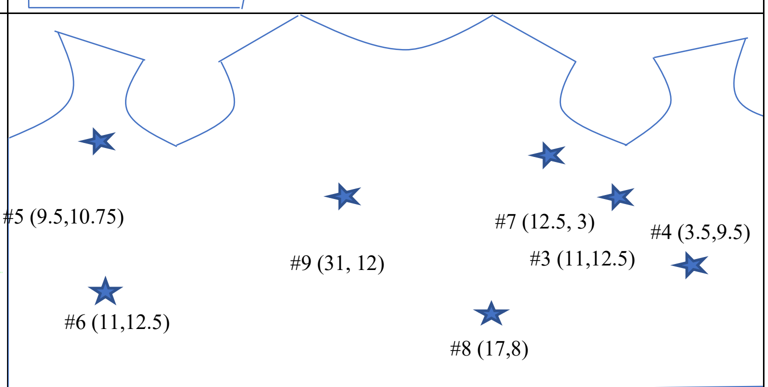


7. Back_Left Side Top

Program No: 382





8. Back_Left Side Bottom Program No: 383 	
9. Back_Right Side Bottom Program No: 384 	
10. Back_Right Side Top Program No: 385 	

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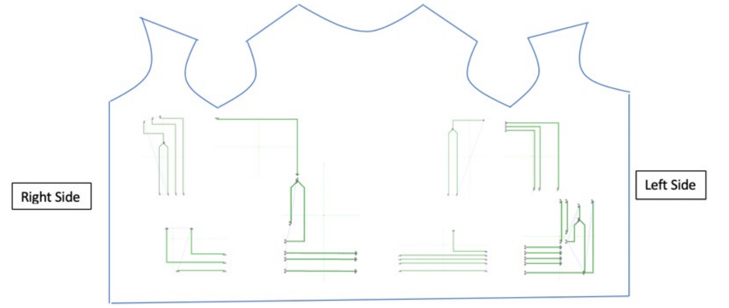
(wrong/back side of the fabric)</td><td colspan="2">
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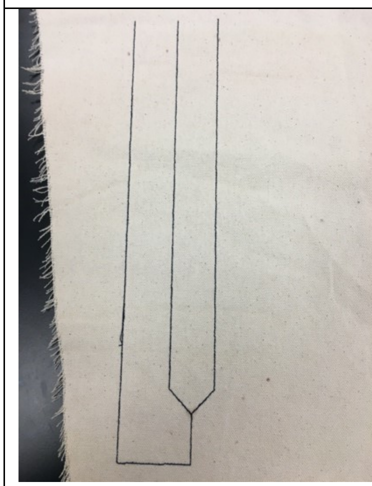
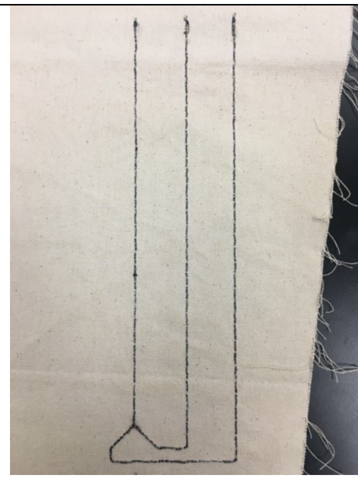
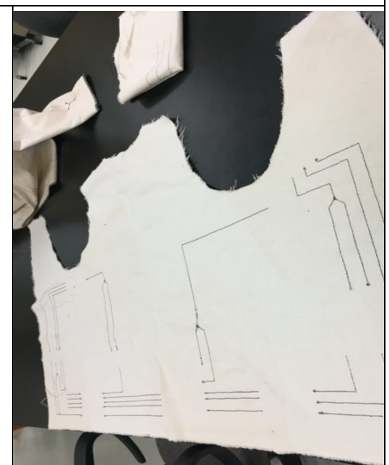
<tr><td></td><td></td><td></td></tr>
</table>

Figure 77: Final trace layout designs for the final production

4.2.2.2.3 Trace crossing and seam crossing

A draft of the trace layout was developed and implemented for the production. In Figure 78, the blue line shows the trace layout where a connection is needed (traces should be stitched on the right side of the fabric) and the red lines show the traces that should not touch each other (traces should be made on the wrong side of the fabric). The major advantages of the new trace layout technique over previous technique was that it simplified the process of transferring trace layout to the garment pieces by allowing drawing 10 starting points (instead of drawing individual trace lines) using the pattern template. Since most of the trace lines were straight-lined, it was easy to eyeball with the help of the blue and red lines. It significantly cut down the operation time as well.

4.2.2.2.4 Insulation Material

As described in Section 3.3, insulation could help protect the electronics from regular wear, and tear, and washing. While traditional insulation material (e.g. silicone) could be effective in protecting surface-mount components of an e-textile circuit, such materials aren't always convenient to the user and may add extra weight to the garment. As my study results suggest, film-based insulation materials also can be used to protect e-textile components and could be an effective alternative to traditional insulation material. Moreover, film-based protection materials are more common in the textile industry and

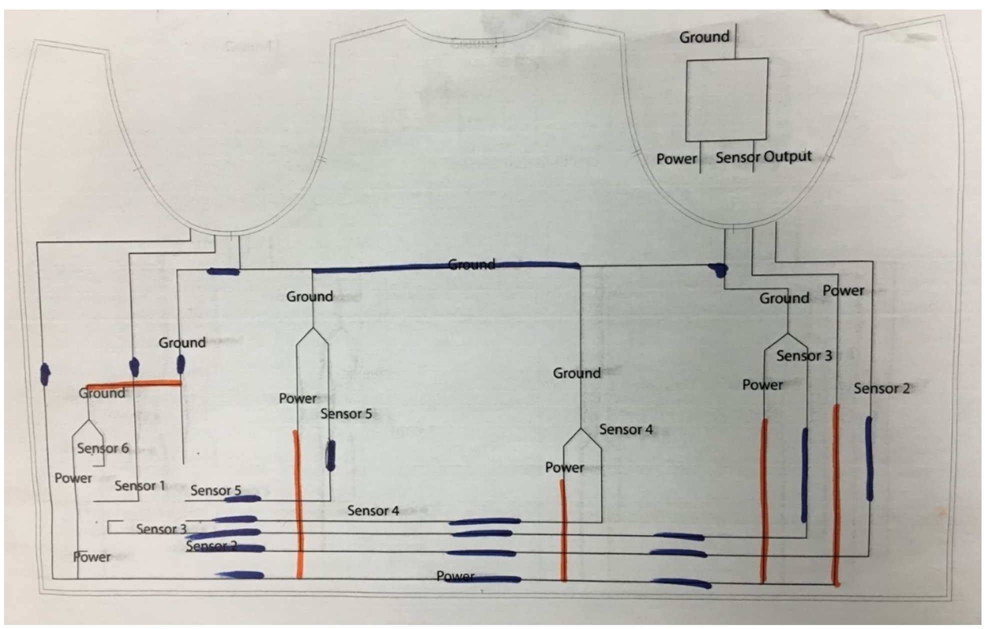


Figure 78: Trace crossing and seam crossing

they add minimum weight on the user body. Therefore, for the final production study, I decided to use an insulation material to protect the sensors. In my previous study, I found Bemis tape was effective in protecting e-textile components. However, Bemis tape wasn't available in the market at the time of my study and hence, I looked for something which could replace Bemis tape. I found Melco seam tape had the same form factor as Bemis tape and could provide similar level of protection as Bemis tape. After testing with a few e-textile samples, I decided to use Melco seam tape to insulate sensor components for the final production study. It was expected that the Melco seam tape would be able to protect the component from wear and tear due to human handling during mass production.

4.2.2.2.5 Developing technical documentation for production

Technical documentation or a tech pack is one of the most crucial tools in developing a product in a mass manufacturing setting. A tech pack is a communication sheet that is typically developed by a designer to communicate with a manufacturer. A tech pack contains all the necessary components needed to construct a product. It gives the manufacturer a concrete guideline to the product so that they can accurately translate the idea into a product. During apparel manufacturing, a tech pack is developed for a particular style that contains all the important specifications for products, such as the design of the garment, materials, measurements, colors, sizes, construction operations, and any other relevant information necessary for continuous and uninterrupted production. Similarly, a tech pack needs to be developed for e-textile garments manufacturing. A technical package was created for both the traditional thermal firefighter liner and for the e-textiles version (see Appendix F). The tech pack contains a bill of materials used to produce the garment, including both textile materials (i.e. cotton canvas fabric, sewing thread, snap buttons, zipper chain, zipper stops, zipper slider, and Velcro strap, etc.) and electronic components (i.e. TMP235 temperature sensor, solder paste, silver coated vectran conductive thread, melco seam tape, and silicone wires, etc.). The bill of material which includes individual prices of all the listed materials. Out of all the textile materials, the canvas fabric comprised the majority of the cost to produce a thermal liner (5.37$ out of $10.38) followed by the zipper chain ($3.51). For the electronic components, the silver coated vectran conductive thread comprised the majority of the cost to produce a sensor-integrated thermal liner garment ($15.84 out of $26.95) followed by the Arduino Nano ($4.29), and TMP 235 sensor ($2.08). In addition to the traditional specifications for the garment, the tech pack will contain full specifications for the integration of electronics, such as component integration methods, QA processes, and the instructions for trace crossing and seam crossing.

4.2.2.2.6 Selection of machines for production

The type, number, and position of the machines used in the production of a garment primarily depend on the sequence of operations. In the previous section, I have described a list of machines and equipment that were required to produce the LED shirt. The same machines and equipment were used for the thermal fire-fighter liner garment.

For this study, I used the Wearable Technology Lab and the Apparel Design Studio in the Department of Design, Housing, and Apparel as my production facility. The type, number, and position of the machines were limited by this facility. In the Wearable Technology lab, we have one pattern stitcher, one serger machine, one lockstitch machine, one heat press machine, and multiple soldering stations. However, we do have 6 overlock machines, and 16 industrial lockstitch machines in the Apparel Design studio that were available for use for this project. Table 12 describes the summary of the machines needed for final production. See Appendix 4 for the complete list of machines and tools needed for all five departments such as cutting, sewing regular garment, sensor development, sewing e-textile garment, and quality assessment.

Machine/Tool Used	**Operation**
Pattern Stitcher	Stitching circuit layout for the sensor circuit
Lock Stitch Machine	Creating both regular and conductive traces; assemble the garment, assembling garments (e.g. zipper, pocket and velcro assembly, hemming)
Serger Machine	Assembling garments e.g. sew sleeves onto the body, serging sleeves, and body hem
Soldering Iron	To make electrical connections among components and traces
Heat Press	Reflow soldering
Digital Multimeter	Testing, and troubleshooting the connections and circuits
Arduino Uno	Testing, and troubleshooting individual sensor connections and circuits
External Hardware with Arduino Nano	Testing, and troubleshooting sensor connections and circuits in the finished garments

Table 12: List of machines and tools used for the production study

4.2.2.2.7 Production workflow

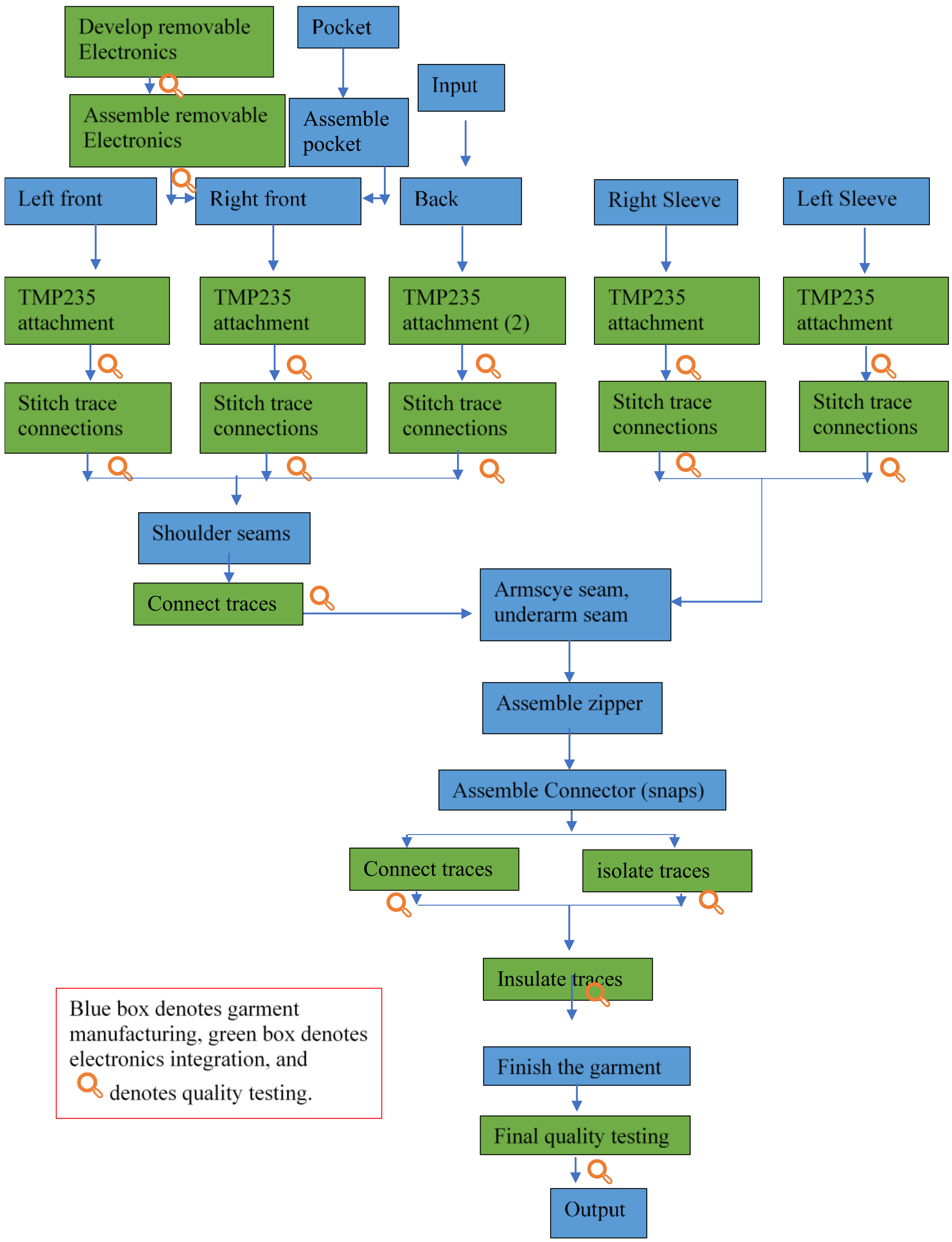


Figure 79: Operation sequence for the production process

Similar to the operation sequence for the product development described in Figure 70, a new workflow was developed for the final production. Processes and operations involved in the regular thermal liner manufacturing process and sensor integrated manufacturing process are depicted in Figure 79, where blue shapes denote regular operations for a typical thermal liner manufacturing and green shapes denote added operations for integrating electronics into the liner. Here, the workflow was particularly developed for the mass production of regular and sensor-integrated thermal liners.

4.2.2.2.8 Quality Assessment Analysis

Based on the outcomes of the pre-production study, a quality assessment technique was developed to identify and analyze the challenges of mass manufacturing of e-textiles. The tools/equipment used in the pre-production study were selected for the final production as well.

- **Guidelines for quality assessment (testing, troubleshooting, and rework)**

Based on my prototype development study and pre-production study results, I determined the stages where more rigorous testing need to be performed and the use of tools/machine which need more systematic guidelines. I used that knowledge to develop a more in-depth quality assessment guideline for the final production study. For example, I realized that participants might find it confusing to differentiate between a "cold solder joint" and a "true solder joint". Hence, I decided to use some example pictures of cold joints and true joints to help the participants understand the main difference between a bad and a good solder joint. For the final production study, a detailed guideline was developed for testing and troubleshooting all the products extensively during manufacturing ensuring all along the way that the newly designed products work effectively. In addition, a protocol was developed for performing necessary reworking of the system where needed. Quality assessment would be performed in different stages of manufacturing. The following section describes the detailed guideline for the quality assessment of the electronic system.

- **In-line quality assessment**

Similar to the pre-production study, an in-line quality assessment would be performed after each of the following stages during final production:

  - **Affixing the removable electronics onto the garment**
  - **Mounting the TMP235 sensor onto the stitched traces**
  - **Insulating the TMP235 sensor**
  - **Connecting traces on the body and sleeve**
  - **Connecting traces over seams**
  - **Isolating traces**

If there were any faulty connections identified in the quality assessment step, the necessary troubleshooting and rework were performed before moving to the next operation. A detailed instruction for performing in-line quality assessment was developed for the final production as described below.

- **Step 1: Visual quality assessment**

The first step of the quality assessment is to perform a visual assessment of the system. Visual inspection was performed to determine if there was any connection issue or sizing faults in the garment. A phone microscope (30x magnification) was used to aid the visual quality assessment process (Figure 80). Pictures of true joints and cold joints were provided in the instruction manual, so that the participants could use them as a reference to identify faulty joints (Figure 81). Visual quality assessment was performed to detect shorts between traces, broken solder joints, broken trace connections, and weak connections, etc.

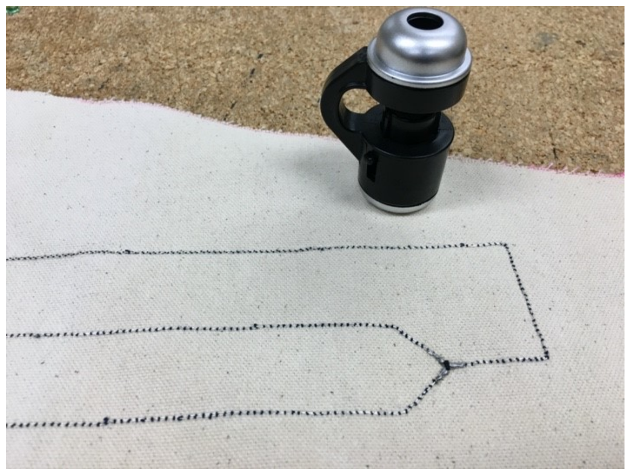


Figure 80: Visual inspection will be performed with a phone microscope

- **Step 2: Digital Multimeter**

If no faults were detected visually, the connections should be further analyzed using a digital multimeter. A digital multimeter was used to test the connectivity issues (i.e. short among sensor power, ground, and output; un-interrupted connection, etc.) between traces (Figure 82). While testing individual sensors, the voltage difference between power and ground should be ~5V and the voltage difference between ground and power should be ~ 0.72V. If the voltages differ from these numbers, the connection needs to be checked and visual inspection needs to be performed.

Figure 81: Example of good (top) and bad (bottom) solder joints

- **Step 3: A hardware set up using an Arduino Uno-PC set up for testing individual sensors**

The next step is to test the individual sensors using an Arduino Uno-PC set up. A hardware set up consisting of an Arduino Uno-PC set up was used for testing the functionality of the e-textile circuit at the product development stage. The same hardware set up was used for testing the individual sensor and the garments system during and after the final assembly (to test individual sensors). Sensor data was read using the serial monitor in the Arduino. Both voltage and temperature were measured using the Arduino Uno-PC set up. For temperature, anything between 65 ^{0}C to 80 ^{0}C (room temperature), and for voltage, anything between 0.70V to 0.73V were considered in the acceptable range.

- **Post-production quality assessment**

Once the garments were completed, a final quality assessment of the whole system would be performed to check the overall quality of the garment and the electronic system. Ananalysis would be performed to determine the sources of any problems. Minor rework would be performed at this stage such as fixing a broken connection or solidifing a

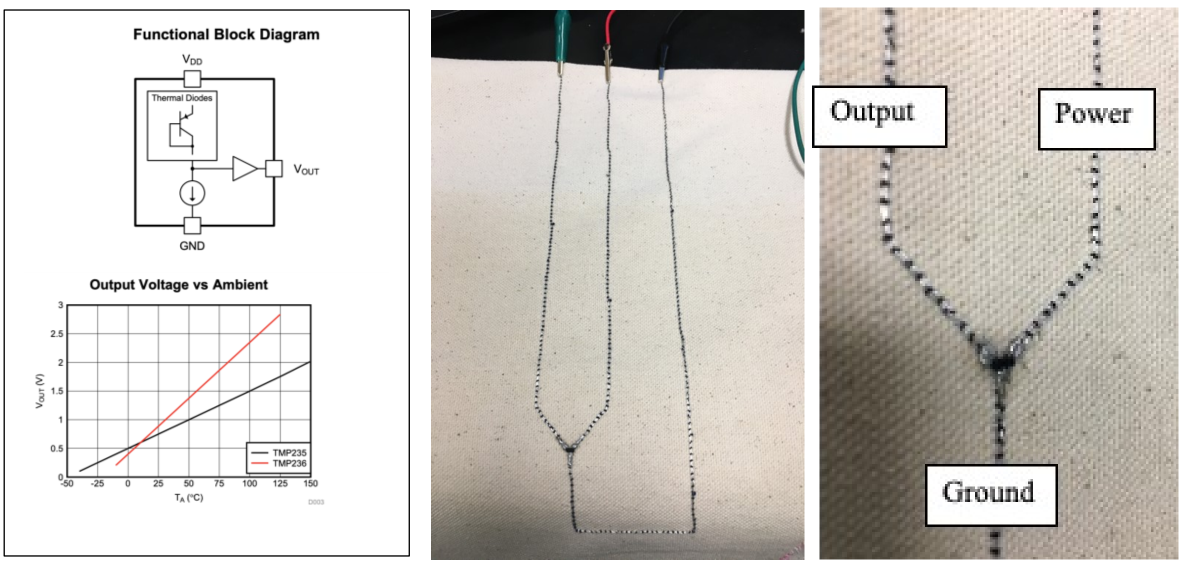


Figure 82: Testing with digital multimeter

connection. If there is a major fault in the system which needs significant effort to fix the garment electronics system, those garments will be separated for a second stage of analysis. Later, a thorough analysis would be performed for the garments with major faults. The major sources of the faults would be identified and analyzed using the tools described above.

- **Step 4: External Hardware for Testing Finished Garment**

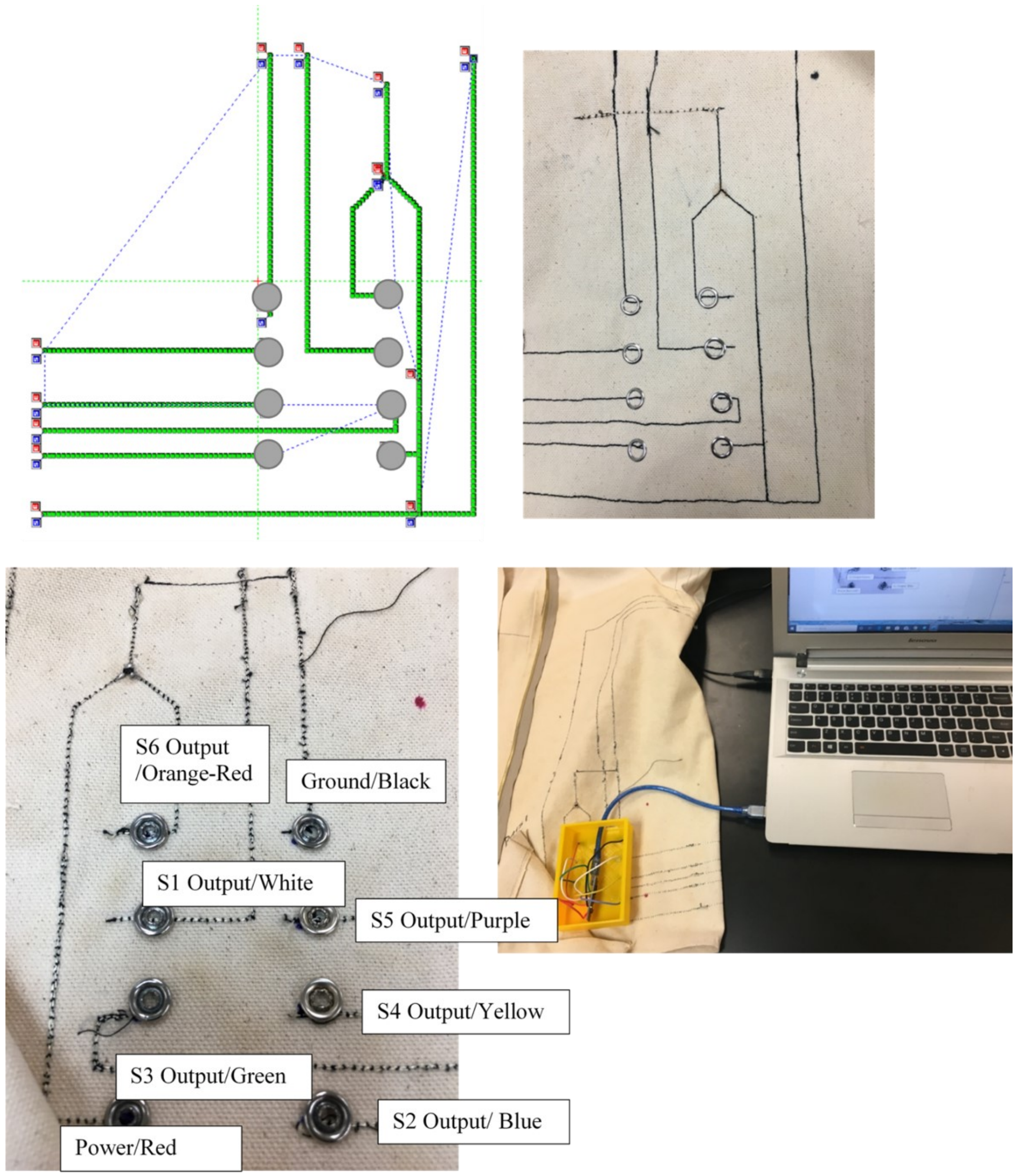


Figure 83: External hardware set up for testing finished garment

For testing the finished garment, an Arduino nano placed in the 3D printed hardware housing was used as described in Figure 83. Six hardware set ups were developed for expediting the quality assessment process. Once the hardware was integrated into the garment, sensor data was assessed by sending the data over a serial monitor in Arduino and confirming that it is in the appropriate range.

The following things were checked to verify the functionality of the electronic system in the finished garment.

- **Check if all the sensor circuits still work.**
- **Check short circuit-does not show any value in the power supply.**
- **Check electricity continuity-shows value in the power supply.**
- **Check resistance measurement-measure the resistance at all the points of measures of the system.**
- **Check voltage test- check if the voltage gives a correct reading. One way to figure this out is to check the voltage level at room temperature and crosscheck with the datasheet. Voltage can be measured using a power supply and a Digital Multimeter.**
- **Check the incorrect orientation of the sensor-check the voltage**

  -If there is a small voltage (~45 mV) passing through the terminals, there is a problem with the sensor or the connections.

  - If there is no change in the voltage level (~5v), there might be a short in the circuit. Check the connection.

  - If the voltage is less than 5V but close to 5V (~4.2v), that means ground is not connected.

Summary:

To identify the tasks involved in transitioning from the prototype development stage to the deployment stage, a manufacturing case study was developed. A temperature-sensing firefighter study was developed as an example e-textile garment which could be later produced in higher-volume in a CMT factory case-study scenario. The sensor-integrated thermal liner garment was developed using the product development process described in Chapter 3. Six analog sensors were integrated using the surface-mount fabrication method and the sensors were spatially distributed all over the garment. A removable hardware was developed to read the sensor data via a microcontroller. Once the garment was developed, a pre-production study was performed to inform decision-making variables for the final production study. A total of 5 sensor-integrated thermal liner garments and a regular thermal liner garment were developed during the pre-production study. A time-study determined the time to perform each operation which was later used to allocate labor, machine, and materials for the production study. Manufacturing tasks involved in transitioning from prototype development to the deployment stage were addressed and described including marker development, stitching conductive traces using the pattern stitcher, trace crossing and seam crossing techniques development, insulation material applications, technical documentation for production, selection of machines and tools for production, production workflow, and quality assessment analysis. The known and unknown challenges faced were described. In the next chapter, I will discuss how these tasks were utilized to produce sensor-integrated thermal liner garments in mass.

Acknowledgement: Several people assisted me at different stages of e-textile prototype garment development. Crystal Compton designed the garment pattern, helped me designing the initial trace layout, and did the sample sewing. Noah Garon made one regular garment. Dylan Osvold made one e-textile garment. Mai Vang assisted me at different stages of four e-textile garments developments. Heidi Woelfle assisted me with sourcing materials from sample development to final production. Several other WTL lab members provided suggestions at different stages of the project. I am grateful to everyone.

CHAPTER 5: DEPLOYMENT OF THE SURFACE-MOUNT FABRICATION METHOD FOR E-TEXTILE GARMENTS

The final part of my dissertation involves the deployment of the surface-mount manufacturing method. This project started with the development of the surface-mount manufacturing method for e-textiles as described in Chapter 3. The method was rigorously tested to ensure that the method is effective, durable, and reliable. The method was then extended to more complex e-textile structures-ranges from swatch to complete garments. The development of these prototypes served as an exploratory investigation to identify the challenges of implementing the method on a larger scale. From the study results, manufacturing variables for manufacturing a surface-mount e-textile prototype garment were identified, and later, the information was used to develop a universal framework for the e-textiles product-development process. At this point, I had a solid understanding of the e-textiles product development process, but there was a need for further extension of the method to a mass manufacturing scenario. The manufacturing of e-textiles is a very new area and has not been the focus of substantial attention in academic research. Existing e-textile manufacturing companies use proprietary e-textiles components and often use craft-based techniques which are difficult to generalize for all kinds of e-textiles manufacturing. Therefore, a thorough and in-depth analysis of the manufacturing process is required to have a better understanding about the challenges involved in transitioning from one-off production to a larger-scale context. That's why I decided to develop an example e-textile prototype garment which could be later implemented in higher-volume production in an apparel factory case study scenario. As discussed in the previous chapters, the case study method provides a high level of detail and could be a useful technique to identify challenges in mass manufacturing. The results from the case-study method could be later used as a guideline for standard e-textiles manufacturing.

As described in Chapter 4, the manufacturing of e-textile involves three major steps: product development, production planning, and production. Therefore, a sensor-integrated thermal liner garment was developed as an example e-textile prototype garment which was described in detail in Chapter 4. The sensor-integrated thermal liner garment was developed following the framework described in Chapter 3 for e-textiles product-development. Once the product was developed, a detailed production plan was developed to deploy the manufacturing method for higher-volume production in an apparel factory case study scenario. While developing the production plan, the tasks and variables involved in transitioning from the prototype development stage to the deployment stage were identified and thoroughly described. The next step is the actual production. This chapter aims to answer the following research questions through the production case-study.

Research Question 6: What is the impact of technology integration into a garment in terms of labor, equipment, and cost during manufacturing of e-textiles as compared to a standard garment?

Research Question 7: What are the factors that affect the quality and scalability of e-textile garments?

To answer the above questions, a production study was performed where forty regular and forty sensor-integrated thermal liner garments were manufactured. To determine the impact of technology integration into textiles, regular and sensor-integrated thermal liner garments were assessed and compared based on machines and tools, time for individual operations, cost, efficiency, labor, bottlenecks, and workflow. The goal of the deployment study includes designing a process for the manufacturing of spatially distributed surface-mount e-textiles, discovering the factors that affect quality and scalability of the process (e.g. labor, equipment, and cost), identifying the operations involved in the process that are required to be measured, discovering the factors that need to be optimized and identifying new variables that emerge from the case study manufacturing process. The ultimate goal of the project is to translate the manufacturing method into a universal manufacturing process for e-textiles which could be deployed in any kind of CMT factory with standard machines and materials with minimum or no additional investment.

In the following section, I will briefly describe the case study method development followed by data analysis techniques for all the research questions mentioned above. Next, I will briefly discuss the findings of the study with discussions which include a summary discussion of the several issues that happened during the manufacturing process along with their possible solutions. Finally, I present several best case-study scenarios to show how this example method could be used as a reference for a universal e-textile manufacturing process.

5.1 Method

5.1.1 Study Location

The manufacturing case study took place in the McNeal Hall between January 3 and January 29, 2020. The study was performed at the Apparel Studio and the Wearable Technology Laboratory at McNeal Hall. The Apparel Studio in the Design, Housing, and Apparel department has an adequate number of sewing machines for assembling the liner garment, and therefore, was selected primarily for performing sewing operations. The existing layout of the machines in the studio was used to simulate a regular apparel production line in a CMT factory setting. Additionally, the Wearable Technology Laboratory has the pattern stitcher, the heat press, the soldering station, the computer stations, and other relevant tools or equipment necessary for electronics integration and was primarily used for electronics-integration operations. Operations were performed in these two locations simultaneously.

5.1.2 Study Participants

A total of 10 part-time employees (participants) were hired to develop forty regular and forty temperature sensing fire-fighter turnout gear coat liner garments, and each participant was compensated $12/hour. The participants were contacted over email and phone. A flyer was posted at different locations of the campus for expediting the hiring process. Once participants confirmed their availability for the study, they were asked to provide a general description of their sewing and other skills relevant to this study. In addition, they filled out an online form with their availability during the dates of the study. Participants were assigned to tasks based on both their availability and their skillsets.

At the beginning of the study, a pre-study questionnaire was used to collect participants' demographic information along with their level of expertise in working with sewing machines, basic electronics, and e-textiles (Table 13). All the participants were undergraduate students at the University of Minnesota during the time of the study. Out of 10 participants, 6 of them were female. Their age ranged from 18 to 29 years. Five of them were majoring in Product Design, 2 of them were majoring in Apparel Design, and 1 of each from Retail Merchandising, Architecture, and Neuroscience departments. When asked about their sewing skills, 5 of them rated their sewing skills as intermediate, 1 rated good, and the rest of them rated their skills as novice. When asked about their experiences with electronics, 5 of them mentioned that they had some level of experience working with soldering, Arduino, and other basic electronics while the rest of them reported having no prior experience in electronics. However, none of the participants reported to have worked with electronic-textiles before.

Participant	**Gender**	**Age**	**Major**	**Sewing Skills**	**Worked with electronics before?**
Participant 1	Female	18	Apparel design	Intermediate	No
Participant 2	Female	20	Apparel design	Intermediate	No
Participant 3	Female	19	Product design	Good	No
Participant 4	Male	29	Retail merchandising	Intermediate	Yes; an audio/visual technician and had computer background as well
Participant 5	Male	20	Product design	Intermediate	Yes; basic coding with Arduino
Participant 6	Female	21	Product design	Intermediate	Yes; Basic experience

					working with LEDs, Arduino, servos
Participant 7	male	24	Architecture	Novice	No
Participant 8	male	19	product design	Novice	Yes; soldering, basic circuits, and motors
Participant 9	Female	20	Neuroscience	Novice	No
Participant 10	Female	20	Product design	Novice	Yes; welding and soldering

Table 13: Participants' demographic information (Production Study Design)

The study took place in a total of 20 sessions (total 395 hours) with each session lasting between 3 and 5 hours with multiple participants. Participants were allowed to take a half-hour break during each session.

Each participant was given verbal and written instructions before performing a new task. The written instruction contained technical documentation along with a list of tasks they needed to do in order to complete an operation. In addition, a demonstration was held at the beginning of each operation to train participants on how to operate the machine/tool involved with each specific task and how to perform their assigned job. Later, participants were given some time to familiarize themselves with the machine, tool, and operation. Participants were encouraged to do a simple demonstration in front of me before starting their respective operations. Once participants were ready, they started their work under my direct supervision. I did not interfere with them throughout the study unless there was an obvious mistake. Participants were encouraged to reach out to me whenever they had questions.

After each task, each participant filled out a form with the time he/she took to perform the operation, the type of failures, and his/her observations about the task. An example template of the form is shown in Figure 84 (more details in Appendix 2). Participants were primarily responsible for executing individual operations of the manufacturing process. The manufacturing variables that emerged from the deployment of the manufacturing method were measured using a time study method. A stopwatch was used to record time for each operation from start to finish. Participants used their smartphones for recording the time of their respective operations. Here, participants collected only the time required to perform an operation, and any other time involved in manufacturing, such as time spent for training, material handling time, etc. was not included in the operation time. More abstract challenges were recorded during and after the study using a post-study questionnaire. In the post-study questionnaire, participants were asked about number of hours spent on the project, operations, machines, and tools they were involved with and their prior experiences with them, operations/machines they found most challenging, and suggestions to improve their experience.

QA and Troubleshooting

Name:
Date:
Fill out the below form
Body

Garment No.	Sensor	Total Time	Type of failure (Chip joint attachment (weak	Time to trouble-shooting	Sensor did work after final troubleshooting (Yes/No)	Notes

			connection, short, etc.)			
1	**1**					
	2					
	3					
	4					
2	**1**					
	2					
	3					
	4					
3	**1**					
	2					
	3					
	4					

Figure 84: QA and Troubleshooting form for the study participants

5.1.3 Production Layout

For the production of both the e-textile liner garment and the standard garment, operations were listed in a process flow, consistent with the techniques used in typical garment manufacturing. A traditional bundle production system for 40 regular and 40 sensor-integrated thermal liner garments was implemented. The machine layout was developed based on the sequence of operations, and each individual was assigned to a particular operation. A total of 90 garment pieces (including 10 extra garment pieces) were cut to produce 80 thermal liner garments (42 regular and 48 e-textile thermal liners). So, the bundle size started with 90 garment pieces and was reduced to 86 garment pieces at the final stage of the study (41 regular and 45 e-textile). Operations for the integration of electronics into garments were included in addition to the basic operations for apparel manufacturing. From the operation sequences, the machines, processes, and operations involved in the integration of technology can be easily separated from the garment manufacturing operations. For instance, in the case of garment manufacturing, many sewing machines were used including serger machines and lock stitch machines. On the other hand, for the integration of electronics, a programmable pattern stitcher, a solder deposition station with soldering materials, and a heat press were used. Processes that need to be added for the integration of electronics include stitching conductive traces for sensor components on fabric pieces, soldering sensor components, affixing connectors for the removable hardware unit, connecting and insulating traces, testing the electronic system, and troubleshooting if needed. A total of six removable hardware systems was developed for convenience in testing.

The production layout was divided into four different units: cutting, regular thermal liner garments assembly, sensor integration, and sensor-integrated thermal liner garments assembly. After finishing the garment assembly, a post-production quality test was performed by me where garments were tested to check the functionality of the garment as a whole as well as the functionality of the individual sensors. The number of working and non-working sensors were recorded and the reasons behind the failed connections were analyzed. A list of operations along with working hours is described in Figure 85.

A detailed draft breakdown of the production activities is described in Figure 86-89. Here, green boxes denote the operations performed for regular thermal liner garments, orange boxes denote the operations performed for sensor-integrated thermal liner garments, blue boxes denote the operations that were performed for both regular and sensor-integrated thermal liner garments, and finally, gray outlines denote the operations performed simultaneously by multiple operators. There were some instances where operations were performed together even though they were dependent on each other. In such cases, one operator started with a piece and sent it to the next person once s/he was done with that. For instance, for serging, one participant first serged the front and back of the sleeve together, the next participant then serged the sleeves to the body, and finally, the third participant serged the sleeves' hem and body hem. All these steps happened at the same time given that the first participant started first followed by the second and third participants. Quality inspection was performed at the end of cutting and during the post-production study for the regular thermal liner garments: no quality inspection was performed during regular thermal liner assembly operations. Since the focus of this project was identifying challenges involved in electronic-integration process, quality inspection was primarily performed for the e-textile operations.

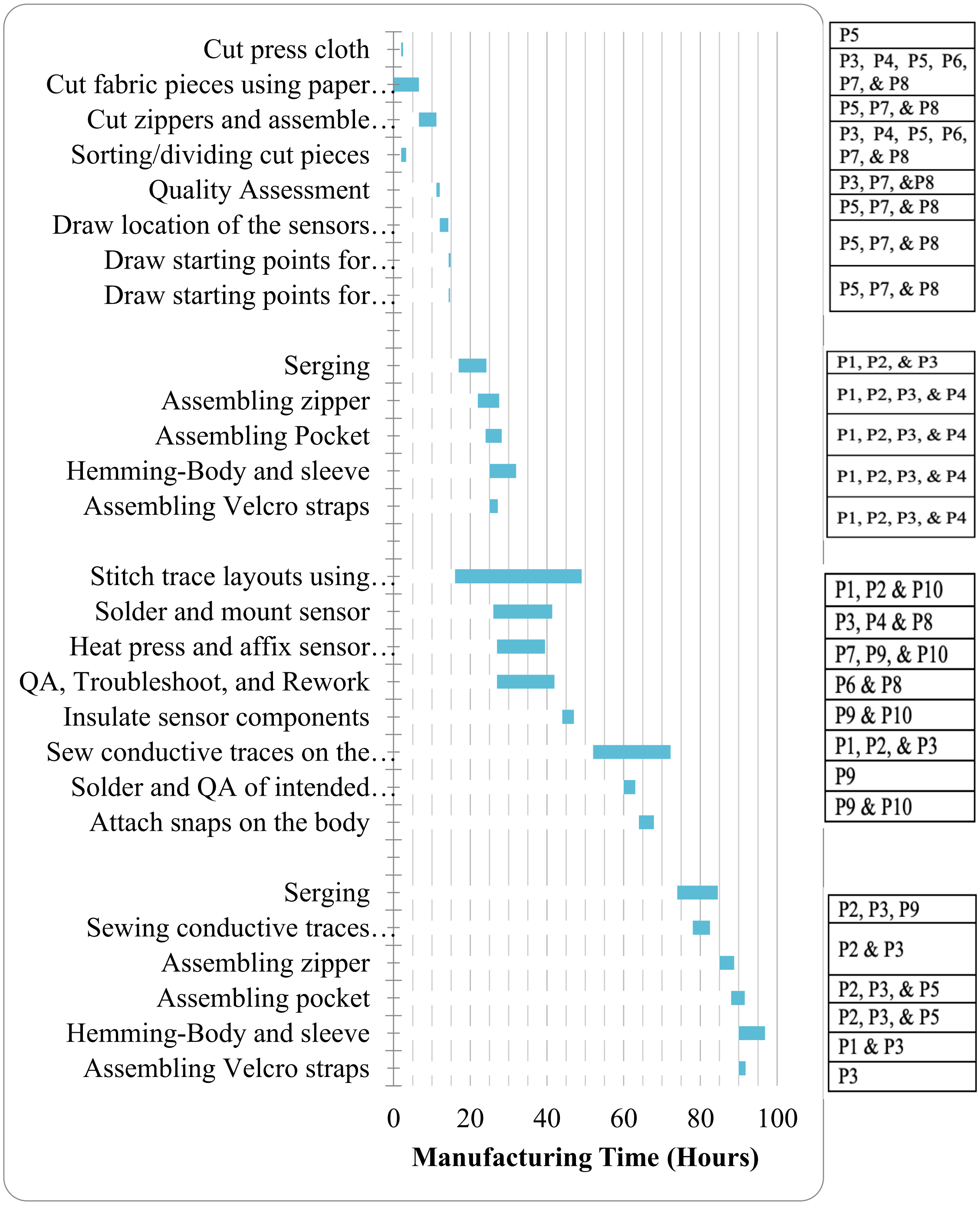


Figure 85: A list of operations including duration (Hours)

Department A: Cutting (Sensor-integrated and regular thermal liner)

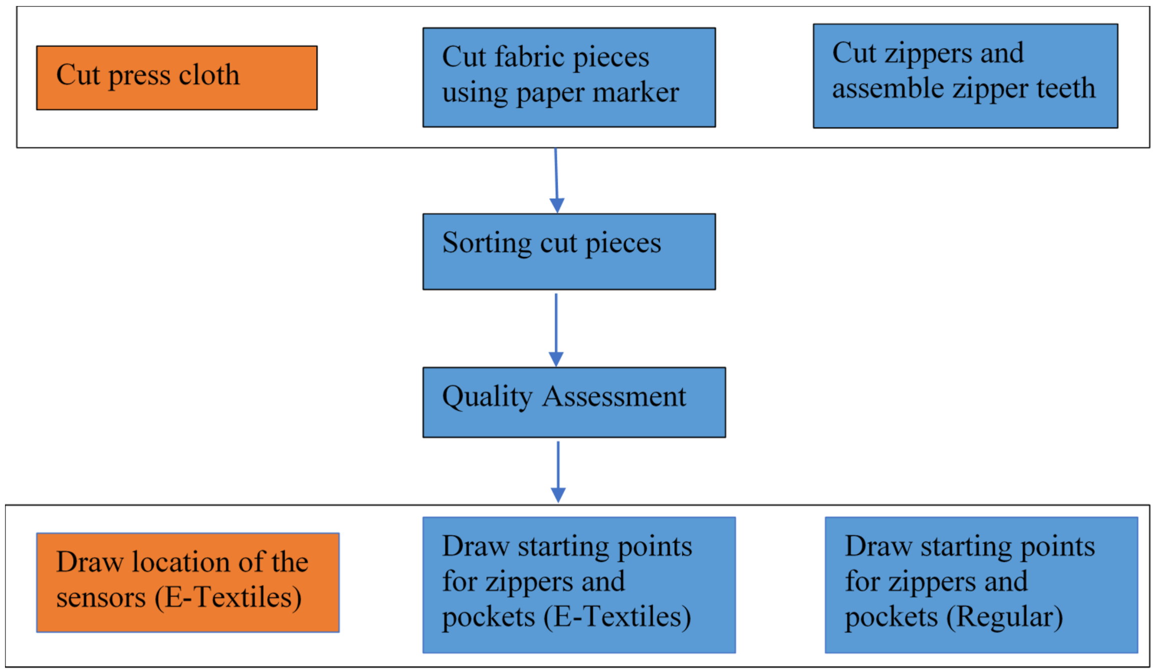


Figure 86: Production workflow for Cutting

During the pre-production study, fabrics were cut for individual garments using a paper pattern. However, during the production study, a marker was developed to cut fabrics in bulk. Therefore, some modifications were made in the cutting department to fulfill the production requirements. Initially, I planned to cut pieces for 96 garments. However, due to fabric shortages, pieces were cut for a total of 90 garments. A total of 3 paper markers was used, and each marker consisted of all the garment pieces to assemble 3 garments as described in Chapter 4. I decided to use fewer fabric plies for the first marker so that the participants could familiarize themselves with the cutting knife and the fabric spreading and cutting processes. Hence, the first marker paper was used to cut 6 fabric plies. I increased the number of plies for the second marker and used 14 fabric plies. For the third and final marker, I used 10 fabric plies.

The cutting was performed in two steps: spreading and cutting. At first, fabric plies were spread on the cutting table and later a marker was placed on top of that. A rotary knife was used to cut the fabric pieces using marker paper. Later, a hand knife was used to cut small pieces such as zippers, and press cloths. In addition, the same hand knife was used to cut the sharp edges of the cut pocket. Three of the participants (P5, P7, & P8) were involved in cutting zipper pieces; one participant of each was responsible for cutting the zipper chain, for assembling the zipper stops, and for assembling zipper slider. One participant (P5) was responsible for cutting all the press clothes.

Figure 87: Participants were performing cutting

Once the garment pieces were cut, they were divided to separate regular thermal liner garment pieces from the sensor-integrated thermal liner garment pieces using the following quantities: Body-regular garment (42), Body-e-textile garment (48), Right Front Sleeve-regular garment (42), Right Front Sleeve-e-textile garment (48), Left Front Sleeve regular garment (42), Left Front Sleeve-e-textile garment (48), Back Sleeve (180), pocket (90), zipper (88), and press cloth (22) (Table 14). Six (P3, P4, P5, P6, P7, & P8) participants were involved in cutting fabric pieces using marker paper and sorting garment pieces. Once all the pieces were cut, five pieces of each body parts were randomly picked, and a quality assessment was performed to check the measurement of the cut pieces using the measurement chart described in Chapter 4. A paper pattern along with a measurement tape was taped onto a table and later used as a reference to check the measurements of the garment pieces as a batch as well as for individual assessment. Finally, a paper template was used to draw location marks for the sensors, the zippers, and the pockets. Three participants (P3, P7, & P8) were involved in quality checking to draw locations of the sensors, zippers, and pockets.

Garment Piece	**Quantity/Garment**	**Quantity/80 garments**	**Allowance (20%)**	**Planned Total**	**Actual Cut Pieces**
Body	1 (3 Markers)	80	16	96	90
Front Sleeve	2	160	32	192	180
Back Sleeve	2	160	32	192	180

Pocket	1	80	16	96	90
Press cloth	1/12 press	20	2 (10%)	22	22
Zipper	1	80	8 (10%)	88	88

Table 14: Garment pieces cut during production

Department B: Regular thermal liner garment assembly

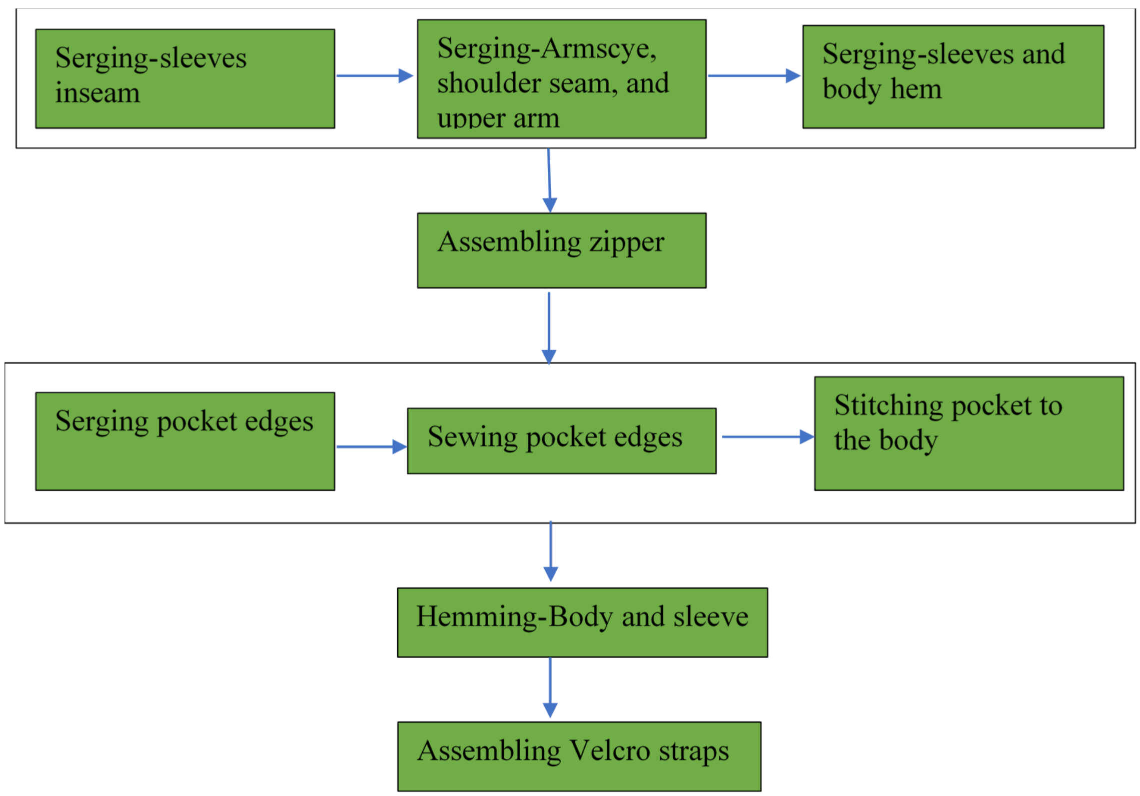


Figure 88: Production workflow of regular thermal liner garment assembly

As described in Chapter 4, sensor-integrated thermal liner garments manufacturing had more processing steps than the regular thermal liner garments manufacturing, and therefore, regular thermal liner garment assembly and sensor attachment for the sensor-integrated thermal liner garments operations were performed simultaneously. I had two distinct groups of participants: some of the participants had self-reported to have some experience in sewing and the rest of them had some level of experience in electronics. Hence, the participants having sewing skills were assigned to the regular thermal liner assembly and the participants having electronics skills were assigned to the electronic-integration part of the sensor-integrated thermal liner garment assembly. Hence, the same set of participants did the garment assembly steps (e.g. serging) for both regular and sensor-integrated thermal liner garments. A total of four participants (P1, P2, P3, & P4) were responsible for producing a minimum of 40 regular thermal liner garments from start to finish. The workflow for assembling regular thermal liner garments is described in Figure 89. The major difference between the pre-production planning and the production study was that the production study divided the garment assembly into more sub-tasks that were divided among more people compared to the pre-production planning, though the overall operations performed were comparable. For example, in the pre-production planning, serging was considered as one task and one person was responsible for performing the whole serging operation. However, during the production study, I found that some sub-tasks took more time than others and that further breakdown might ensure even distribution of the workload, as well as improve the efficiency of the manufacturing method. Hence, I decided to break down the serging into three steps: sleeves' inseam; armscye, shoulder seam, and upper arm; and sleeves' and body hem to equally distribute the workload among all three available participants. Similarly, assembling the pocket was divided into three sub-tasks: serging pocket edges, sewing pocket edges, and stitching the pocket to the body. The first operation for the pocket was performed by a serger machine and the latter two operations were performed by two lock stitch machines. However, all these changes are pretty common in the apparel industry when going from a sample production scenario (when one person is performing all the tasks) to a distributed production scenario (when multiple people are involved in performing all the tasks). Zipper assembly was quite similar to the pre-production study. The location of the zippers was one inch away from the edge and was marked using a washable marker before sewing into the garment. Hemming was performed on the body and on the sleeves to improve the appearance and the look of the garment which was missing during the pre-production study. Then, Velcro straps were cut and assembled within the garment. Finally, a total of 41 regular thermal liner garments were made. Once the garments were assembled, they were kept in two separate boxes for quality assessment purposes.

Department C: Sensor Development

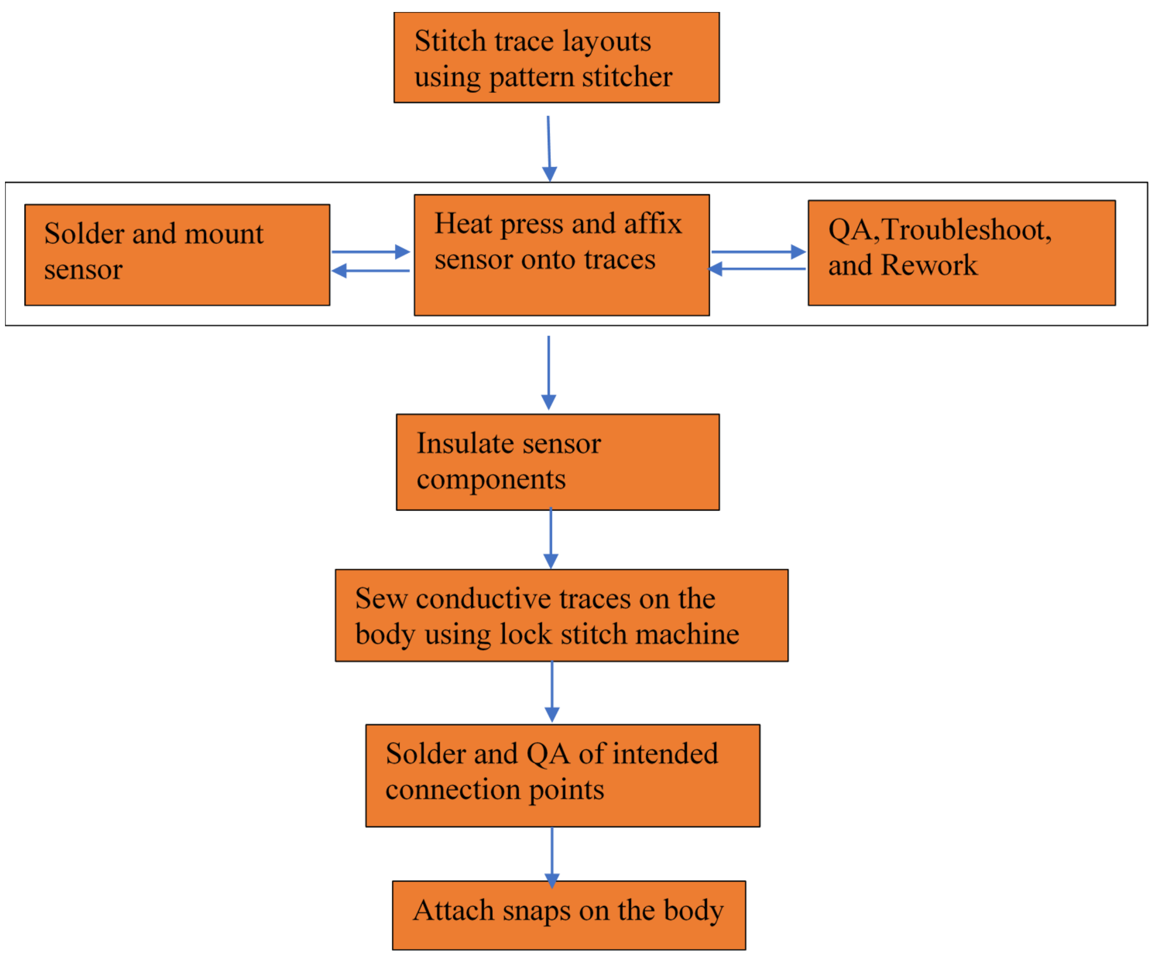


Figure 89: Production workflow of sensor attachment

As mentioned earlier, sensor attachment operations were performed simultaneously with the regular thermal liner garments assembly. The workflow of the sensor attachment department is shown in Figure 90.

Figure 90: Steps involved in sensor attachment: trace layout is stitched using pattern stitcher (top left); soldering and mounting sensor on the trace layout (top right); pressing using heat press (bottom left); Quality Assurance testing using Arduino-Uno setup (bottom right)

The first step of the sensor attachment was "stitching trace layouts using pattern stitcher". Initially, two participants (P1 & P2) were assigned for this task: one participant was responsible for feeding the fabric onto the machine and another was responsible for quality inspection of the stitched trace layouts, winding two extra bobbins, and providing any other support to the first participant. Both the Right Front Sleeve and the Left Front Sleeve had only one pattern and hence, they were stitched first so that soldering and sensor affixing could be done on them without waiting for the rest of the patterns. There were 10 pattern layouts in total, and P1 & P2 stitched and finished two pattern layouts (right sleeve & left sleeve). In addition, they also stitched 8 more body pieces so that these could be later used for soldering while the rest of the layouts were still in the work-in-progress step. Later, P10 was assigned to stitch the rest of the trace layouts using the pattern stitcher. Eventually, all the pattern templates were stitched and if any problem was found in the stitched layout on the garment pieces, these layouts were removed and stitched again on the same garment pieces. Total time was calculated for stitching, quality assessment, rework, and troubleshooting was recorded.

Once pattern layouts were stitched onto garments, they were moved to the next stage: attaching TMP235 sensors onto garment pieces. The attachment of the sensors was divided into three sub-tasks: applying solder and mounting the sensors, heat pressing sensors onto traces, and quality assessment, troubleshooting, and rework. In the beginning, two participants (P3 & P8) were assigned to perform soldering in two stations, participant 7 was assigned for heat pressing, and participant 6 was assigned for quality assessment, troubleshooting, and rework purpose. Later, P3, P4, P5, P9, & P10 were involved at different stages of the component attachment.

Out of these three sub-tasks, heat pressing was taking two or three times more time than the other two (even more time than projected during the pre-production study) and was creating bottlenecks in the process. Initially, the components were pressed at 420° F (215.56°C) for 120 seconds. However, I realized that in most cases components needed to be pressed more than once to have a solid solder connection which eventually added up to more time in the manufacturing process. I found out that the fabric I used for the final production study was slightly thicker (9.5 ounces) than the one used during pre-production and the additional fabric thickness might consume more heat causing cold solder joints. With some iteration, I decided to increase the temperature to 435°F (224°C) from 420° for 60 seconds at which I could have a solid connection without burning the fabric. This cut down significant time in re-pressing the components and eventually improved the overall productivity in the process.

For quality assessment, rework, and troubleshooting, an Arduino-Uno setup was used to test the functionality of the individual sensors. More details can be found in Appendix E. A digital multimeter and a microscope were used for testing faulty connections. Each faulty sensor was re-worked, troubleshot, and re-tested two times. The sensors that did not function after reworking twice were recorded as in-process failures and performed another QA check on them at the end of the study. The next step was insulating sensors using a film-type tape. Two participants (P9 & P10) were assigned to insulating the sensors; one participant cut 5-inch strips and the other participant used a hand iron to affix the insulating layer on top of the sensor. The sensors attached to the front sleeves (total 90 sensors) were insulated for 90 front sleeves. The sensors on the body were not insulated due to the unavailability of the participants. Once all the sensors on the garment body pieces were soldered, an industrial lock stitch machine was used to finish the trace layout of the body pieces. P1, P2, & P3 were assigned to stitching the trace layout on the body pieces. A quality assessment was performed by P9 to assess the accuracy of the trace layout and later, a digital multimeter was used to identify faulty connection issues (e.g., ensuring the circuit made connections where needed and avoided connections between un-intended traces). Soldering was used to fix faulty connections. Finally, two participants were assigned to attach snaps on the body.

Figure 91 describes the workflow of sensor-integrated thermal liner garment assembly. Sensor-integrated thermal liner garment assembly consisted of the same manufacturing steps as regular thermal liner garment manufacturing except for connecting conductive traces from the body to the sleeves using a lock stitch machine. These connections were made after serging the sleeves to the body. Once the connections were made, the rest of the garment was assembled using the same processes as described for the regular thermal liner garments. Four participants (P1, P2, P3, P5, & P9) were involved in assembling a total of 45 sensor-integrated thermal liner garments. To keep things consistent, the same participants (P1, P2, P3, & P5) who were involved in assembling regular thermal liner garments were assigned to assembling sensor-integrated thermal liner garments.

Department D: Sensor-Integrated thermal liner garment assembly

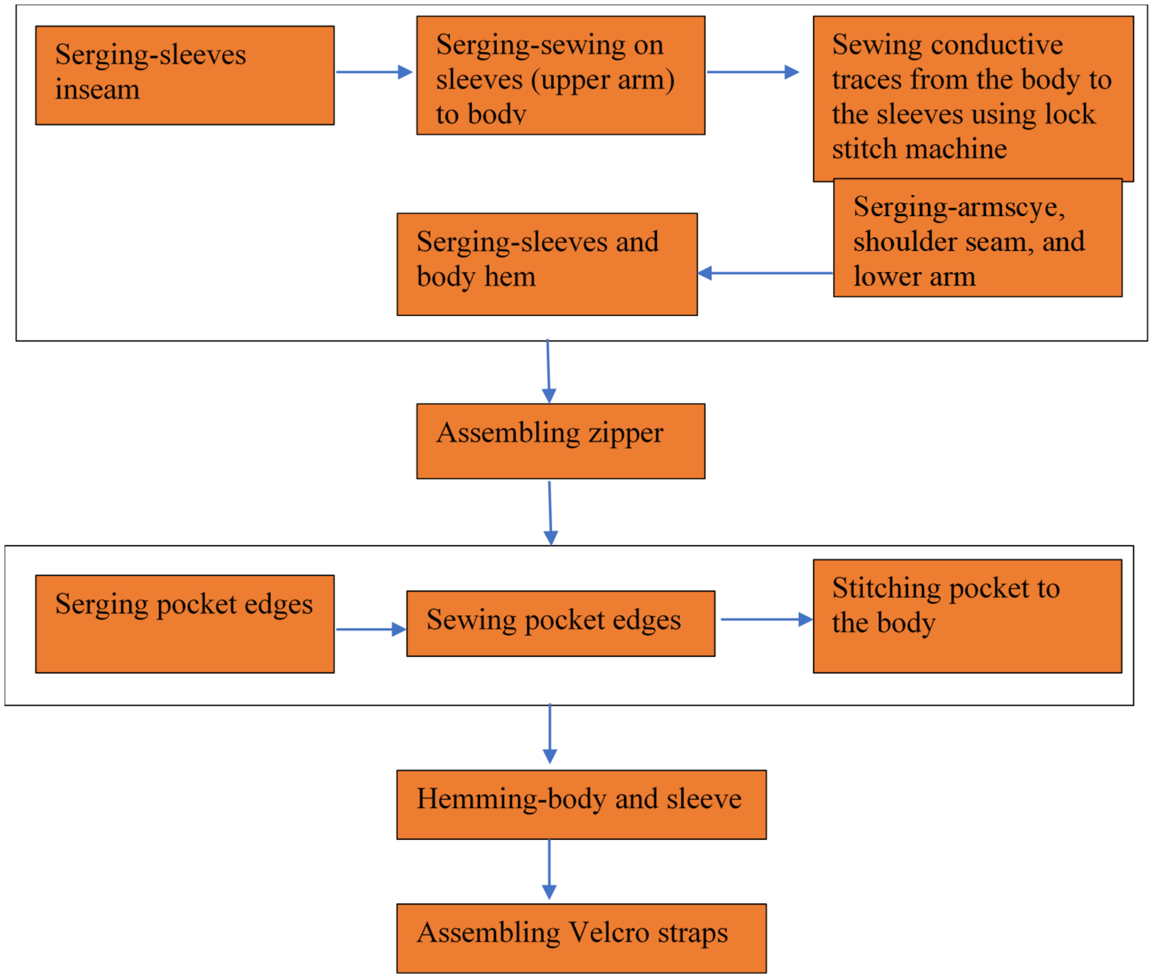


Figure 91: Production workflow of sensor-integrated thermal liner garment assembly

Department E: Post-production quality assessment

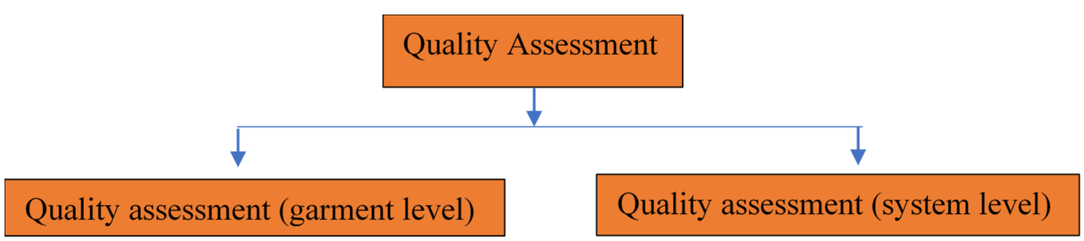


Figure 92: Quality assessment workflow of the finished garments

A quality inspection was performed at the end of the study where garments were measured using the size chart to check whether garments were produced within the tolerance limit (Figure 92 & Appendix 2). A total of five garments were randomly picked from each of regular thermal liner garment (41) and sensor-integrated thermal liner garments (45). A measurement tape was used to measure the dimensions of the garments. In addition, quality assessment was performed to test the functionality of all the sensor-integrated thermal liner garments in system level where sensors were tested as an individual as well as a whole in the finished garment.

5.2 DATA COLLECTION

This study aims to perform a comparative study between e-textile garment manufacturing and regular garment manufacturing. One of the proposed research questions is:

Research Question 7: What is the impact of technology integration into a garment in terms of labor, equipment, and cost during manufacturing of e-textiles as compared to a standard garment?

To determine the impact of technology integration into a garment during manufacturing of e-textiles as compared to standard garments, machines and tools, time, cost, efficiency, and operation workflow for forty regular and forty sensor-integrated thermal liner garments were assessed. For data collection, machine and tools needed for sensor-integrated thermal liners were identified, time for each operation was recorded using a stopwatch, materials costs were collected from the manufacturers and retailers, and critical operations were identified by analyzing the operations that took a significant amount of time, by analyzing the post-study questionnaire, and from personal observations.

The ultimate goal of the study was to determine how different it is to mass-produce e-textiles in terms of machine and tools, time, cost, and operation process from regular garments. The expected outcomes are to:

-Determine the average time to finish an operation

-Perform an estimation of cost to produce e-textile garments in mass

-Determine the impact of operator efficiency on the production time and quality

-Determine the most critical operations in the process and the reason behind that

-Identify the major quality failure issues in the process

-Stages when the majority of the failures occur

-Time for troubleshooting and reworking at different stages

The next research question the study aims to answer is:

Research Question 8: What are the factors that affect the quality and the scalability of e-textile garments?

To answer this question, the major elements that determine the effectiveness of a manufacturing process in mass level (e.g. efficiency, quality, use of industrial machines and tools, etc.) were assessed. The factors calculated include time (time to finish an operation), quality (e.g., types of quality issues, number of failures in each stage of production, and time for quality assessment, troubleshooting, and rework), worker efficiency (comparing time to finish an operation by different workers and comparing time to finish an operation by an expert vs. a novice operator), bottlenecks (comparing tasks that take the maximum time to finish), tools and machines (analyzing the hand-operated and automated machines and tools used in the production), cost (comparing cost for manufacturing e-textiles in mass). All these manufacturing variables were collected and analyzed to determine the scalability of the method. The expected outcomes are to:

- Determine the additional time required to produce e-textiles compared to regular garments
- Identify the most common failures that occur in e-textiles production.
- Determine the impact of operator efficiency and skills on the quality, time, and cost of the garment
- Identify the tools and machines that can improve the quality and scalability of e-textile garments

The study initially aimed to produce forty regular thermal liner garments and forty sensor-integrated thermal liner garments. A few extra garments were produced due to the availability of the raw materials. Finally, it took a total of 395 hours (total 20 sessions) to finish the production of 41 regular and 45 sensor-integrated thermal liner finished garments. For data analysis, 40 pieces each of regular thermal liner garments and sensor-integrated thermal liners were considered.

Time

Time studies were performed for both thermal liners (41 pcs) and sensor-integrated liner garments (45 pcs). However, average time was calculated for 40 of each of regular and sensor-integrated thermal liner garments. For this study, the average time to perform an operation was calculated and was later multiplied by 40 to get the total time for 40 regular and 40 sensor-integrated thermal liner garments. Using the time study, time to perform each operation and total manufacturing time were calculated. A smartphone stopwatch was used to collect start and finish time for performing an individual operation.

Everything that happened between the start to finish of a process was included in the operation time. For instance, cutting time for fabric pieces involved spreading fabric plies, laying marker on top of the fabric pieces, cutting using a rotary knife, and hand knife where needed. However, time for handling materials, training participants, taking breaks during the study was excluded from the operation time. The following formula was used to calculate the total time for the study:

Total manufacturing time for the regular thermal liner unit, $t_1 = t_{cutting} + t_{sewing}$

Total manufacturing time for the sensor-integrated thermal liner unit, $t_1 = t_{cutting} + t_{sensor\ development} + t_{sewing}$

Where,

$t_{cutting} = \sum_{i=1}^{n} t_{cu\ i}$

$t_{sewing} = \sum_{i=1}^{n} t_{sw\ i}$

$t_{sensor\ devlopment} = \sum_{i=1}^{n} t_{fin\ i}$

(where *i*= a finish unit)

Bottlenecks

From the manufacturing workflow, critical operations or bottlenecks of the operation sequence were identified. In production, a bottleneck is a process in a chain of processes that notably reduce the efficiency of the whole production chain. Bottlenecks are one of the main reasons of production slowdowns and disruptions.

To determine bottlenecks in this project, the time needed to perform each operation was measured using a stopwatch. After the study was complete, the operations that took longer than usual and caused a temporary standstill in the process to finish were selected as the bottlenecks of the process. Bottlenecks were identified for both manufacturing regular thermal liners and sensor-integrated thermal liners. A list of expected sources of increased time and complexity are described below.

- **The operations which were particularly involved in the integration of technology into apparel operations could have an impact on the efficiency of the manufacturing process. It was assumed that technology addition would create additional challenges to regular garment manufacturing, i.e., more time would be required to assemble the technology-integrated garment (excluding total time required to integrate the electronics) than the regular garment. The impact of technology into apparel operations was tested using the time study method, where actual time for each operation was calculated and later compared for the sensor-integrated thermal liner garment and the regular liner garment.**
- **We expected to have more complications when electronics were integrated into garments, especially during sensor development, connecting or insulating traces and quality testing of the electronic system, and thus, it might take more time than operations involved in regular garment assembly. Therefore, operations that involve the integration of electronics into clothing were separated and extensively analyzed in terms of time, efficiency, and the number of errors. The reasons behind the bottlenecks are identified and suggestions are provided for future developments.**
- **Sensor attachment and in-line troubleshooting were assumed to be the most critical operations of this production process. To test this, total time was measured for all sensor attachment and in-line troubleshooting operations,**

and was compared with the overall time it took to finish a garment. If a measurably higher amount of time is spent on these two types of tasks, then these two activity areas would have a strong influence on the overall production process.

An operation could be critical for several reasons, such as lack of worker skills, complexity of the operation, or lack of appropriate tools. Hence, the source of increased working time was identified and analyzed.

Efficiency of the Participants

Participants' skillsets also determine the success of an individual operation. Although only 10 participants were recruited to produce regular and e-textile garments, their skillsets largely varied. Both quantitative (i.e., comparison of time to finish the same operation by different workers and comparison of time to finish an operation by an expert and a novice operator) and qualitative analysis (i.e., personal observations and post-study questionnaires) were performed to understand the effect of workers' skills and efficiency on the production of both regular and e-textile garments. The impact of participants' backgrounds, experiences, skillsets on their performance, and quality of the finished garment was analyzed. The learning curves of the participants (a process where people develop a skill by learning from their mistakes) were studied. The learning curve of an individual was measured by comparing operation times at the beginning and end of the study for a particular operation.

Material Costs

The materials needed to perform the production study were bought between July 15, 2019 and January 17, 2020. Material costs for manufacturing regular thermal liners and sensor-integrated thermal liners were calculated and compared. The materials costs were mostly collected from the retailer/manufacturers' websites which means they are mostly retail costs, not wholesale costs. However, material cost can vary depending on the availability of the materials, lead time for buying materials, delivery cost, etc.

Post-Production Quality testing

A post-production quality test was performed by me at the end of the study. The primary objective of the quality testing was to determine the overall quality of the production run. The following data were collected during the post-production quality test:

- **Percentage of joint failures in each stage of manufacturing (chip attachment and garment handling during and after production). The sensors that didn't work for the first time were troubleshot, reworked, and re-tested two more times before moving to the next stage. The percentage of joint failures were calculated after re-testing.**
- **Time for troubleshooting**
- **Sources of errors, their frequency and relative importance on the overall manufacturing process**

The above data were used to perform an analysis of the most common types of failure (including the failures that couldn't be addressed during the in-process QA checks) and the sources of failures in the case-study manufacturing process. Planned troubleshooting and re-work techniques were further assessed to evaluate their effectiveness in producing functional and durable e-textile garments. Troubleshooting time at various stages of production was calculated and the relative importance of quality assessment tasks for the successful production of e-textiles was evaluated. Finally, all the findings were used to provide design guidelines for manufacturing surface-mount e-textile products.

Simulated best-case scenario

A few simulated models were developed at the end of the study to determine the best-case scenario of the manufacturing method in terms of labor, equipment, cost, and efficiency within the given context. The basic assumption behind the models were that all the labor and machines would perform at their maximum capacities. Here, I took all the best possible and realistic manufacturing time and cost from the study results. A more detailed description of the simulated models is described in the respective sections.

New manufacturing variables

A thorough analysis of the manufacturing process and a post-production quality assessment were performed to identify new variables emerging from the case study e-textiles manufacturing process that could be later investigated for future development. The changes in the new manufacturing process between production study and pre-production planning were observed and recorded. During the post-production QA investigation, sources of failure that were not adequately addressed during in-line QA strategies were characterized. A qualitative assessment of the unexpected elements occurring during the production process (such as failures detected during QA checks that could not be resolved using the prescribed processes) was also performed. These methods were used to discover new variables and process elements and their relative importance in overall manufacturing, which could later be used to provide recommendations for future e-textiles manufacturing.

5.3 RESULTS AND DISCUSSION

5.3.1 Pre-production study Vs. Production Study Results

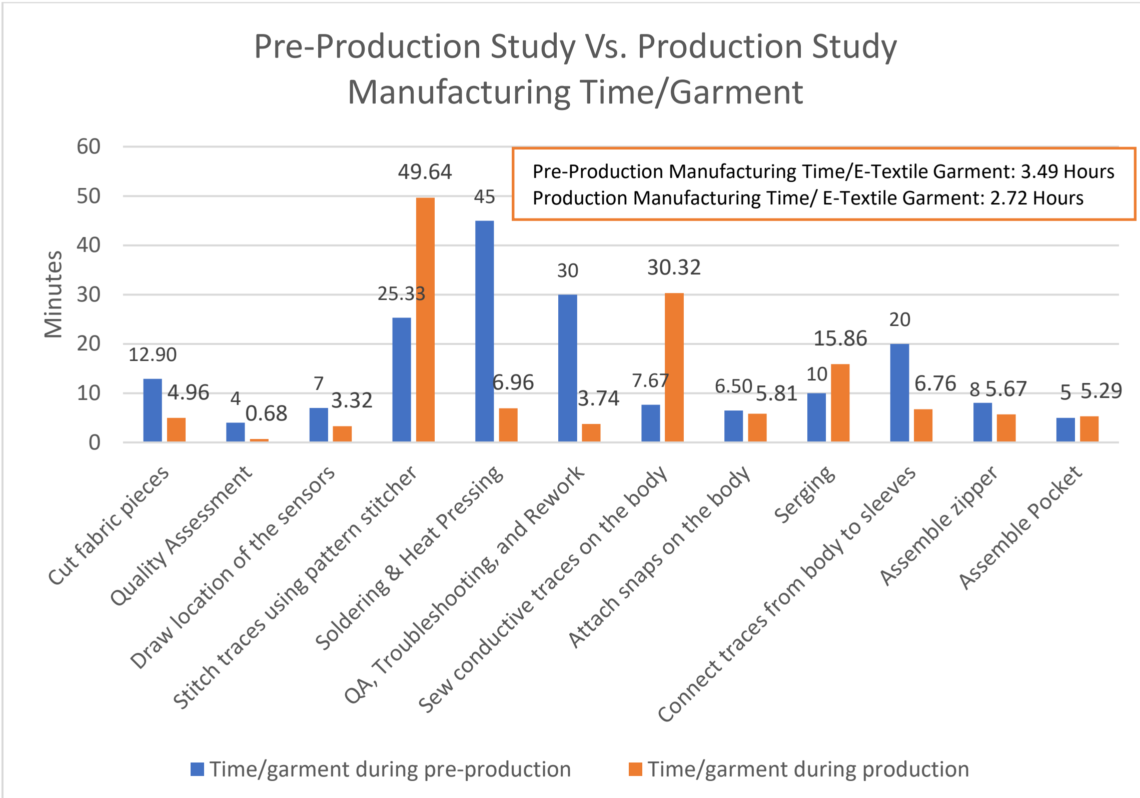


Figure 93: Manufacturing time per garment for Pre-Production Study Vs. Production Study

Figure 93 describes the time to perform each operation during the pre-production study as compared to the production study. As showed in the figure, overall, it took more time to produce an e-textile garment during the pre-production study (3.49 hours) compared to the production case study (2.72 hours). The average manufacturing time for an individual garment is lower when e-textile garments are produced in bulk in an assembly line setting, which is consistent with traditional apparel manufacturing outcomes. For individual operations, almost all operations except for "Stitch traces using pattern stitcher", "Sew conductive traces on the body", and "Serging" took less time during the production study compared to the pre-production study. Out of all the non-e-textile operations, surprisingly serging took more time during the production study compared to the pre-production study. Since, serging is a standard sewing operation, my assumption was that the operation time for serging would be similar for both pre-production and production study. It might be possible that stitching conductive traces from the body to the sleeves creates additional complexities that were responsible for higher manufacturing time, though it could not be confirmed. There were some instances during production study where trace layouts in the sleeves did not perfectly align with the trace layouts in the body. Participants' skill differences between the pre-production study and the production study might also have some influence on the higher serging time during the production study. Furthermore, differences in the workflow were observed between the pre-production study and the production study. For the pre-the production study, the trace layout was stitched onto the sleeve before joining with the body, and connections were made between the body and the sleeves after the serging was done. Due to the three-dimensional shape of the sleeves, it was inconvenient and more time consuming (e.g. if the traces don't line up and need adjustment) to connect the traces and follow the trace line if the trace layout was stitched on the sleeves (before joining with the body). Therefore, the conductive trace was stitched after the sleeve was joined to the body during the production study.

Some of the time differences observed in Figure 93 are due to changes in the production process between pre-production and production study. These changes are unanticipated changes that happened during production study and were not included in the original production plan I described in Chapter 4. Several manufacturing operations were modified, and new manufacturing operations were added while transitioning from constructing a single prototype to performing a bulk production process. A brief overview of changes observed during the pre-production study and the production study is described below.

Department A: Cutting

As shown in Figure 93 overall, it took 23.90 minutes for cutting and drawing sensor locations for a single garment during pre-production, compared to 14.78 minutes per garment for performing the same operations for the production study. The major difference between manufacturing a single thermal liner garment and manufacturing in mass is the use of a paper marker to cut a multi-ply layup instead of cutting individual single-ply pattern pieces. Cutting multiple garment pieces at the same time decreased cutting time by 62%. As shown in Figure 93, cutting fabric pieces for individual garments during production study was lower (4.96 minutes/garment) compared to that of pre-production study (12.90 minutes/garment). However, the development of marker from pattern paper is an additional task and is commonly used for cutting pieces in bulk.

A rotary knife was used for cutting pieces in bulk whereas a hand knife was used for cutting small pieces and sharp edges of the cut pieces. The use of a rotary knife required some additional training and needed extra precaution. Fabric spreading also took a good amount of time (around 20-30 minutes). While spreading the fabric plies, it took some time to lay the fabric flat on the table to ensure even tension between corners and to avoid any fold or crease marks between layers. However, it would be lot faster if I could use an industrial spreading machine which was out of the scope of this project. Sorting pieces is another task that needs to be performed for mass production of apparel. Another major difference in transitioning from a single prototype to bulk production is the involvement of the number of people. During sample development, typically one person is responsible for manufacturing the complete garment. On the other hand, during production, the same garment might be developed by several people involved in the production. Therefore, during production, a lot of things need to be done to ensure consistency throughout the production which can be ignored during sample development. For instance, to correctly identify the right orientation of the fabric (face side and back side), the fabric layers were laid out in such a way so that the face side would be always on the top and the cut pieces were marked using a marker immediately after cutting. For consistency and quality assurance across all the garments, locations of the sensors, zippers, and pockets were marked as well. Similarly, for sensor-integrated garment, sensors locations were marked using a paper template.

Department B: Regular Thermal Liner Assembly

During assembly of a single thermal liner, one person finishes the garment from start to finish. On the other hand, during production, garments are produced in an assembly line setup. That means, the complete assembly operation is divided into several sub-tasks and each person is responsible for assembling only one part of the garment. For the production study, there were more sub-tasks involved than the pre-production study. For instance, I used serging as a single operation during the pre-production study, whereas, it was divided into three more sub-tasks during the production study: serging sleeve inseams; serging armscye, shoulder seam, and upper arm; and serging sleeves & body hem. A lot of these changes were dictated by the availability of skilled participants and industrial machines. Since there were four participants involved in manufacturing all the regular thermal liner garments, I had to utilize them properly to ensure the best outcome. Dividing tasks into sub-tasks ensured that no one was sitting idle, and hence, improved the overall efficiency. Furthermore, to improve the appearance of the garments I added two additional tasks that were not included during the pre-production study: hemming the body and sleeve and assembling Velcro straps. Hemming the body and sleeve took approximately 10.27 minutes per garment and assembling Velcro straps (which includes marking Velcro strap locations, cutting Velcro straps, and sewing onto the garment) took 2.71 minutes per garment. Some participants were more experienced and skilled than others and that was reflected in their performance.

Department C: Sensor Attachment

Most of the tasks for sensor attachment during the pre-production study were quite similar to the production study. In terms of manufacturing time, it took 114.5 minutes per garment for sensor attachment during the pre-production study, compared to the 101.78 minutes to perform the same operations for the production study. The major difference between the pre-production study and the production study was stitching the trace layouts. As described earlier, for the production study, a total of 10 trace layouts were stitched using a pattern stitcher which produced most of the complete trace layouts (as compared to a smaller portion of the total trace layout stitched using the pattern stitcher for the pre-production study). It took 49.64 minutes for stitching all 10 trace layouts onto a garment using the pattern stitcher in the production study. Out of that, the actual stitching time was 34.38 minutes, and troubleshooting time was 15.23 minutes per garment. Here, the stitching time includes placing the fabric on the machine bed, adjusting the location of the needle, and finally stitching. Both soldering and heat pressing (6.96 minutes/garment vs. 45 minutes/garment) and testing, troubleshooting, and reworking (3.74 minutes/garment vs. 30 minutes/garment) did take less amount time during the production study compared to the pre-production study.

Department D: Sensor-Integrated Thermal Liner Garment Assembly

It took 43 minutes to assemble a sensor-integrated thermal liner garment during the pre-production study and it took 46.56 minutes to do the same operations during the production study. As with the standard thermal liner production, two new tasks were implemented during the production study: hemming the body and sleeves and sewing Velcro straps. These took 12.98 minutes and were the primary reason for the higher manufacturing time compared to the pre-production study (Figure 93). The operations performed in the sensor-integrated thermal liner assembly were pretty similar to the operations performed for regular thermal liner garments assembly. The only e-textile-specific operation for sensor-integrated liner garments was connecting traces from the body to the sleeves. In terms of participants, the same set of participants were involved in the regular thermal liner garment assembly and sensor-integrated thermal liner garment assembly. Therefore, participants were familiar with the assembly process and that is reflected in the data as well.

5.3.2 Impact of technology integration into a garment during manufacturing in terms of *TIME*

The average manufacturing time to produce a regular thermal liner garment and a sensor-integrated thermal liner garment is described in Figure 94. As shown in Figure 94, it took more time to produce forty e-textile thermal liner garments compared to forty regular thermal liner garments. The additional operations needed for integrating sensors into the garments were primarily responsible for that. However, time differences were

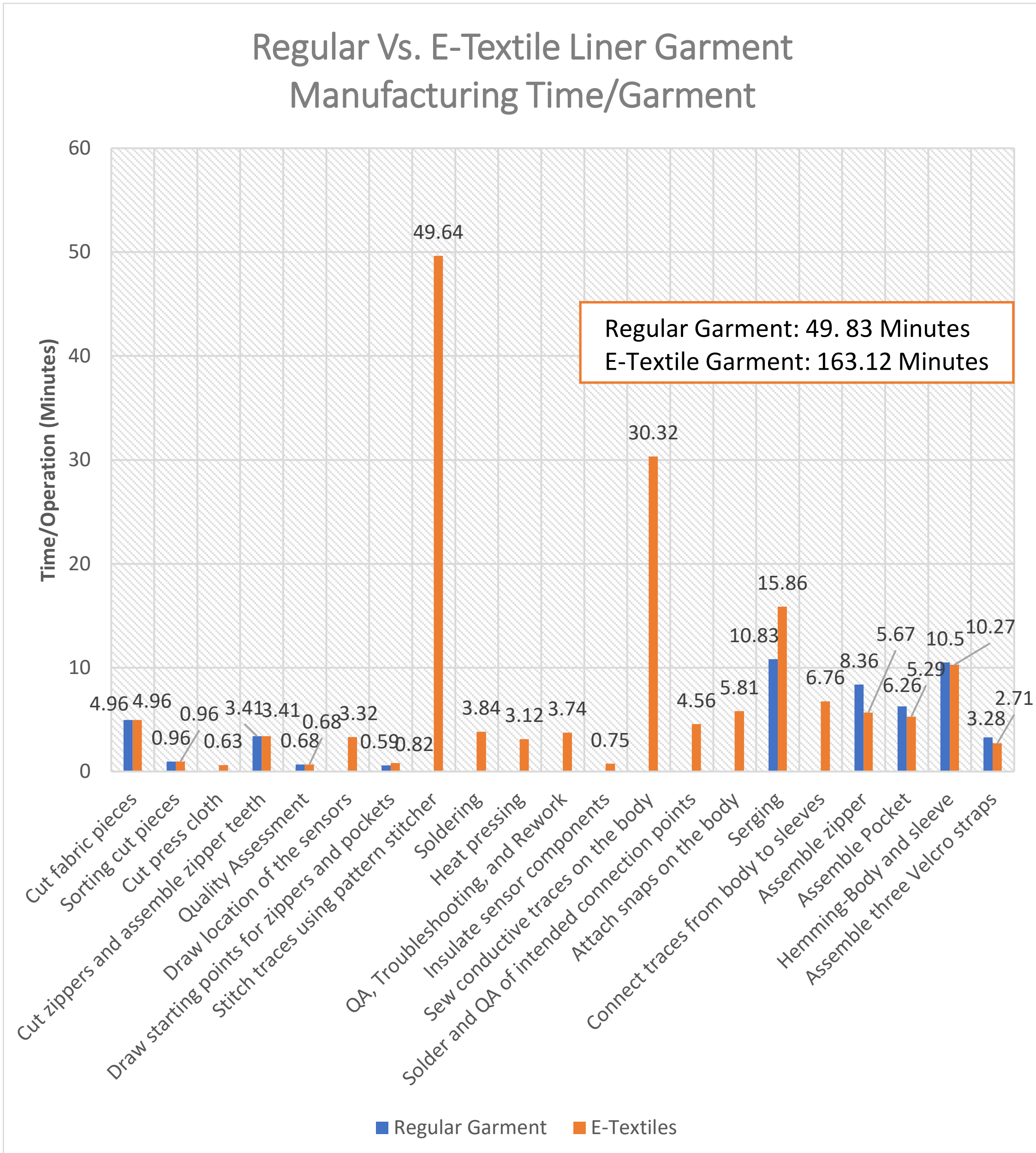


Figure 94: Average manufacturing time per garment for regular thermal liner garments Vs. sensor-integrated thermal liner garments

observed for some operations that were common between sensor-integrated and regular garments. My study results showed that it took more time to perform serging operations for the e-textile thermal liner garments compared to the regular liner garments. For the e-textile thermal liner garments, conductive traces were stitched all over the body which might create additional challenges during serging (e.g. may take more time during the handling of the garment pieces). However, operations that were not influenced by electronics integration such as assembling velcro straps, pocket, zipper, and hemming took less time to manufacture for e-textile thermal liners compared to regular thermal liners. Since the e-textile thermal liner garments were assembled after regular thermal liner garments, participants were familiar with the process by then and took less time to perform similar operations.

5.3.3 Bottlenecks of the process

As described in the method section, the operations that took a long time, needed more time for troubleshooting, caused a temporary standstill in the process to finish, and eventually reduced the overall efficiency of the workflow were considered as the critical operations and bottlenecks for this study. Figure 95 describes a precedence diagram for each of the regular thermal liner garment and the sensor-integrated thermal liner garment. For the regular thermal liner garment workflow, operation 6 (serging) and operation 7 (assemble zipper) were the most critical operations across all the operations. These two comprised 38.5% of the total manufacturing time of a regular garment. Out of these two, serging was the most critical since 4 different operations (operation 7, 8, 9, & 10) were dependent on serging. Among the serging operations, some of them took longer than others and some operators took more time than others for the same serging operation which might have influenced rest of the operations to some extent. For instance, serging armscye, upper arm, & shoulder seam took longer than serging sleeves together. Operation 9 (Hemming-body and sleeve) took about the almost same amount of time as serging, however, it had a lower impact on the overall efficiency of the production process since no other operation was dependent on it.

A precedence diagram for the Regular Thermal Liner Garment

A precedence diagram for the Sensor-Integrated Thermal Liner Garment

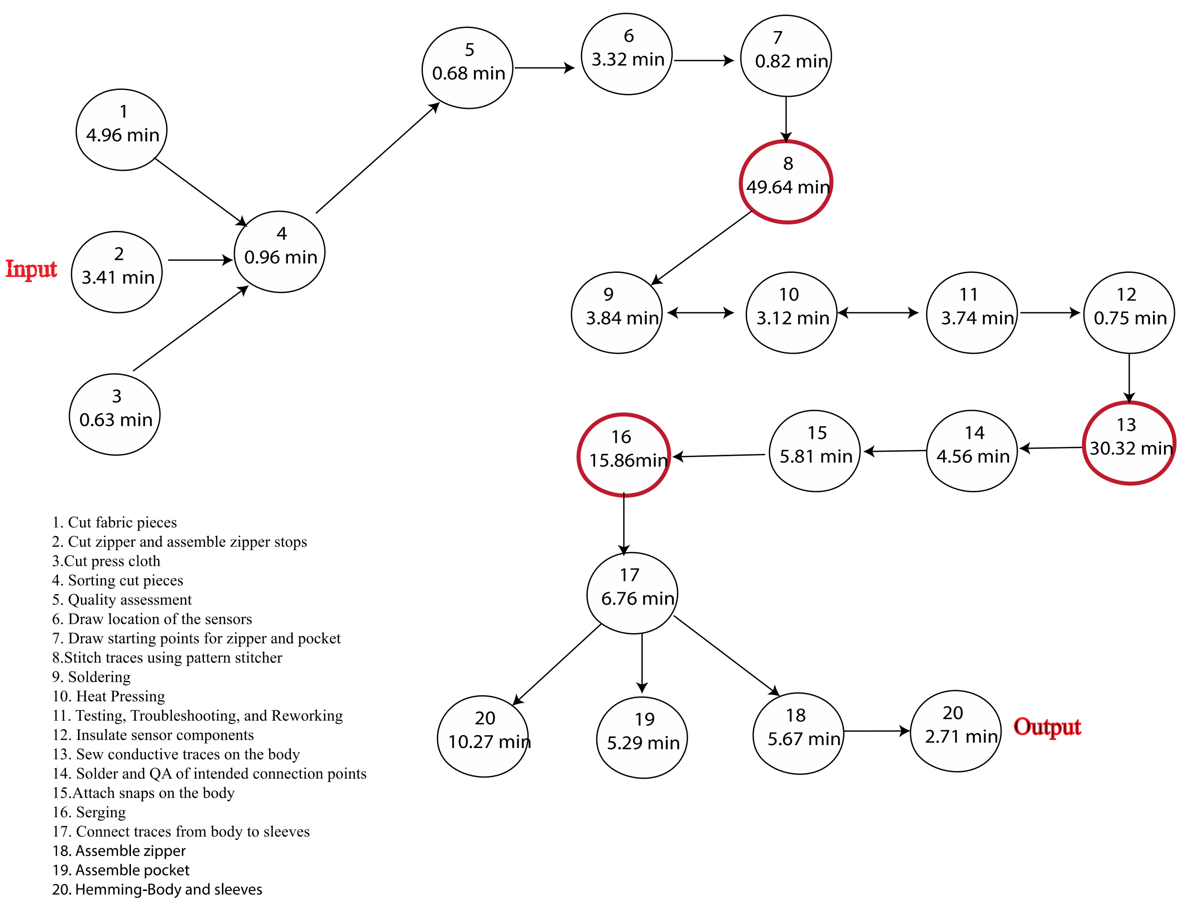


Figure 95: Workflow and operation time for regular thermal liner garment assembly (top) and sensor-integrated thermal liner garment assembly (bottom)

In the case of the sensor-integrated thermal liner garment, it is clear that “stitching traces using pattern stitcher”, “sewing conductive traces on the body”, and “serging” are the major bottlenecks of the study. The first two operations comprised 58.74% (95.82 minutes out of 163.12 minutes) of the total manufacturing time. The “stitching traces using pattern stitcher” operation took the most time (49.64 minutes per garment) to perform and was the major bottleneck of the process during the “sensor attachment” stage as well as for the entire study. There was only one pattern stitcher available during the study and it went through a lot of troubleshooting during the study which consumed approximately 31% (49.64 minutes per garment) of the total operation time. In an ideal situation, the same operation could be performed in 20 minutes.

“Sewing conductive traces on the body” was the second most time-consuming operation and was the next major bottleneck operation of the sensor attachment stage as well as the entire study. On average, it took 30.32 minutes to sew conductive traces on the body. This was an operation which was entirely new to the study participants and it took some time to get familiar with the design. The most challenging part for the participants was to stitch the trace layout accurately onto the garment. The trace layout was printed on paper and hung in front of the participants. Participants had to create a mental map of where a connection should be made and where it should not. There was a total of five instances where a trace needed to cross another trace. In such a situation, a hand needle was used to take the thread to the other side (wrong side) of the fabric and create a knot by hand. Later, an industrial machine was used to stitch a trace on the wrong side of the fabric and again a hand needle was used to take the thread to the right side of the fabric and manually knot with the conductive trace to create the desired connection. This whole process took a significant amount of time. I think there is still room for improvement in trace crossing methods. Several other approaches could be applied for an efficient trace crossing. One possible solution could be the use of automatic machines to avoid manual handling during trace crossing and seam crossing, and to improve the efficiency and accuracy of the process. Another solution could be to use insulated conductive thread for trace layout and later, remove insulation on specified locations for making trace connections. Finally, trace crossing could be performed by using multiple layers of fabric where each layer is used as an insulator. Serging was the next most critical operation of the sensor-integrated thermal liner garment process and consumed 9.71% (15.86 minutes per garment) of the total manufacturing time.

While looking at the individual departments, in the cutting department, zipper stop attachment (3.41 minutes per garment), and drawing locations of the sensors (3.32 minutes per garment) took a longer time than expected and were the bottlenecks of the process. In the sensor attachment department, “stitching traces using pattern stitcher” and “sewing conductive traces on the body” were the major bottlenecks. “Serging” and “hemming-body and sleeves” took a notable amount of time for both regular thermal liner garment and sensor-integrated thermal liner garments and were the major bottlenecks during assembly.

However, these bottlenecks were created due to limited resources and could be easily avoided or minimized by adding more machines and workers. The most straightforward solution to this problem is line balancing of the operations during production. Line balancing is commonly used in the apparel industry. Line balancing can be described as assigning more machines and workers to the most critical operations of a manufacturing process so that the input and output ratio always remains constant as the operations proceed. For this particular study, the most critical operations were: "stitching traces using pattern stitcher", "sewing conductive traces on the body", and "serging". Here, the pattern stitcher operation is purely a machine variable. While the machine speed could be increased to some extent within the machine, it could be significantly improved by adding more machines. On the other hand, the latter two operations are highly dependent on human skill. A skilled operator could perform these operations significantly faster than an amateur and unexperienced operator. Even in this study, I have noticed higher efficiency among the participants who have previous experience with a serger machine compared to the participants who never used the serger machine before or had limited experience. Therefore, more machines and skilled operators should be assigned to these critical operations so that the next operation could run smoothly. For example, the manufacturing time for Operation 8 (stitching traces using pattern stitcher) was 49.64 minutes per garment and the manufacturing time for operation 9 (soldering) was 3.84 minutes per garment. Which means manufacturing time for operation 8 was almost 13 times higher than that of operation 9. Hence, one should use 13 pattern stitcher machines against one soldering station so that soldering station does not have to wait too long for the stitched patterns to work on. Similarly, the rest of the operations could be balanced within the manufacturing process. However, one should keep in mind that adding more workers or machines only decreases cost if the bottleneck results in idle workers. If all workers are working continuously, adding workers to an operation decreases the throughput time but not the per-unit time (cost). In that case, we are still paying the additional workers, and it still takes the same number of person-hours.

5.3.4 Impact of technology integration into a garment during manufacturing in terms of *COST*

Figure 96 describes the cost of producing regular thermal liner garments and sensor-integrated thermal liner garments. As you can see from the figure, it cost around $69.98 to produce a sensor-integrated thermal liner garment which is almost 243.88% higher than producing a regular thermal liner garment ($20.35) and the largest portion of the cost comes from the labor cost. Here, the cost represents only the materials and labor costs, not any other direct or indirect costs such as research & development cost, delivery cost, equipment cost, facility cost, etc. There would be higher research and development cost for the sensor-integrated thermal liner garment than regular thermal liner garment. Though $69.98 for manufacturing sensor-integrated thermal liner is a little higher than manufacturing a regular thermal liner garment, it is comparable to currently available e-textile products in the market. Figure 97 describes a list of some of the promising e-textile products currently available in the market and their retail costs. In addition to the manufacturing cost, I have also calculated the wholesale price (multiplied manufacturing cost by 2) and retail price (multiplied wholesale cost by 2) of the sensor-integrated thermal liner.

Importantly, some of the material costs included in the cost analysis in Figure 97 represent retail costs and actual production cost would be lower if the materials were sourced from the wholesalers. Similarly, since the study was performed in a laboratory setting with inexperienced workers, its efficiency level would be much lower than the

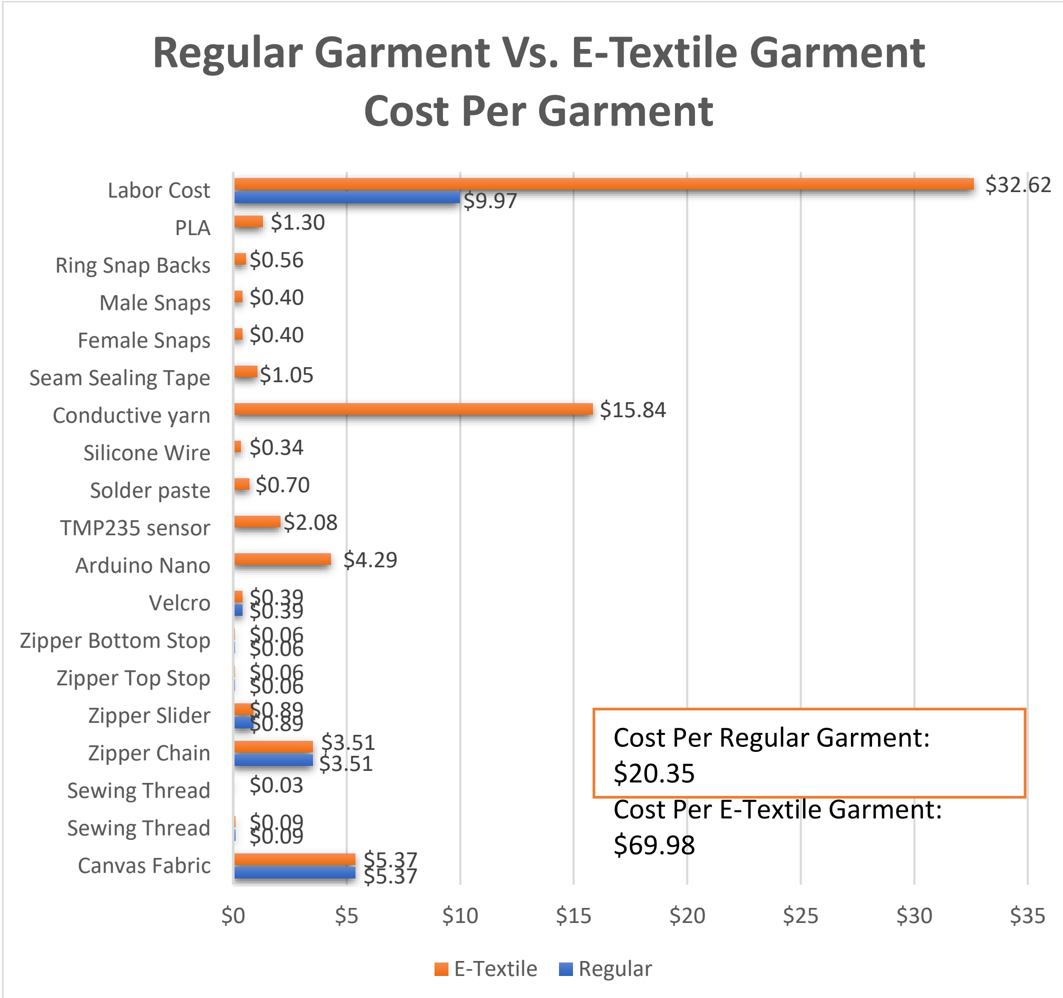


Figure 96: Cost for producing regular thermal liner garments vs. sensor-integrated thermal liner garments

industry standard. With standard and sophisticated tools and experienced workers, the cost could be curtailed. For example, in a standard CMT factory, it could take somewhere between 1.33 to 1.67 minutes (e.g. considering 80-100 garments/hour) to assemble one liner garment with standard industrial machines and skilled operators in a fully efficient assembly line (e.g. 20-30 workers). On the other hand, in my final production study, it took around 39.23 minutes to assemble one thermal liner garment with fewer number of machines (4-6 machines) and inexperienced operators (3-4 operators). If we extend this for the sensor-integrated thermal liner garment, with the same machines, labor, and efficiency, it would take around 4.35 to 5.47 minutes to produce one sensor-integrated thermal liner garment. Furthermore, if the e-textile liner garment assembly were performed in a developing country where labor cost is usually cheaper than the developed countries, the manufacturing cost could be cut down significantly.

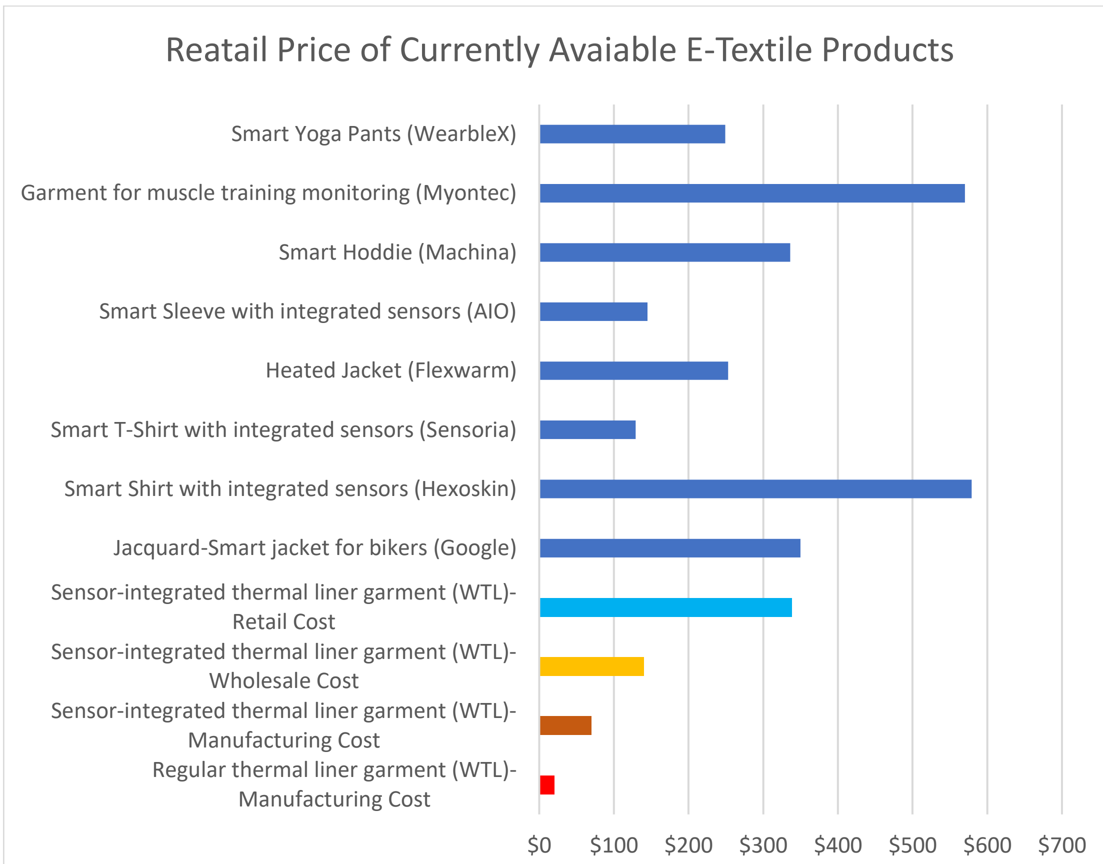


Figure 97: Retail price of some of the currently available e-textile products in the market

A rough estimation of the per unit machine cost is described in Table 15. With an initial investment of $24,999, anyone can start manufacturing e-textile garments in a new facility with no prior equipment. Out of all these machines, the Brother BS-342G Electronic Programmable sewing machine (pattern stitcher) and heat press were specifically used for e-textiles related operations. The rest of the machines (serger and lock stitch machines) are very common in the apparel industry and widely used for garment manufacturing. With some limitations, all these tools and machines are pretty common in apparel manufacturing and an apparel manufacturer anywhere in the world can easily start manufacturing e-textiles with almost zero investment. However, depending on the expected output of the production, one may have to buy multiple of these machines which will cost extra money. While adding more machines will increase the overall efficiency of the manufacturing system, it will increase the production cost as well. For example, in this project I used three lockstitch and serger machines. So, by adding the cost of two extra lockstitch and serger machines, total manufacturing cost would be $30,597. Finding and maintaining the right balance between expected output, availability of labor, and number of machines required will be crucial for manufacturers.

Equipment/Tool	**Cost/unit (Approximate)**
Brother BS-342G Electronic Programmable Sewing Machine	$22,000
Industrial Lock Stitch Machine	$799
Industrial Serger Machine	$2,000
Heat Press	$200
Total	$24,999

Table 15: Equipment and tools cost

5.3.5 Impact of technology integration into a garment during manufacturing in terms of *LABOR*

Participants spent a total of 394.81 hours to produce 41 regular and 45 sensor-integrated thermal liner garments. Out of 394.81, 199.42 hours were actually spent on manufacturing related activities e.g. cutting, sewing, sensor-integration, etc. Which means participants spent almost half of the production time (195.39 hours) on other non-production related activities including training, break time (e.g. restroom break), waiting time, filling out pre-study and post study forms, etc. Though I did not record how much time it took to train participants for individual operations, overall it took somewhere between 5 minutes and 20 minutes depending on the complexity and novelty of the task and previous experience of the participants. The time spent on training participants depended on the novelty of the task and the prior experience of the operators. The operations which were more traditional such as serging and hemming were familiar to the participants who had sewing experience and did not need much instruction. On the other hand, the operations which involved e-textiles were mostly new to almost all the participants and needed a demonstration. I have noticed that people who have some experience working with electronics were more comfortable working with e-textile related operations. For instance, participants who had previous experience with soldering were quick learners since they could easily transfer their electronics soldering skills to soldering textile-based electronics. Participants were encouraged to learn from each other as well as from their own mistakes.

During the study, several common errors were observed which were more specific to the manufacturing process. For example, some participants found it difficult to place the "correct amount of solder" on the traces. Too much solder can result a short in the circuit and too little solder can result a weak or broken connection. Hence, finding the balance is important while soldering and it took some trial and error for participants to get to that point which might have impacted the quality and efficiency of the process. In our original method, we used a stencil to overcome this problem. Due to the small spaces between pads of the sensor, we thought the stencil would not be suitable for solder application (there was a higher chance of creating short between traces due to manual soldering) and hence, it wasn't used during the production study. However, stencils are commonly used in the electronics industry for solder deposition since they allow even distribution of solder among traces and could be applied to e-textiles with the help of automatic stenciling and using skilled laborers. Overall, I found that training people on integrating electronics was complex to some extent. However, with the right documentation and proper training, anyone could be trained to be an expert in manufacturing e-textiles. Since most of the participants didn't have a prior knowledge about how e-textile circuits work, having a few separate training sessions with hands-on experience on e-textile manufacturing would definitely improve their overall understanding of e-textiles and could motivate them to improve their performance. A dedicated team where each participant knows from the beginning what operation s/he is going to perform from start to end of the manufacturing process and is trained accordingly could deliver a better output. Furthermore, based on the suggestions I received from participants during and after the end of individual operation, some of the operations could be modified or performed in a simpler way (e.g. using a better QA set up) to make them efficient and easier to follow for novice participants. In some cases, instructions could be further simplified for better understanding of the operation, especially for electronics-integration related operations (e.g. adding illustrations for the steps involved in the “stitching conductive traces on the body” operation). Familiarity with the operations can speed up the learning of the participants. All the operations I have used in this study are somewhat common to either the electronics or the apparel manufacturing industry. Hence, even though none of my participants had worked with e-textiles before, they could still relate these experiences with their prior experience, making it easier to become familiar with a new operation and get ready to start the operation.

5.3.6 Quality Assessment study results

In-line QA

A total of 45 sensor-integrated thermal liner garments were made, and each garment contained 6 sensors. Therefore, 276 sensors were soldered in total. Each sensor was tested immediately after soldering During the study, the average room temperature was around 73 ^{0}F (0.72V). For testing purposes, a temperature range between 65 ^{0}F to 80 ^{0}F (Voltage- 0.65V to 0.80V) as recorded by each sensor was considered as an acceptable range, and indicative of a functioning sensor. If any sensor did not work, troubleshooting and reworking were performed two more times before moving to the next step. The sensors that didn’t work even after final troubleshooting and rework were recorded and considered as an in-process error (either human error or system error) and moved to the next step so that they could be re-assessed again during post-production. Around 89.17% (248 out of 276) sensors worked during the in-line quality assessment, including both the sensors that worked the first time (no rework needed) and sensors that worked after two rounds of troubleshooting and rework (Figure 98). The other 10.73% of sensors did not work even after two-times troubleshooting and reworking. Weak or poor solder connections and broken solder were the major reasons for failures described by the participants. There were a few instances where participants noticed shorts between traces. In addition, participants detected several failures during QA checks that could not be identified using the prescribed processes (i.e. connection issues with solid solder connections, and problems while testing with alligator clips). These issues could happen either due to human error (e.g. lack of skills) or system error (e.g. sensor or conductive thread burned out). Hence, skilled workers, industrial machines (e.g. pick-and-place machine and automatic reflow technique), more advanced and sophisticated testing instruments could improve the process errors and even may avoid needing to rework in the first place.

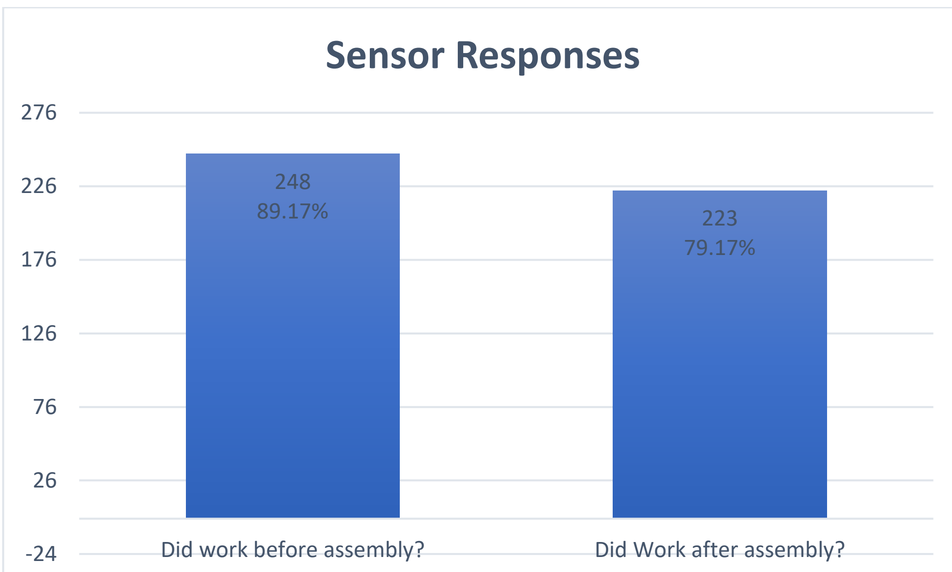


Figure 98: Pre-study and post-study sensor responses

Post-Production Study QA

The sensor-integrated garments went through a series of operations from sensor attachment to the finished garment. During this whole period, garments were handled by several participants and they were folded, wrinkled, contacted with hard tools and objects like the snap setting tool, passed through sewing machines, etc. This means the sensors attached to the garments went through a lot of handling during the production process. Therefore, the durability and functionality of the sensors were challenged. A post-production quality assessment was performed to check the durability and functionality of the sensors once all the sensor-integrated thermal liner garments were assembled. Similar to the in-line QA, the same temperature range was used for the post-production QA test. When I tested the finished garments with the external hardware (sensors were tested using an Arduino Uno-set up during assembly), I found that only the sensor closest to the external hardware worked for most of the cases. However, when each sensor was tested individually, in most cases they worked. This suggests that the un-insulated conductive thread provided an unstable connection, and the signals sent from sensors farther away from the external hardware could not reach the external hardware. My pre-production study results did not show any sign of voltage drop when testing with a long length of thread. This warrants more thorough research. The study results showed that 79.17% (223 out of 276) sensors were functional after production and 20.73% had some issues (Figure 98). Out of the 20.73% non-functional sensors, 10.73% were already recorded as being unfunctional after in-line testing. That means, 10.11% (25) sensors broke during the production process. While looking at the causes of failures, the results showed that weak or poor solder connection (16 out of 53) was the main reason for sensor failures (Figure 99). Broken solder joints (15) and shorts (6) were the other major causes of connection failures. Interestingly, 16 sensors showed higher voltage readings (>0.78 volts compared to the expected voltage at around 0.72) though the reason is unknown. Perhaps, weak solder connections and the flexible structure of the un-insulated conductive thread had some influence on the incorrect voltage readings. Further analysis is needed to have a better understanding of this matter.

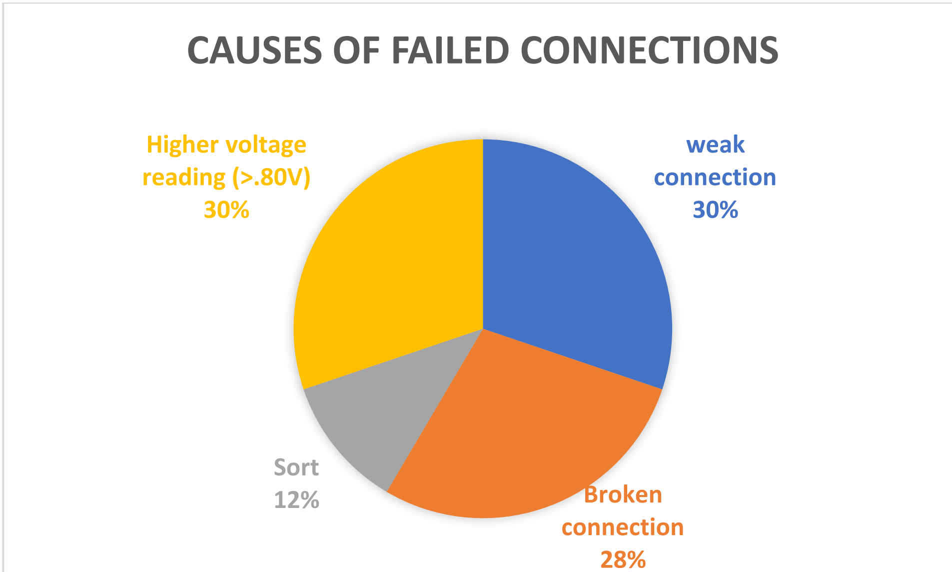


Figure 99: Causes of failed connections

However, in addition to failed connections, there were several other variables that might have direct influence on the circuit performance such as accuracy of the sensor responses, connections and isolation among traces in the fully-assembled garment, voltage drop within the trace, connection between the external hardware and the rest of the e-textile components in the garment, and finally overall performance of the e-textile components within the garment. The threshold we used in this study may or may not realistic (e.g., the product would be still considered a failure if the accuracy of the sensors were not up to the industry standard). The inconsistencies could be caused by errors within the manufacturing processes (e.g., human errors during soldering) or they could be due to errors in the materials themselves (e.g., unreliable connection due to inconsistent resistance of the conductive thread). Therefore, both the errors in the manufacturing method and inconsistent properties of the e-textile components need to be rigorously tested to ensure reliable and durable e-textile garment products. In addition, quality assessment techniques used to evaluate the e-textile garments need to capture more subtle changes within the circuit to validate the product. Therefore, a more comprehensive study may be necessary to evaluate the nuanced performance of the finished e-textile garments which was out of the scope of this project. Since this project primarily aims to evaluate the feasibility of the surface-mount fabrication method for large-scale production, more focus was placed on the development and implementation of the method than developing a comprehensive quality testing tools and matrix. However, future studies should perform a more sophisticated quality testing to ensure a robust testing at the garment level for the mass-produced e-textile garments.

5.3.7 Variability in the sensors' data

On several occasions, sensor responses were not stable across all the sensors' data, and variability was observed among the sensor responses. Variability was observed when the fabric was wrinkled, stressed, and pressed. The uninsulated conductive threads seem to be primarily responsible for unstable connections. For instance, Figure 100 shows the recorded voltage across all the sensors. As you can see, there was variability in voltage across all the sensors. However, a linear relationship between the voltage and the temperature was observed as expected (Figure 100-right). Variability was also observed within the same sensor. For instance, Figure 101 shows variability within the same sensor with no pressing on the fabric vs. while pressing the fabric. As shown in the Figure 101 (right), a fluctuation was noticed within the same sensor data over time. The fluctuation increased when the fabric was pressed or folded (Figure 101 left).

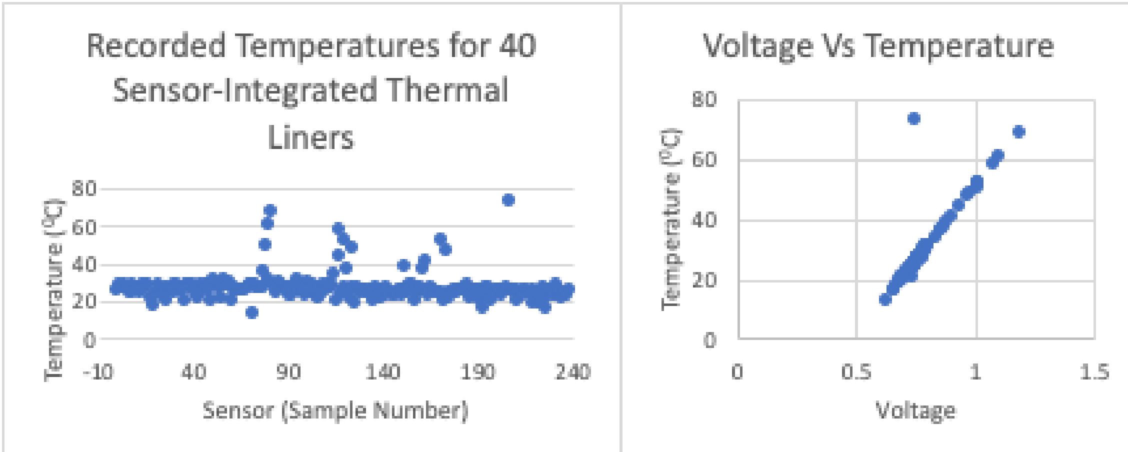


Figure 100: Variability across all the sensors data (left); relationship between voltage and temperature (right)

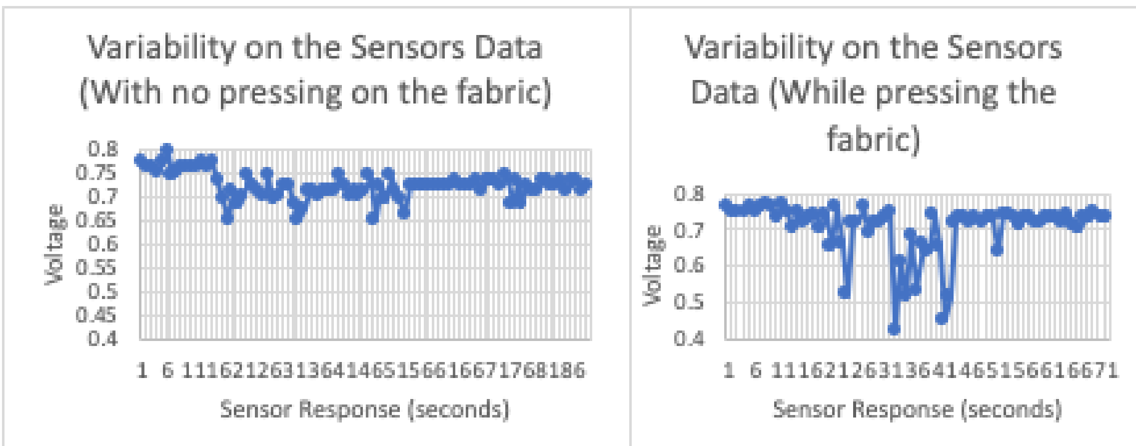


Figure 101: Variability in the Sensors' data

5.3.8 Process Improvements

Several new manufacturing tasks were added, and new variables emerged while transitioning from manufacturing a single prototype to performing bulk production for both regular and sensor-integrated thermal liner garments. A few unexpected elements were observed during the production process. The following sections provide a summary of the unexpected elements observed and new variables identified while transitioning from single prototype development to the production study.

5.3.8.1 Errors made in the process

5.3.8.1.1 Issues during cutting

There was an error with the pocket measurements in the cut pieces, and the shape of the pocket pieces turned out to be too small. Hence, a new marker was used to cut new pocket pieces separately later. It took approximately 45 minutes to cut new pocket pieces which eventually added to the final cutting time. This error was a human error and could easily be avoided. Furthermore, participants recorded around 141 minutes spent performing miscellaneous tasks during cutting, including cutting the sharp edges of the pockets, organizing fabric pieces, etc. Pockets had several sharp corners and hand scissors were used on top of the rotary knife to cut those corners which consumed more time than expected. The use of a straight knife or automatic cutting machine (such as a Gerber Cutting Machine) would be more useful in cutting sharp edges of small pieces. By utilizing more sophisticated machines and efficient workers this could be cut down to close to zero. Finally, cutting zippers and assembling zipper teeth took a significant amount of time. Surprisingly, it took 3.41 minutes per garment to assemble zipper stops which I did not anticipate. Participants used pliers to assemble zipper stops on the chain. Those pliers were not specifically designed for zipper assembly and hence, influenced the efficiency of the cutting time. The lack of experience of the participants further exacerbated the efficiency. Based on my observation, with better tools that are designed for zipper assembly and experienced workers, the assembly time could be reduced to around 1 minute from 3.41 minutes. Figure 103 describes the actual cutting time during the pre-production study, production study, and cutting time for the simulated best scenario. For the simulated best-case scenario, cutting time for extra pockets and miscellaneous tasks were considered to be zero, and zipper assembly time was cut down to 1 minute.

5.3.8.1.2 Issues with Pattern Stitcher Machine

A few unanticipated manufacturing variables were identified while stitching conductive traces using the pattern stitcher. First, I noticed several issues with the pattern stitcher machine itself. I found that stitching trace layouts using pattern stitcher was taking way more time than the rest of the operations. It took 49.64 minutes to stitch all 10 trace layouts onto a garment using the pattern stitcher and out of that, actual stitching time was 34.38 minutes and troubleshooting time was 15.23 minutes per garment. In an ideal situation with no or minimum troubleshooting, it should not take more than 30 minutes to stitch all the layouts. While trying to determine the reasons for troubleshooting, I discovered that the pattern stitcher went through a lot of mechanical issues and a significant amount of time was spent on fixing the machine which was not anticipated initially. Since there was only one pattern stitcher, this unanticipated delay made the whole production flow inefficient. To fix mechanical issues of the pattern stitcher, I made some mechanical adjustments on the machine such as adjusting the tension of the needle thread and bobbin thread, replacing the used needle with a new one, etc. which were successful in cutting down the troubleshooting time and speeding up production (Figure 102).

To further cut down the stitching time and increase the efficiency of the process, the pattern stitcher speed was adjusted. In the beginning of the production study, the machine speed was set up for 400 inches/minute whereas suggested stitching speed for the pattern stitcher is 2600 inches/minute (according to the manual) for normal garments. The Vectran silver coated conductive thread used for this study was stronger and more durable than the regular polyester thread and might not be suitable for stitching at the same rate as normal garments. In the beginning, I increased the machine speed from 400 inches/minute

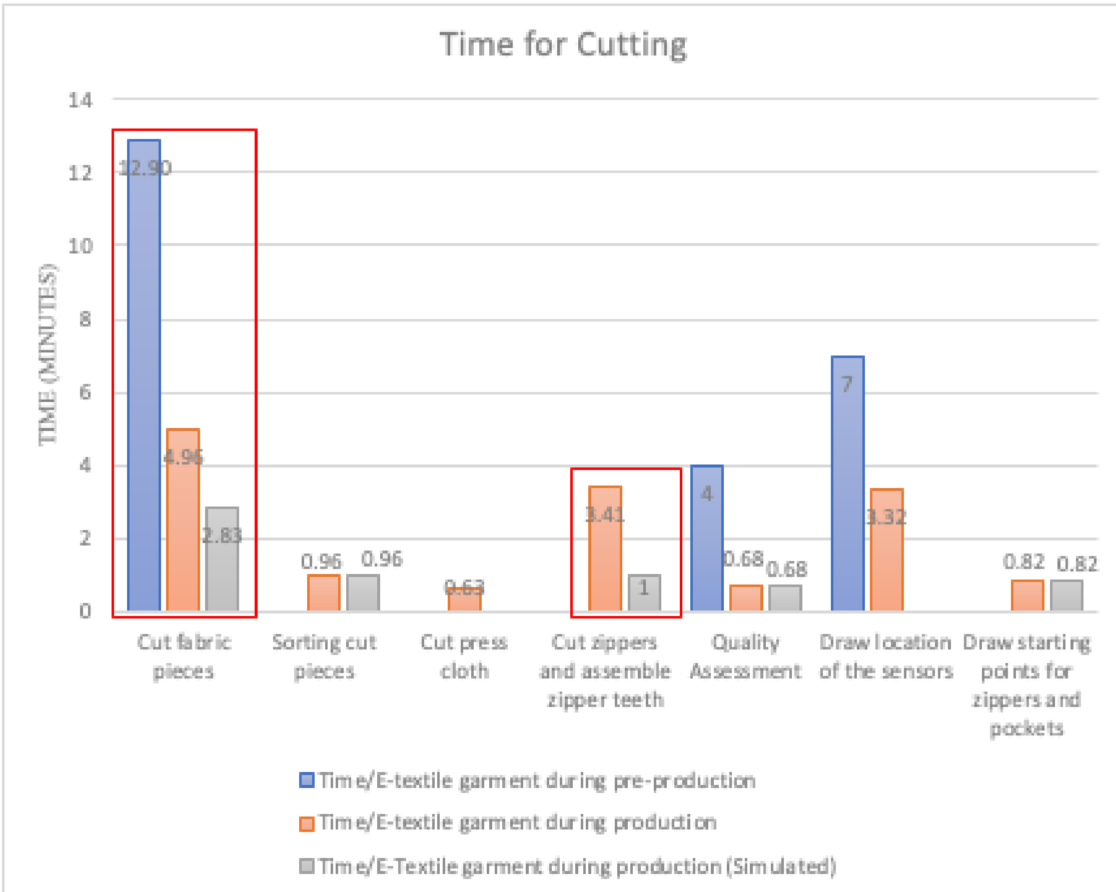


Figure 102: Simulated cutting time for the best-case scenario

to 2000 inches/minute to enhance the productivity of the output. At 2000 inches/minutes, I noticed some stitch-related issues such as missed stitches, loose thread, faulty seamlines, etc. on the stitched pieces due to the intense movement of the needle. To minimize these issues, I tried to slow down the needle speed and find the optimum speed for the pattern stitcher. With some more adjustments, the speed was finally fixed at 1200 inches/min which was still three times higher than the original speed (400 inches/min). I found that at 1200 inches/min machine can stitch the pattern layouts without any major issues and that significantly improved the productivity of the pattern stitcher. At 1200 inches/min speed with a well-maintained pattern stitcher, all ten layouts could be stitched in 20 minutes where the average stitching time during production study was 49.64 minutes (at 400 inches/min) which is showed in Figure 103.

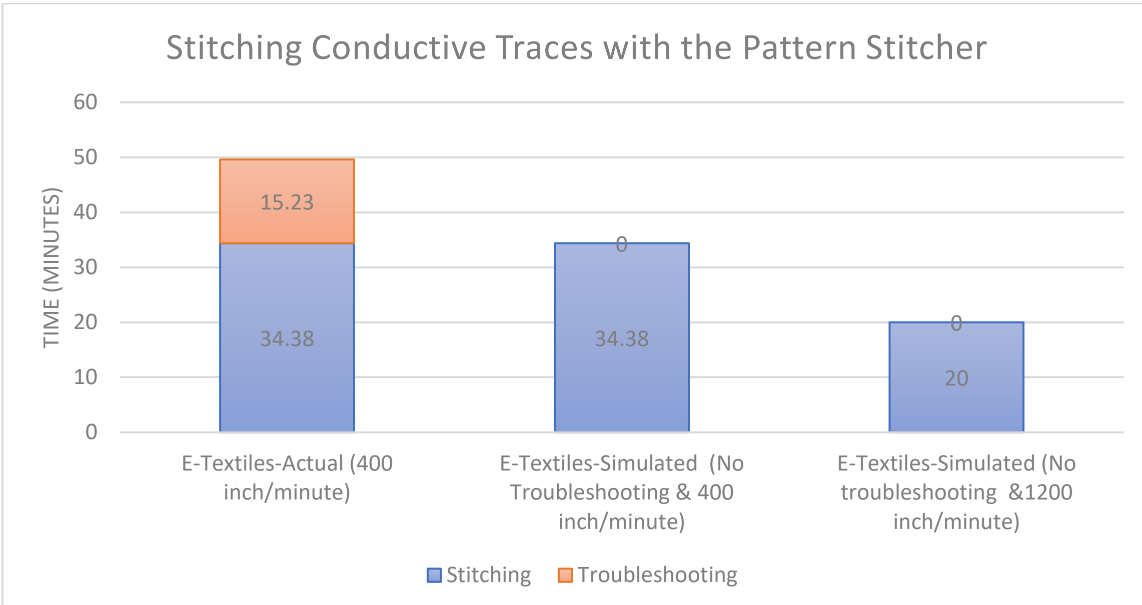


Figure 103: Stitching Conductive Traces with the Pattern Stitcher: Actual Vs. Simulated

5.3.8.1.3 Issues with marking sensor locations

An error occurred while marking sensor locations on the garment due to human errors. After stitching the pattern layout for all the right sleeves (almost 60 pieces) which took almost 3 hours, I noticed that they were stitched wrong way due to an unintended mistake that occurred while marking the face and back of the sleeve pieces in the cutting department. Therefore, we had to re-stitch the right sleeve pattern layout for all the right sleeves. In a factory setting, it would make more sense to cut extra sleeve pieces for re-stitching. But I had limited resources for this study. I did not have enough fabrics to cut extra sleeve pieces to cover up the errors, neither had enough manpower and machines.

Hence, I had to re-stitch the layout on the faulty garment pieces. Re-stitching the pattern layout involves two steps: removing the faulty stitched layout and re-stitching the correct trace layout. After removing some faulty trace layouts, I noticed that removing faulty stitches from the garment pieces was taking significant time and was negatively affecting the overall output of the process. To cut down the troubleshooting time and speed up the production, I decided to use the right sleeves allocated for regular garments since they were identical to those allocated for e-textile garments. The participants marked the sensor locations using the paper template developed during cutting and later, the right sleeve pattern layout was stitched on them. I used the right sleeves with faulty traces for assembling regular garments and decided to remove faulty stitches during the post-production quality assessment. A total of 8 faulty front sleeve stitches were removed and re-stitched; the rest were replaced with the front right sleeves previously separated for regular garments. This error eventually took approximately 5 hours and added up more time with the manufacturing process. Figure 104 describes the adjustment for operation time with and without marking error.

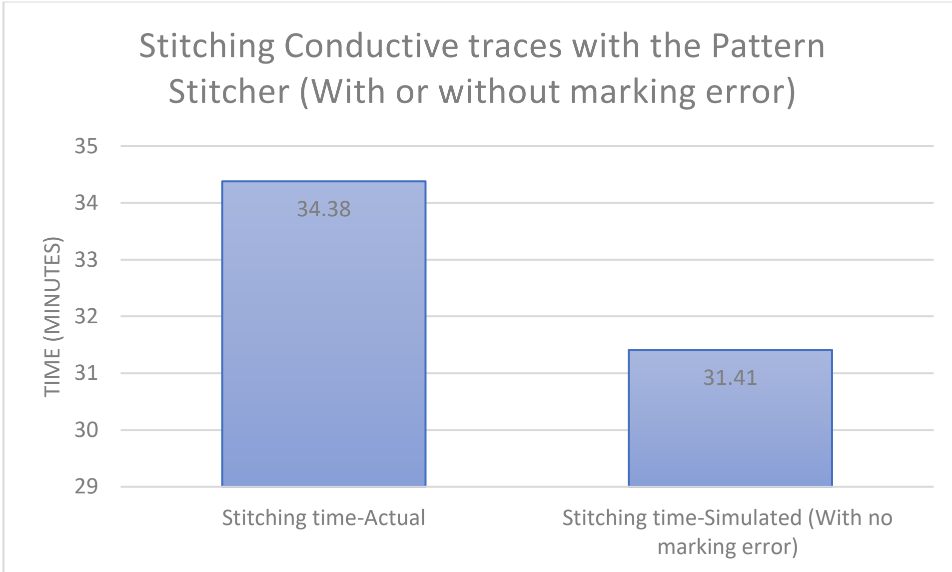


Figure 104: Stitching Conductive Traces with the Pattern Stitcher (with or without marker error): Actual Vs. Simulated

5.3.8.1.4 Uneven distribution of heating of the heat press

The heat press used in this study has a heating area of 20 x 20 inches. That means multiple small fabric pieces (e.g. sleeves) could be pressed using the heat press if they are placed strategically. However, the heat press has a top and bottom bed, and heating comes from the top bed, mostly from the center of the bed. This means the central area of the bed provides the maximum heating whereas areas close to the edges provide the minimum heating. At the beginning of the study, multiple sleeve pieces (3 sleeve pieces) were pressed together to cut down the operation time. However, the pieces which were close to the edges of the bed did not get enough heat to create a solid solder connection and hence needed to be pressed multiple times. To avoid this problem, only one piece was pressed at a time. The area of the body was too large compared to the sleeve and only one sensor could be pressed at a time. This is another variable that was observed when transitioning from a one-off a garment to mass production. A heat press with even heating and larger heating area that can press an entire body of a garment and multiple pieces could make the process more scalable. Figure 105 describes the adjustment for single pressing and multiple pressing.

5.3.8.2 New variables that would need to be considered in designing an e-textile production process

5.3.8.2.1 Machine optimization variables

Several machine optimization variables emerged during the production study which were unnoticed during the pre-production study. One of the major variables noticed during the production study was the smooth-running capability of the machines. The machines used in the production study need to be well-maintained and must ensure continuous production with no or minimum troubleshooting. I had several mechanical issues with the pattern stitcher during the production study which caused bottlenecks in the process. The machine went through a lot of troubleshooting which significantly subsided the overall efficiency of the production. The main causes of troubleshooting include bobbin and needle thread unthreading, resetting the machine, seam ripping and re-stitching, winding bobbin, changing the bobbin, loose thread, incorrect stitching, tension adjusting, etc. Some of these were caused due to human errors and some due to mechanical issues. I would like to mention here that the pattern stitcher used in this study was a four-year-old machine that went through regular wear and tear, and this was the first time the pattern stitcher went through such a large-scale production. With better-maintained machines, efficiency could be improved significantly.

In addition, study results showed that machine speed can significantly impact the productivity of the manufacturing process. During the production study, stitching conductive traces using pattern stitcher took 30% (49.64 minutes out of 2.72 hours) time of the total manufacturing time and created a bottleneck in the process which significantly influenced the rest of the production process. By increasing the machine speed 3 times (as I did during the latter part of the study), the production time could be cut down to one third (Figure 105). Similarly, by increasing the pressing temperature for the heat press, the operation time could be cut down significantly. However, while increasing the speed of a machine, one should make sure the increased speed does not create any additional complexities such as burning the fabric in the process.

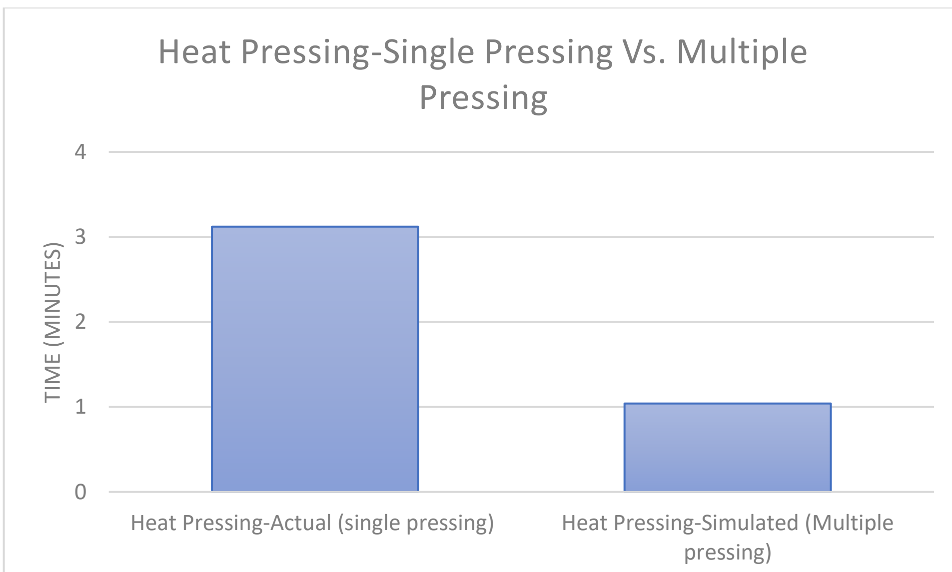


Figure 105: Heat pressing: Actual Vs. Simulated

5.3.8.2.2 Human error variables

Throughout the study, I have noticed errors due to design errors (e.g. incorrect pocket sizes), incorrect orientation of the fabric (e.g. wrong marking on the right sleeve), and improper optimization of the machine and process (e.g. higher machine speed, higher temperature for the heat press, etc.). Some of these errors happened due to personal mistakes, and some of them happened due to inexperience of the participants. Most of these errors that happened in this study could be avoided to some extent by executing better planning, with experienced participants, and automatic machines. However, even with these things, there will always be a possibility of some errors due to human involvement. The e-textile developers should keep that in mind when handling with participants and always be prepared to mitigate the impact of the problem caused by human errors.

5.3.8.2.3 Process variables

In addition to machine and human error variables, several process variables emerged during the production study. First, marking the location for sensor placement was a new variable that was noticed during the e-textiles production. In this study, a paper template was used to mark the locations of the sensors for sensor-integrated thermal liner garments. Even though it sounds like an easy straight forward process, a simple error in marking can cause a significant wastage of resources. A mistake in marking caused me to un-thread and re-stitch 60 right sleeves. In a factory setting. an automatic machine such as a pick and place machine could be used to properly orient and mark the fabrics to improve the accuracy and efficiency of the process. Similarly, the process involved placing the fabrics on the machine bed for stitching conductive traces onto the fabric that could be improved as well.

Another variable noticed during the study was stitching conductive traces using an automatic machine (e.g., pattern stitcher) vs. semi-automatic machine (e.g., industrial lockstitch machine). During the pre-production study, most of the conductive stitching was performed using an industrial lockstitch machine, whereas, during the actual production study, most of the conductive stitching was performed using the automatic pattern stitcher.

While it took more time to produce the conductive trace layout on the garment using the pattern stitcher compared to the industrial lockstitch machine, the pattern stitcher has several benefits over the industrial lockstitch machine and provides more benefits over a traditional lockstitch machine for stitching conductive traces on the garment. The pattern stitcher requires minimum human handling, can stitch automatically, and hence, is more scalable and suitable for mass manufacturing of e-textiles. Furthermore, the speed of the pattern stitcher is adjustable and with the proper setting, the stitching time can be significantly cut down. However, a pattern stitcher is more expensive than an industrial lockstitch machine and is not readily available to many apparel manufacturers. Therefore, it's possible that the method can be implemented with very skilled operators in contexts where skilled labor is affordable. On the other hand, the same technique could be utilized in a context where having cheap and somewhat skilled labor is more economical then buying expensive sophisticated machines. But if the focus is on the automation of e-textiles manufacturing, then the pattern stitcher should be the way to move forward.

Stitching conductive traces using the pattern stitcher also saw the most errors, needed more time for troubleshooting, and hence took a significant amount of time to finish. Using a new machine or well-maintained new-like machine could ensure more time on stitching and less time on troubleshooting. Better training of the participants could also help in this cause. One way better training could be done by providing better instructions on how to handle the machine's "resume function" when an issue arises. The pattern stitcher has a "resume" feature which allows the user to stop at any point of the stitching, fix the problem, and then resume stitching (instead of unthreading and re-stitching the same stitch layout). Utilizing this feature could significantly cut down the troubleshooting time.

Another thing that could be improved in training is teaching participants how to wind the bobbin properly. Sometimes participants spent more time on winding small bobbins that added extra time on the production. Having two persons instead of one could improve the efficiency as well where one person could always be in charge of the stitching and the other person would be responsible for other stitching related tasks such as winding the bobbins, QA, etc. A few other things that could be improved in training include training on how to control the proper tension of the machine, changing needles, bobbin, etc.

Some parts of the operation sequence were revisited during the production study. Some operations need to be performed after a certain operation. For instance, during the production study, I realized that snaps should be affixed after sensor attachment. At first, snaps were attached before soldering all the sensors. Later, I found out that snaps added an extra layer for heat pressing sensor components close to them, and hence, required multiple pressing for affixing the sensor components. Later, snaps were affixed onto the body once all the sensors were heat pressed and tested. However, it was not too obvious since the snap attachment was an independent process and should not be affected by other processes. Hence, it remained unnoticed during the pre-production study.

5.3.8.3 Limitations of the study

One of the major limitations of this study was limited resources. Limited availability of machines and inexperienced participants had greatly influenced the overall efficiency of the study. For instance, both stitching pattern layouts and affixing components using the heat press were largely affected due to limited resources. There was only one pattern stitcher and one heat press which created a bottleneck in the sensor development process. Adding more machines would significantly improve the efficiency of the process.

Additionally, some of the participants involved in sensor development did not have any prior experience and took more time at the beginning of each operation. Since all the operations in sensor attachment were very new to the participants, it took some time for them to get used to the processes, which was particularly true for stitching conductive traces on the body using an industrial lock stitch machine. Overall, there is a lot of room for improvement in this department that should be considered in future studies.

5.3.9 Simulated best-case scenario

5.3.9.1 Simulated best-case scenario for *TIME*

In the previous sections, I discussed the unanticipated process, machine, and human errors that occurred during the production study and provided suggestions for process improvements. Based on these suggestions, I adjusted operation time for cutting (e.g. minimizing extra time during cutting fabric pieces, zipper assembly etc.), worker skill and learning effects (e.g. using skilled and efficient operators SMV), machine downtime and troubleshooting (e.g. reducing pattern stitcher troubleshooting time), and machine optimization variables (e.g. increasing the pattern stitcher speed, using a high temperature for the heat press to speed up the process). In this section, I combined all the above information to provide a summary of simulated study results for the best-case scenario for time using existing resources. For the simulated best-case scenario (Figure 106), I took all the best possible and realistic manufacturing times from the study results. Here, the general assumption is that all the participants are experienced, and the machines are well maintained and require no or minimum troubleshooting. For instance, it took 49.64 minutes to stitch 10 trace layouts using the pattern stitcher. However, with the increased speed (1200 inches/minute) all 10 trace layouts could be stitched within 20 minutes given that

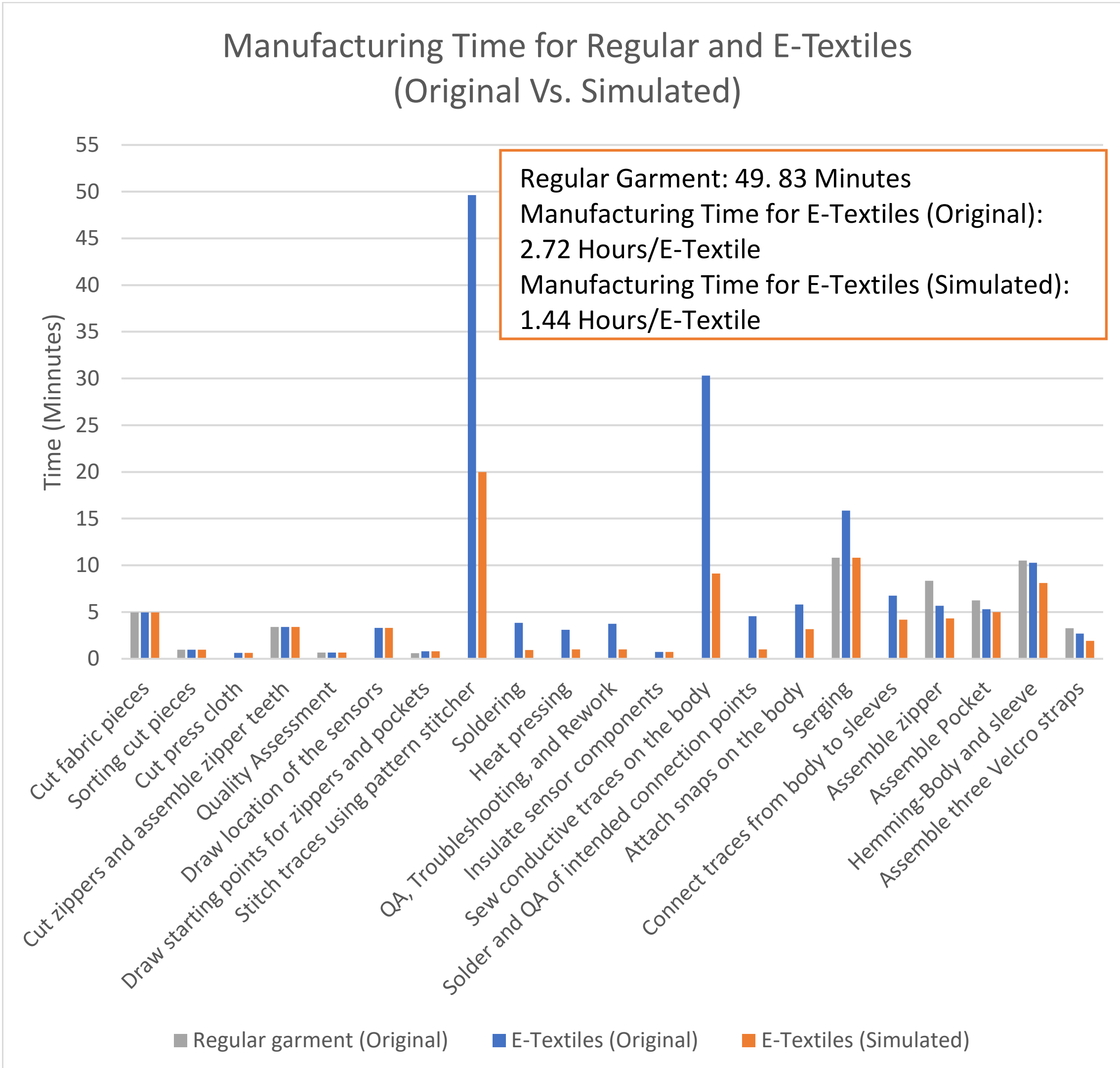


Figure 106: Manufacturing time for e-textiles: Actual Vs. Simulated

the pattern stitcher is well-maintained and fully functional and no troubleshooting is required. For the “sewing conductive traces on the body” operation, the average stitching time was 30.32 minutes per body with the maximum and the minimum value was 94 minutes and 8.57 minutes per body. I picked the minimum value for the simulated best-case scenario. For heat pressing, sensors were pressed for 1 minute at 435 ^{0}F in the best case scenario and thus, included here. Similarly, I picked the best manufacturing time for the rest of the operations for the simulated best-case scenario. Later, all these adjusted operation timings were plotted against the average manufacturing time for the regular and sensor-integrated thermal liner garment as showed in Figure 96.

As shown in the figure, with experienced workers and well-maintained machines each sensor-integrated thermal liner could be produced in 1.44 hours. That means manufacturing time could be cut down by 47% with the existing resources.

5.3.9.2 Simulated Best-Case Scenario for *COST*

Similar to manufacturing time, a simulated manufacturing cost model was developed for the sensor-integrated thermal liner garment (Figure 107). The materials costs provided in the previous section are mostly retail prices. However, when garments are produced in a large quantity (for instance, 5,000 pieces), the components could be purchased at wholesale rates. For simplicity, I assumed that the wholesale price of each material would be about half of the retail price. To give an idea of the wholesale price of the sensor-integrated garment, I cut all the material prices in half and plotted against the actual retail cost. Here, labor cost was calculated as $12/hour for 1.44 hours (simulated manufacturing time for each garment). Figure 108 describes a comparative study between the actual manufacturing cost and the simulated manufacturing cost for producing a sensor-integrated thermal liner garment. As shown in the figure, the simulated cost to produce a sensor-integrated thermal liner would be $35.96, which is almost 49% lower than the actual retail price ($69.98).

Furthermore, if the garments were produced in a developing country such as Bangladesh where the minimum hourly salary is approximately 50 US cents, the new labor cost would be 72 cents. However, a transportation cost would be added which will probably add up to $1 per garment. This means the manufacturing cost could be cut down to $19.40. Figure 109 describes a simulated best-case scenario for producing e-textiles in a developing country.

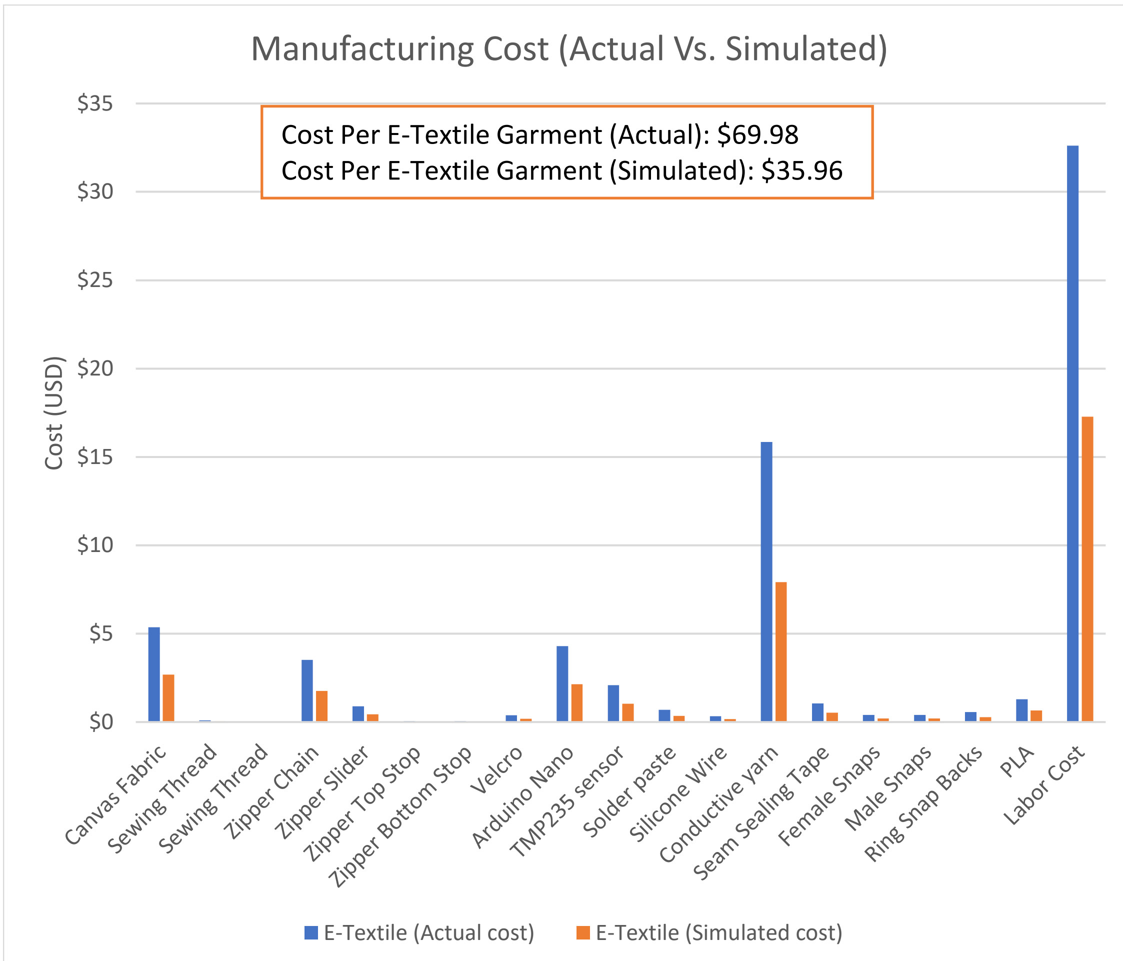


Figure 107: Manufacturing cost: Actual Vs. Simulated

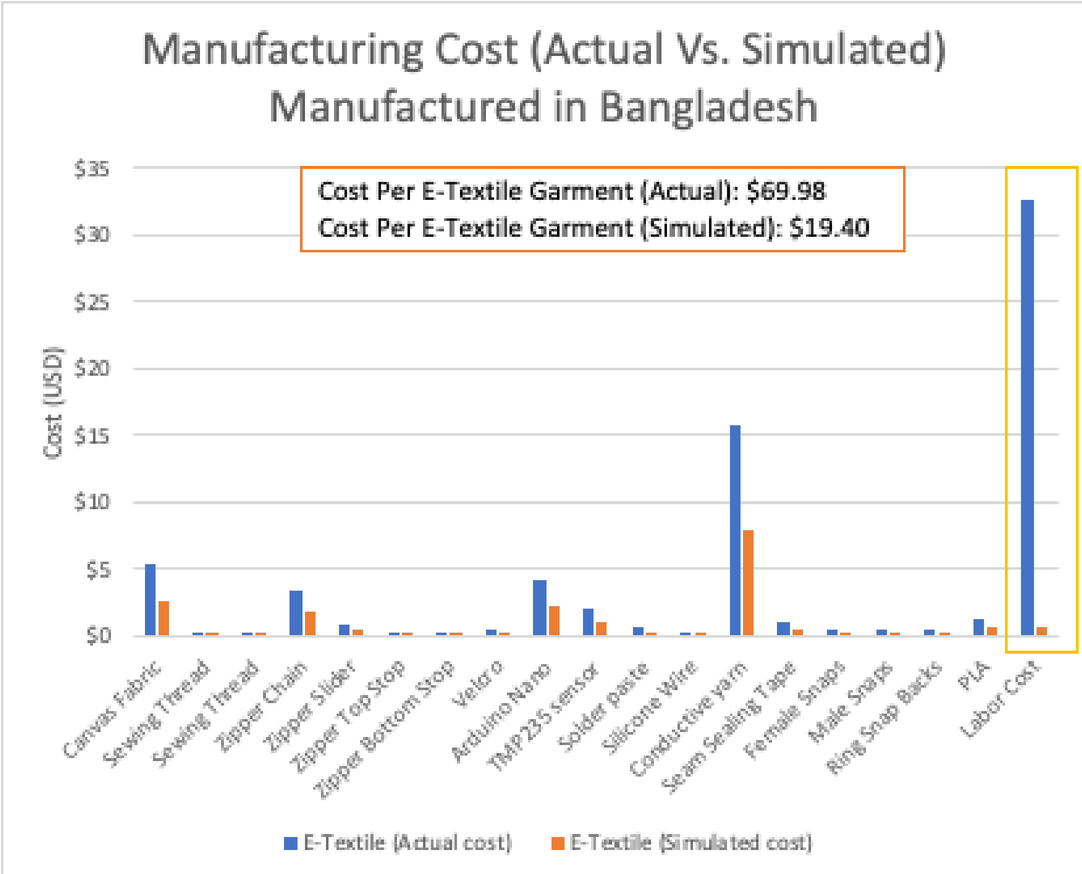


Figure 108: Labor cost-actual vs. simulated

5.3.10 OTHER OBSERVATIONS

5.3.10.1 Variability Among the Operator's Experience Level

Variability among the operators' efficiency was observed across all operations. People who had skills and previous experience with certain operations showed higher efficiency while performing those operations. For example, Figure 109 describes the time took to applying solder to a sensor for two different participants (P8 & P10). Participant 8 had previous experience with soldering and took on average 0.96 minutes to solder one sensor component. On the other hand, Participant 10 had no previous experience with soldering and hence, took on average 5.18 minutes to solder one sensor component.

However, irrespective of their previous experience, I observed an increase in efficiency over time across all the participants until it hits their maximum peak. In Figure 109 (right), it took 56.83 minutes for participant Y to solder the first sensor component, which decreased over time to around 2 minutes for the 93rd sensor component. A similar pattern was observed across all the operations. On the other hand, P8's efficiency was consistent throughout since it was around his maximum peak (Figure 109-left).

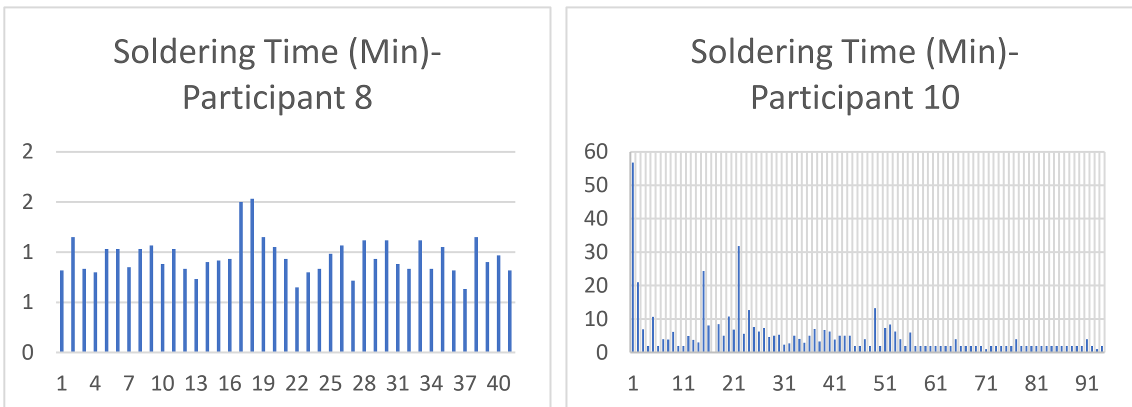


Figure 109: Example of Variability Among Participants for soldering time

Study results show that certain operations would be benefitted more from skilled operations than others. The operations that were more complex and required more human labor were more likely to benefit from skilled and experienced operators. For instance, soldering was divided into two steps: applying solder and heat pressing, and two different participants used two different machine and tools to perform these tasks. During the production study, applying solder to small components onto the flexible fabric substrate is a difficult and complex job and it requires some time to familiarize oneself with the process. So, the operation would benefit by utilizing skilled and experienced laborers. On the other hand, use of the heat press is pretty straight forward and a skilled operator might not have a significant impact on the efficiency of the process. Several operations (i.e., soldering, stitching conductive traces using industrial lock stitch machine, etc.) showed distinct changes in timings as the operator improved. For instance, when P3 first started the “stitching conductive traces on the body” operation, it took her 42.82 minutes to perform the first operation. However, it improved over time and eventually it took her 9.20 minutes to finish the same operation. Study results showed that the more novel and complex the process is, there is more room for improvement. Once a participant figures out how to perform a complex task, it is then all about improving his/her skill by performing the task repeatedly.

5.3.10.2 Participants’ Efficiency

Differences among participants' efficiency were noticed throughout the study. Study results show that some participants were naturally more efficient than others. Some participants were fast learners, and some were not. In fact, differences in efficiency within participants for the same operation were noticed during the study. Participants tend to be slower at the beginning of the study. Once they got familiar with the process, they became more efficient as time passed. The difference in participants’ skill sets influence the study results. For instance, Figure 110 describes the variability in manufacturing time for soldering, heat pressing, testing, troubleshooting and rework, stitching conductive traces-Body, and stitching conductive traces: Body to sleeve across all participants. As you can see, the maximum time took to solder one sensor component was 56.83 minutes per garment whereas the minimum time was 0.63 minutes.

Similar patterns were observed for heat pressing, testing, and troubleshooting & rework operations, and conductive trace stitching. The largest variability observed for stitching conductive traces-Body operation with Standard Deviation (SD) of 14.90

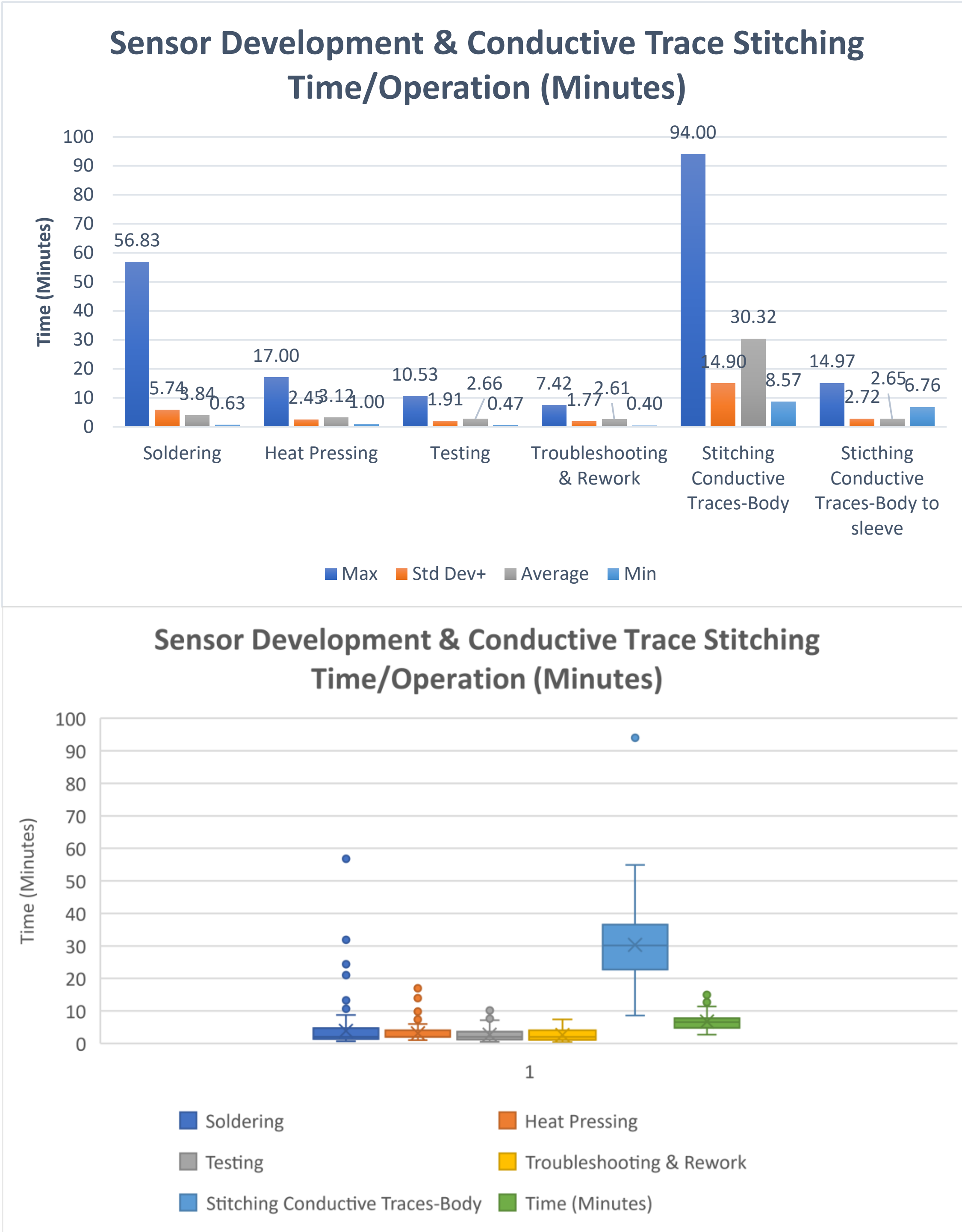


Figure 110: Variability in participants' efficiency

followed by soldering, stitching conductive traces-Body to sleeve, & Testing with SD of 5.74, 2.72, & 2.45. Stitching conductive traces-Body and soldering were the most complex operations among sensor-integrated thermal liner garments operations and took longer than the rest of the operations. Once the participants became familiar with the process, their efficiency increased, and manufacturing time decreased over time. This might explain why some operations had a bigger spread than others. Heat pressing, and testing and troubleshooting & rework had the lowest level of variability among participants' efficiency with SD of 1.91 & 1.77 respectively. The sensors were pressed for 120 seconds in each press for most of the cases where few of them were pressed for one minute. Though some of the sensors had to be pressed multiple times to get a solid connection. Besides, Heat pressing was mostly performed by P7 & P10. Therefore, variability between and within participants was lower in the case of heat pressing. This also happened with troubleshooting and rework. P6 & P8 had previous experience working with Arduino and they were assigned for troubleshooting and rework. Therefore, their performance was comparable.

5.3.11 Participants post-study feedbacks on the Manufacturing Process

A post-study questionnaire was used after each session to collect participants' feedback about the manufacturing process. The questionnaire was used to identify the most challenging tasks or sub-tasks, machines, and tools throughout the production process, and potential solutions to these challenges. Participants identified several issues within the manufacturing process that required further attention. A brief overview of the participants' observations is described below.

Several participants found it challenging to solder sensor components onto textile substrates. The size of the sensor was very small, and traces stitched onto the fabric for soldering purposes were designed to be very close to each other. Therefore, soldering needed to be very precise and accurate. A larger amount of solder could increase the possibility of shorts and a very little amount of solder could cause a weak or broken connection. The protruding fibers of the textile substrate made the process more difficult.

Participants also raised concerns about the testing and troubleshooting process. An Arduino Uno set up along with alligator clips was used to test the functionality of individual sensors. However, the alligator clips create unstable connection issues making troubleshooting difficult and time-consuming. Protruding fibers in the un-insulated conductive thread were partly responsible for unstable connection issues. Participants had to place the alligator clips in multiple locations on the conductive thread to get the desired sensor responses. The testing and troubleshooting process warrants significant improvements for future studies.

Several participants mentioned that they found stitching conductive traces on the body (more specifically, trace crossing) difficult and time-consuming. To avoid unintended trace connections, participants had to manually take each individual trace to the other side (wrong side) of the fabric, continue stitching using a lock stitch machine, and later move back to the right side of the fabric using a hand needle, and tie them together by hand. The whole process was very time consuming and took a lot of time.

Participants faced several issues while performing regular garment assembly operations. There were a few occasions they found that trace layouts in the sleeves did not perfectly align with the trace layouts in the body. Some of them also found it difficult to stitch the curved seams on the body such as serging the armscye and sewing the zipper on the neck area. However, all of these issues are common to traditional apparel manufacturing and could be fixed easily with experience.

In addition, the participants reported facing several mechanical issues with the industrial serger and lock stitch machines. There were a few occasions where the needle broke. In some cases, machines came unthreaded and re-threading took a lot of time. There was an issue with the tension of the lock stitch machine, especially when stitching conductive threads. All these issues were fixed but troubleshooting took a significant amount of time.

5.4 Summary and future work

In this chapter, the deployment of the surface-mount fabrication method was described. A mass-manufacturing case study was performed where 41 regular fire-fighter thermal liners and 45 sensor-integrated thermal liners were produced in an apparel factory setting. The study took place in a total of 20 sessions (total 395 hours) with each session lasting between 3 and 5 hours with ten participants. For the production layout, a bundle production system was used and a machine layout was developed based on the operation sequence. The production layout was divided into four different units: cutting, regular thermal liner garment assembly, sensor attachment, and sensor-integrated thermal liner garment assembly. A post-production quality inspection was performed at the end of the production run, and in-line QA was performed dudring production. Each participant was given verbal and written instructions before performing a new task. The manufacturing variables that emerged from the deployment of the manufacturing method were collected using a time study method. Several manufacturing variables were measured including operation time, bottlenecks, the efficiency of the participants, and material costs. More abstract challenges were recorded during and after the study using a post-study questionnaire. Finally, a few simulated best-case scenarios were presented at the study to provide the best outcome of the study in an ideal situation.

The study results showed that it took more time to produce an e-textile garment during the pre-production study (3.49 hours) compared to the production case study (2.72 hours). Several operations including “stitching traces using pattern stitcher”, “sewing conductive traces on the body” and “serging” took longer during the pre-production study compared to the production study. Differences in participants’ skillsets, dividing operations among multiple participants, and a few modifications in some of the operations were responsible for the lower manufacturing time in the final production study. As expected, it took more time to produce the same amount of sensor-integrated thermal liner garments (163.12 minutes or 2.72 hours per garment) compared to regular garments (49.83 minutes or 0.83 hours). While looking at the bottlenecks of the manufacturing method, serging and assembling zippers were the major bottlenecks of the regular thermal liner garments. On the other hand, “stitching traces using pattern stitcher”, “sewing conductive traces using lock stitch machine”, and “serging” were the major bottlenecks of the sensor-integrated thermal liner garments, where the first two operations consumed 58.74% (95.82 minutes out of 163.12 minutes) of the total manufacturing time. It cost around $69.98 to produce a sensor-integrated thermal liner garment which is almost 243.88% higher than producing a regular thermal liner garment ($20.35) and a significant portion of the cost comes from the labor cost ($32.62) followed by the conductive thread ($15.84). However, in an ideal situation, it would take 1.44 hours and cost $19.40 to produce a sensor-integrated thermal liner garment given that all the machines and tools are functional, workers are experienced and skilled, and the production is performed in a developing country (e.g. Bangladesh) where labor wages are comparatively lower than developed countries (e.g. US).

Furthermore, the study results showed that 79.17% (223 out of 276) sensors were functional after final production and 20.73% had some issues. Out of the 20.73% non-functional sensors, 10.73% of sensors were recorded as non-functional after in-line testing. The remaining 10.11% (25) of sensors broke during the production process due to human handling and friction with the machines and tools. Weak solder connections and broken solder joints were the primary causes of failures. Furthermore, variability of the sensor data and differences in operators' efficiency were observed throughout the study. Several new variables including machine optimization variables, human error variables, and process variables were noticed throughout the study.

One of the major benefits of this manufacturing case study is that it uses machines and tools that are readily available in a standard CMT factory. As I have shown in this chapter, with minimum investment, this manufacturing study could be easily deployed in a CMT factory anywhere in the world. Therefore, it lowers the barrier to large-scale manufacturing of smart garments. Furthermore, the method can be extended to develop more complex e-textile garments with other surface-mount components (e.g., multipin-ICs, flip chip, etc.). The use of automatic stenciling and reflow techniques should be used to improve the efficiency and reliability of the method. More sophisticated quality testing tools should be used to cut down troubleshooting time. A pattern stitcher with a larger bed would allow the e-textiles developer to stitch the complete trace layout into the garment (instead of dividing the main trace layout into multiple stitched layouts). To assess the effectiveness of the method in the real world, future studies should be performed in a real factory setting under the direct supervision of factory managers. Even though the manufacturing case study used a stitch-based surface-mount manufacturing process, the same process could be translated to other popular integration methods such as conductive ink printing, weaving, or knitting. While some of the issues discussed here would be very specific depending on the applications of the e-textile product and the integration method, the majority of the variables discussed here (such as durability, washability, insulation, trace routing, seam crossing, etc.) would be universal irrespective of the integration method used Hence, the framework used in this study could be used as a reference for general e-textile garments manufacturing. It could be further extended to develop more complex e-textile garments with other integration techniques and the results could be utilized to develop a universal manufacturing process for e-textiles.

CHAPTER 6: CONCLUSION AND FUTURE WORK

There is great potential for the growth of garment-integrated technologies globally. These technologies can be widely applicable from general consumers to the military to space suit applications and people around the world can benefit. The integration of electronic and computing technologies into garment form is a relatively new technique for apparel manufacturers and designers. While adding electronic components into textiles creates new design opportunities for apparel designers, the integration of electronics into the body space creates new challenges for technology designers. Many smart garments with embedded electronics suffer from the dominance of one of these two approaches. While integrating electronics into textiles seems very promising to apparel manufacturers and designers, a gap exists in the provision of designers with a common understanding of embedded technology. The design and development of smart garments with embedded electronics crosses the boundaries between textile engineering, apparel manufacturing, electronic engineering, material science, industrial engineering, fashion design, and human biology. Therefore, it is often not pursued by apparel manufacturers due to their lack of understanding of the influencing design variables that lie outside their scope of experience.

While hand-made fabrication methods are common in the e-textiles community, these methods are not suitable for producing e-textiles in mass. The inconsistency between electronics manufacturing systems and apparel manufacturing practices make the integration process a complex task. Differences in product development cycles, technological advances, and work practices are major barriers to the development of scalable garment-integrated technologies that can effectively bridge the two disciplines. Production of body-worn technologies is largely dominated by electronic manufacturing systems that often have limitations in terms of the feasible scope of body distribution of system components, flexibility in the electronic system design, and comfort. Merging of electronic and apparel manufacturing systems could enable better progress toward solving these problems. Manufacturing of garment-integrated technologies requires an efficient, scalable process that blends manual processes with automation. This research project emphasizes developing a hybrid manufacturing process with a focus on leveraging the benefits of the traditional labor-intensive apparel industry and the automated electronics industry. Here, I describe a summary of my work that exemplifies my contribution in this space.

Development of a Fabrication Method for E-Textiles

Stitched methods of e-textile fabrication offer durability and flexibility benefits, as well as relatively un-constrained layout patterns. The ability to affix discrete component packages without a PCB substrate would improve the overall flexibility and comfort of an e-textile garment. However, that level of integration between electronic and apparel manufacturing processes is difficult to achieve. Here I present the development of a stitched method of fabricating e-textile circuits with surface-mount components [51]. This evaluation extended the method developed by Berglund et al. [5] which uses an embroidery machine (instead of an industrial pattern stitching machine) to stitch conductive traces onto a fabric surface in a 2D pattern and a reflow soldering technique to affix standard electronic components. In this dissertation work, we modified, refined, and extended the method. Here, we used more sophisticated pattern stitcher machine instead of the embroidery machine and performed more rigorous testing to assess the effectiveness of the method. More specifically, we evaluated in more depth the parameters of trace design and their effect on durability, and refined the manufacturing process for solder deposition and reflow. The work is primarily motivated by an emphasis on developing hybrid manufacturing processes that facilitate the distribution of only those components of a system that rely on spatial localization, while continuing to leverage the durability and manufacturing efficiency benefits of centralized electronics. It allows us to make electronic circuitry minimally perceptible in clothing by replacing rigid circuit boards with textile-based flexible circuitry, but to retain the efficiency and scalability offered by traditional electronics by using typical component packages and soldering techniques. Further, it explores the potential of the apparel or sewn products factory as a key partner in the fabrication of the distributed portion of the system, without imposing a radical change to the technology, capability, or workflows of a typical cut-make-trim (CMT) apparel fabrication facility.

Testing of the Fabrication method

The method was rigorously tested to ensure the method can produce efficient, durable, and reliable e-textile circuitry that can withstand regular wear and tear and washing. For that purpose, hundreds of fabric swatches having surface-mount components were developed and tested. Using a simulated high-intensity wear test, we evaluated the durability of this method for circuit architecture variables of component size, trace width, and trace orientation, as well as for methodological variables of solder deposition technique and reflow process [51]. We showed durability of 3% failure after a 14-hour wear test for the best manufacturing conditions. We also show that the larger the component size, the stronger the connection; the wider the trace width, the sturdier the connection, and that perpendicular trace layouts provide more durable connections than parallel trace layouts.

While only small-batch production was conducted, reliant on manual stenciling and population of the stitched substrates, I believe these methods could ultimately be translated to higher-volume production using automated stenciling and pick-and-place operations.

We extended our method to evaluate the robustness to home laundering of the surface-mount fabrication for e-textile circuits. We performed a durability test based on machine washing and drying while varying the textile substrate, component size, and intensity of the laundering cycle. After around 17 hours of rigorous washing and drying, we measured a 1.5% failure rate for component solder joints. 1.25% of these failures occurred during the first wash/dry cycle. The overall durability exceeded that measured using the tumble test alone in the durability study, despite the overall test time being longer (1000 minutes vs. 845 minutes).

Next, we evaluated the effectiveness of insulation material in protecting stitch-based surface-mount components. Alternative surface insulation materials, textile substrate properties, and soldered component joints were evaluated. After around 1000 minutes (16.67 hours) of rigorous washing and drying, we measured a best-case 0% failure rate for component solder joints, and a best-case 0.38 ohm/m maximum increase in trace resistance. Liquid silicone seam sealer was effective in protecting 100% of solder joints. Two tape-type alternative surface insulation materials were effective in protecting bare traces and component attachment points respectively. Overall, results demonstrate the feasibility of producing insulated, washable cut-and-sew circuits for smart garment manufacturing.

In summary, the method presented here has demonstrated good durability over high-intensity wear and launderability testing. Further, it leverages technologies that are common to apparel and sewn product manufacturing. As such, it may present a compelling alternative to traditional hard-goods electronics manufacturing for smart clothing and textile-integrated wearable technologies.

Translation of the Fabrication Method for More Complex Structures

After developing and validating the method for e-textiles fabrication, the next step was to extend that method to garment-scale fabrication. To develop a manufacturing process and identify the fabrication and manufacturing variables for e-textile garments, I developed several e-textile prototypes of increasing complexity, which ranged from a swatch to a complete garment using the methods previously described as well as novel methods required by these more complex structures. To demonstrate the manufacturing method with a slightly more complex circuit, a custom-designed stitch layout was used to connect an array of RGB LEDs to an Arduino microcontroller. An inertial sensing unit provided the input to the display, which changes color depending on the motion and orientation of the sensor. Later, the LED display was integrated into a motion responsive visual display garment to explore garment-level integration variables when the fabrication technique is combined with a multi-piece garment design that also integrates peripheral PCBs, a microcontroller, and a power source. Importantly, the shirt is constructed using industrial sewing techniques and aims to preserve the look of a typical garment. The development of these prototypes served as an exploratory investigation to discover the major challenges of fabricating garment-scale e-textile products. Some of the major challenegs identified for stitched-based surface-mount e-textile product development included smaller package size integration, trace crossing and seam crossing, testing and troubleshooting of the finished garment, and reparability of the system by the users. In addition to that several manufacturing variables were identified that need to be considered while designing e-textile garments including: conductor integration method, design of trace layouts, limits for elctronic component package sizes, selection of electronic component package types (e.g. surface-mount LED, PCB flip chip), spatial distribution of the component packages, methods for integration of PCB-mounted hardware system components (e.g. microcontroller, bluetooth, battery etc.) into the garment, suitable connectors for removable system components, insulation techniques for traces and component packages, trace crossing method, performance and quality testing of the product, operation sequence, and tools/machines for the product development. A design framework has been developed for the product development process of e-textile garments, with a focus on development for manufacture. The focus is on the design issues that arise from the development of smart garments with embedded electronics. An in-depth analysis is presented to identify design development tasks and attributes during the product development stages including design, fabrication, and quality assessment. The garment and the electronic system are much more tightly intertwined than simple attachment of a stand-alone system to a stand-alone garment and the study results provide a more granular understanding of the steps involved in the integration of electronics. All the findings provide insight on all the nuanced and detailed known and unknown challenges and variables involved in e-textile product development and extend our current understanding on the product development process for e-textiles.

Deployment of a Case Study Manufacturing Process

Manufacturing e-textiles in mass likely involves additional processes and variables not addressed when developing a prototype or individual sample. Therefore, a case-study manufacturing process was developed which involved three major steps: product development, production planning, and production. For the product development step, a temperature-sensing firefighter e-textile liner garment was developed to serve as an example case study for a manufacturing process. The sensor-integrated fire-fighter liner aims to detect the change in temperature inside the garment and between the system layers. The garment was fabricated using the product development framework developed previously. A pre-production study was performed to identify the tasks involved in transitioning from prototype development to the final production. A total of five sensor-integrated thermal liner garments and a regular garment were developed. A time study was used to determine the time needed to perform each operation which was later used for production planning purposes for the final production process. Several manufacturing variables and steps that were involved in transitioning from prototype development to the factory setting were developed and described including: developing a pattern marker, stitching patterns using the pattern stitcher, providing for trace crossing and seam crossing, integration of insulation material, technical documentation for production, selection of machines and tools for production, development of a production workflow, and quality assessment analysis. Finally, for the production study, 41 regular and 45 sensor-integrated thermal liner garments were produced in a CMT factory case study scenario. The study results show that it took approximately 1.28 times higher in terms of time to produce an e-textile garment during the pre-production study compared to the production case study. The study results show that the average manufacturing time to produce a sensor-integrated thermal liner was 3.27 times higher than producing a regular thermal liner garment, given that all the materials, labor, and machines remain constant. “Stitching traces using pattern stitcher”, “sewing conductive traces on the body”, and “serging” were the major bottlenecks of the manufacturing process and took 58.74% of the total manufacturing time of the sensor-integrated thermal liner garment. The sensor-integrated thermal liner garment cost around 3.44 times more to produce compared to the regular thermal liner garment. However, further analysis showed that by optimizing some of the processes, and using fully functional machines and skilled laborers, the production cost of the same sensor-integrated garment could be cut down by almost 51% and if the production takes place in a developing country where labor cost is much lower than in developed countries, the cost of production could be cut down to as much as 72%. Moreover, it would require more skilled laborers and better training of the laborers to produce e-textile garments compared to regular garments. Furthermore, I identified the more abstract challenges and variables (e.g. machine optimization variables, human error variables, process variables, participants' efficiency, and previous experience, etc.) involved in transitioning from one-off production to a larger-scale context in a CMT factory setting, somewhat independently of the operations used. A thorough analysis was provided to describe the challenges observed and what could be done to minimize them in future followed by a simulated best-case scenario for time and cost. In summary, this study contributes to the literature several ways including designing a process for the manufacturing of spatially distributed surface-mount e-textiles, discovering the factors that affect quality and scalability of the process (e.g. labor, equipment, and cost), identifying the operations involved in the process that are required to be measured, discovering the factors that need to be optimized and identifying new variables that emerge from the case study manufacturing process.

There is a lack of acceptable standardized processes for manufacturing e-textiles that allow components to be distributed over a garment surface. Manufacturing of e-textiles has not been the focus of substantial attention in academic research. The current manufacturing techniques used in the industry have several limitations. Existing leading e-textile manufacturing companies use proprietary e-textiles components and often use craft-based techniques which could not be generalized for all kinds of e-textiles manufacturing. In this study, we have developed a durable, scalable, efficient, and reliable manufacturing process, and the method is thoroughly tested to validate its effectiveness. The method allows spatial distribution of the components on a garment, while simultaneously preserving the human factors of apparel including aesthetics and physical comfort. By using off-the-shelf components with existing machines and tools that are readily available in the standard CMT factory, it lowers the barrier-to-entry to smart clothing and wearable technology for apparel manufacturers and technology developers. This method has the potential to develop flexible, adaptable garment-integrated architectures for sensing and actuating technologies that will facilitate the development of a wide variety of applications without the need for new hardware development. Moreover, the case study results identify the challenges (both known and unknown) of manufacturing e-textiles in mass and offer avenues to overcome them. Garment-integrated technologies haven't made significant progress to date because of the lack of understanding among the hardware manufacturers or device designers of apparel production methods and the lack of understanding among textile and apparel manufacturers of electronics or hardware manufacturing techniques. The case study results will help to fill these gaps between two diverse fields. While the case study provides insight regarding the deployment of a specific surface-mount manufacturing method, the lessons learned from this study's insights could be used as a reference for general e-textiles manufacturing. Therefore, the study results will contribute in developing a universal manufacturing process for e-textiles which could be deployed in any kind of CMT factory in any part of the world with standard machines and materials with minimum or no additional investment. This will support more widespread application of garment-integrated technologies and people around the world may benefit from this. Through this corpus of work, I have helped contribute to a possible compelling alternative to traditional hard-goods electronics manufacturing for smart clothing and textile-integrated wearable technologies.

Future Work

Though the method showed very promising results in producing durable, reliable and scalable connections, there remains room for improvement for longer-term development. In this project, I have used several different electronic components for surface-mount e-textiles manufacturing, but most of them were relatively simple packages due to reliance on manual soldering, stenciling, and population of the components. These methods could translate to higher-volume production using automatic soldering and stenciling, and pick-and-place operations. However, utilizing automatic soldering and pick-and place operations would bring new challenges for the manufacturing of e-textiles. The flexible mechanics of textiles along with protruding fibers on the fabric surface would create unique challenges during automatic soldering and stenciling. Furthermore, the automatic reflow machines used in the electronics industry operate at high temperatures and might not be suitable for textile components since the high temperature might burn the fabric structures. Hence, a modification of these equipment would be needed in order to use them for e-textile applications. In future, the method could be extended to more complex surface-mount component integration techniques. For example, with further refinement, the technique could be used to attach more sophisticated components such as multi-pin ICs that would allow the development of more complex circuits. Manual stenciling and reflow techniques are often not suitable for soldering tiny multi-pin ICs. In future, use of automatic stenciling and reflow technique along with quality assessment tools should be utilized for attaching more sophisticated components. Similar techniques could be used to develop multi-layer stitched circuits where conductive traces are stitched on either side of a fabric layer or multiple fabric layers that serve as insulators to allow trace crossing without creating a short, in combination with through-hole components or junctions that pass through the fabric layup to interconnect layers when needed. Another application of this method could be extending the method to include flip chip packages where solder bumps are used to connect component packages with embedded traces. There were several occasions where connections were unstable because conductive thread had poor connections and variable resistance. Future studies should explore insulated conductive threads for more stable connections among the components. The quality testing matrix used in the study was designed for testing simple circuits and might need to be adjusted to evaluate more complex circuits. More sophisticated quality testing tools and techniques need to be included to evaluate more nuanced performance of the circuits. More sophisticated e-textile garments should be developed and deployed, and the finished products should be rigorously tested to ensure the scalability and efficiency of the method at a large scale. More extensive lab testing and human study should be performed to ensure the produced e-textile garments can withstand regular wear and tear, can be washed like regular garments, and meet the requirements for post-consumer use (e.g. fulfill the basic requirements of consumer products). Finally, the case study was deployed in the laboratory to simulate a CMT factory set up. However, the factors that determine the scalability of a manufacturing method such as labor, machines, materials, and workflow would be somewhat different in a real factory (e.g. much more efficient and standardized). To understand the true challenges of garment-integrated technologies, one needs to deploy the method in a real CMT factory. Therefore, in future the method should be deployed in a real apparel factory setting.

PROJECT PUBLICATIONS

Conference Proceedings

- **M. T. Islam Molla, C. Compton, and L.E. Dunne, "Encapsulation methods for Cut and Sew E-Textiles", in *Proceedings of the 2018 International Symposium on Wearable Computers (ISWC 2018)*, Singapore, 2018.** https://dl.acm.org/citation.cfm?id=3267255 **(Full Paper)**
- **M.E. Berglund, E. W. Foo, M.T. Islam Molla, S.M. Sudheendra, C. Compton, and L.E. Dunne, "MAKE IT BLUE: A Controllable, Color-Changing Dynamic Costume", in Proceedings of ISWC, 2018.** https://dl.acm.org/citation.cfm?id=3267304 **(Design-Exhibition)**
- **M. T. Islam Molla. Towards Development of Scalable Garment-Integrated Technologies, In Proceedings of the 2018 ACM International Joint Conference on Pervasive and Ubiquitous Computing, Singapore, 2018.** https://dl.acm.org/doi/abs/10.1145/3267305.3277836 **(Workshop paper)**
- M. T. Islam Molla, S. Goodman, N. Schlief, M.E. Berglund, C. Zacharias, C. Compton, and L.E. Dunne, "Surface-mount manufacturing for e-textile circuits", in *Proceedings of the 2017 ACM International Symposium on Wearable Computers*, Maui, Hawaii, USA, Sep. 2017. https://doi.org/10.1145/3123021.3123058 (Full Paper)
- **M. T. Islam Molla, "A Scalable Manufacturing Method for Garment-Integrated Technologies", in *Proceedings of the ACM International Conference on Ubiquitous Computing (UbiComp)*, Maui, Hawaii, USA, 2017.** https://dl.acm.org/citation.cfm?id=3123194 **(Doctoral Colloquium)**

- **M.T. Islam Molla, C. Compton, and L.E. Dunne, "Launderability of Stitched Surface-Mount E-Textiles. International Textile and Apparel Association Annual Conference, November, 2018, Cleveland, Ohio, USA. (Abstract)** https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=3120&context=itaa_proceedings

- **M.T. Islam Molla, C. Compton, and L.E. Dunne, "Identifying challenges of fabricating e-textile garments via a case study", International Textile and Apparel Association Annual Conference, October, 2019, Las Vegas, Nevada, USA. (Abstract)** https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=3120&context=itaa_proceedings

- **M.T. Islam Molla, C. Compton, and L.E. Dunne. "Product Development Process for E-Textiles garments: A Design Guideline for Apparel Manufacturers", International Textile and Apparel Association Annual Conference, Denver, Colorado, USA, November 2020**

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APPENDIX A: STUDY QUESTIONNAIRE

Pre-study Questionnaire

Session #: _________________

Name: ____________________

Gender: ____

Age: ____

Major: ____

Q1. Sewing Skills: Please rate your sewing skills below.

Novice	Intermediate	Good	Expert

Q2. Have you worked with electronics before? If yes, then please briefly write down your level of involvement with electronics.

Q3. Experience with E-Textiles: Have you worked with E-Textiles before? If yes, then please briefly write down your level of involvement with E-Textiles.

Post Study Questionnaire

Date:

Name:

Q1. Hours spent on this project (approx.)_______________________________________

Q2. Operation (s) you were involved with______________________________________

Q3. Machine/tool you have used during the study________________________________

Q4. Have you used the machine/tool before ____________________________________

Q5. Machine/operation/task that was most challenging to you & why________________

Q6. Do you have any suggestions to improve the operation?________________________

APPENDIX B: STUDY GUIDELINES

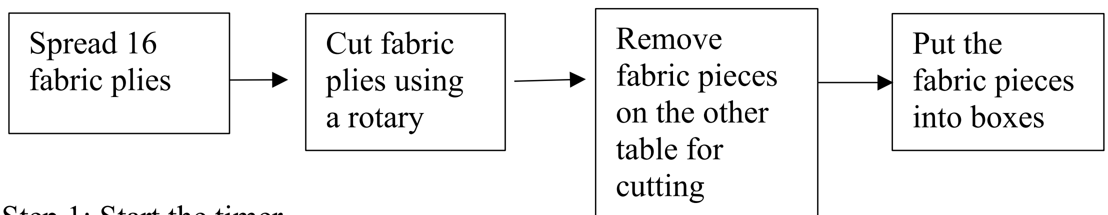
Start the timer at the beginning of each task.

Stop the timer when you are done.

Fill out the form given to you.

Department A: Cutting

Task 1: Cut Pattern pieces out of fabric (for both regular and e-textile garments)



Step 1: Start the timer

Step 2: Spread 16 plies of fabric layers onto a table (Outer side of the roll is the face side)

Step 3: Place a pattern marker on top of the fabric layers and cut

Step 4: Use an industrial rotary knife to cut the fabric into small pieces according to the size of the pattern pieces

Step 5: Place first pattern marker and cut

Step 6: Cut the notches and sort fabric pieces (put a cross mark on the back and leave face side on the top)

Step 7: Follow with the next marker, continue until all the fabric is cut

Step 8: Put fabric pieces in eight different boxes labeled as “body-Regular” (42), “body-e-textiles” (54), “right front sleeve-regular”(42), “right front sleeve-e-textiles”(54), “left front sleeve-regular”(42), left front sleeve-e-textiles”(54), “back sleeve” (196), “pocket” (88).

Task 2: Cut press cloth, zipper, remove zipper teeth, assemble zipper stops

2.1: Cut Press Cloth

Step 1: Cut the press cloth using pattern (10” x 10”) provided to you.

Step 2: Put fabric pieces in the box labeled as “press cloth”

2.2: Cut zipper and zipper stops, assemble zipper stops

Step 1: Cut zipper using scissors

Step 2: Remove two teeth from each side of the zipper using pliers.

Step 3: Attach zipper stops

Step 4: Put fabric pieces in the box labeled as “zipper

Task 3: Quality assessment of the cut pieces

Step 1: Pick five Body pieces from the box labeled as “Body”.

Step 2: Check if the measurements of the fabric piece match with the size provided in the spec sheet.

- If the measurements match with the spec sheet, put them in to a separate box labeled as “completed”.
- If the measurements do not match with the spec sheet (if the tolerance is higher than ½ inch), label the faulted area with a sticker and put them in to a separate box labeled as “Faulty pieces”.
- Check rest of the garment pieces for the same problem.

Step 3: Repeat the same thing for left sleeve, right sleeve, pocket, & zipper.

Step 4: Count number of faulty cut pieces and remove them from the production process.

Task 4: Draw markings using paper templates

Task 4.1: Draw Trace layout onto wrong side of fabric pieces using trace template (E-Textile Body)

Step 1: Take the box labeled as “body-e-textiles” (70).

Step 2: Place trace template onto a fabric piece and draw circle using sharpie.

Step 3: Give inch space on either side of shoulder seam.

Task 4.2: Draw traces onto wrong side of fabric pieces using trace template (Right-hand front and left-hand front)

Step 1: Take the boxes labeled as “right front sleeve-e-textiles” (54) and “left front sleeve-e-textiles” (54).

Step 2: Place trace template onto the wrong side of fabric piece and draw circle using sharpie.

Step 3: Give inch space on either side of shoulder seam.

Order:

Left Front Sleeve → Right Front Sleeve

Task 4.3: Draw location of the pocket and zipper (All body)

Step 1: Take the box labeled as “All Body” (70).

Step 2: Place trace template onto a fabric piece and draw circle using sharpie.

Department B: Regular Garments Sewing

Task 5: Serge garments with the Serger machine (Regular garment)

Step 1: Serge ¼” seam allowance.

- Hem
- Body bottom

- Sleeve cuff
- Front opening
- Neck
- Edges of pocket

Step 2: Underarm seam

Step 3: Armscye

Step 4: Upper arm and shoulder seam

Step 5: Serge mitered corner

Task 6: Assemble zippers (Regular Garment)

Step 1: Attach zipper.

- **1" seam allowance**

Task 7: Assemble pocket (Regular Garment)

Step 1: Crease pocket (sewing)

Step 2: Attach pocket to body

- **1/16" seam allowance**

Task 8: Assemble Velcro straps (Regular Garment)

Step: Attach 3 2-inch Velcro straps on the neck.

Task 9: Hemming (Regular Garment)

- Fold serged edges
- Stitch the corner

Department C: Sensor Development for E-Textiles

Task 10: Stitching with the Pattern Stitcher (E-Textile)

Start 1: Start the pressure pump by pressing “start” and wait about a minute until the pressure pump stops.

Step 2: Start the pattern stitcher by pressing “start”.

Step 3: Set the model number.

Step 4: Move the machine bed by pressing left pressure foot.

Step 5: Place the main body fabric piece on the machine bed in the right orientation (wrong side of the fabric will be top (marked with “x”) and align with the trace layout and make the fabric flat by hand.

Step 6: Press the right pressure foot to lower the machine bed and fix the fabric into the machine. Make sure the fabric piece is lying flat with no wrinkles. Check if the fabric is tightly placed onto the fabric and is ready for sewing.

Step 7: Press the left pressure foot again to start the machine.

Step 8: When the machine stops, remove the fabric from the machine bed.

Step 9: Do a visual inspection. Re-stitch the sensor circuit if there is any issue (e.g. machine stops, threads came out etc.).

Step 10: Repeat for other 5 components

Step 11: Once all sensors are stitched onto the garment pieces, put the pieces in the boxes.

Stitching with Pattern Stitcher

Step 1: Set up the program no and raise the clamp.

Step 2: Orient the fabric according to trace layout (put the wrong side (the side with the x mark) of the fabric on the top)

Step 3: Make the fabric flat and avoid any wrinkle.

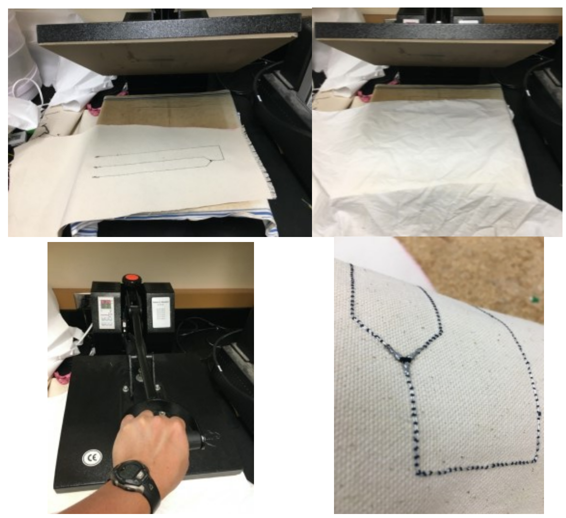
Start 4: Lower the clamp and start stitching.

Start 5: Inspect stitch (visually) e.g. missed stitch.

Trace layout using Pattern Stitcher

Task 11: Quality Assessment to Check Faulty Stitched Traces

Step 1: Perform a quick visual inspection for individual stitched circuit to see if the conductive traces are stitched properly on the machine.



- Ensure conductive traces are visible from the other side of fabric
- Ensure seam line is stable with no or minimum protruding fibers
- If the traces are stitched properly, put the garment piece into a box labeled as "completed".
- If there is an issue remove the stitched thread using a seam reaper and put the garment piece into a box labeled as "Rework needed".

Step 2: Send the "Rework needed" box to the station 1 to re-stitch the sensor circuit.

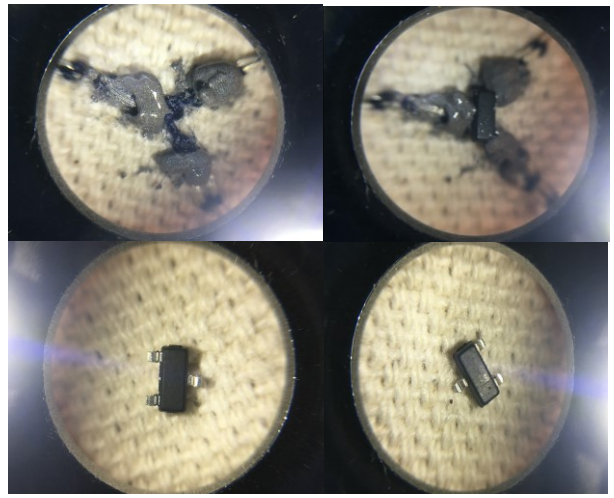
Step 3: Repeat step 1 & 2.

Task 12: Soldering

Step 1: Check if there is any short using a digital multimeter.

Make sure all three traces (power, ground, and output) should not touch each other.

Step 2: Pick up a fabric piece and place it on the table.



Wrong Right

Step 3: Put solder paste onto traces with the help of an awl. Make sure traces/solder don't touch other.

Step 4: Take a TMP235 sensor and orient the sensor on the right direction (sensor pads will lay flat on the surface).

Step 5: Mount TMP235 sensor using a tweezer and an awl. Add more solder if needed.

Task 13: Heat Pressing

Step 1: Start the heat press.

- **Set the temperature and time 420^0F and 120 seconds respectively.**

Step 2: Place the sensor under the heat press.

Step 3: Place a press cloth on top of the sensor.

- **change the press cloth after 12 presses or if its look dirty**

Step 4: Press the TMP235 using heat press and hold it for 120 seconds.

Step 5: Leave the TMP235 onto the heat press bed for 30 seconds.

Step 6: Visually inspect individual connection using microscope.

- Check if the traces are touching each other (if there is any short)

- Check if the solder is broken
- Check if the solder connection is weak
- Check if the trace connection is broken
- Perform rework if needed

Step 7: Repeat the process for all the sensor circuits and for all the fabric pieces

Task 14: Sensor Testing, Troubleshooting, and Reworking

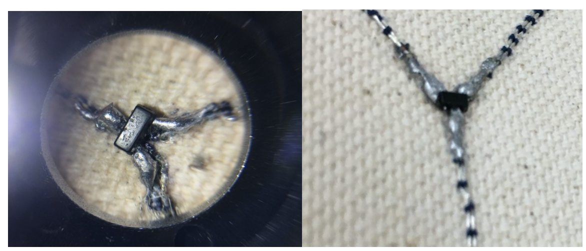
Testing the circuit using Arduino Uno.

Step 1: Connect “black” wire to the ground, “red” wire to the power, and “green” wire to the output.

Step 2: Plug in Arduino Uno (if unplugged) and click serial monitor on the Arduino interface.

Step 3: Use the Arduino Uno-PC set up to check if you are getting the desired temperature reading of the sensor.

- Acceptable range 60^0C- 80^0C
- If the temperature is different then check the connection and perform troubleshooting of the sensor circuit.



Example of good (shiny) solder joints

Example of bad (cold) solder joints

Troubleshooting

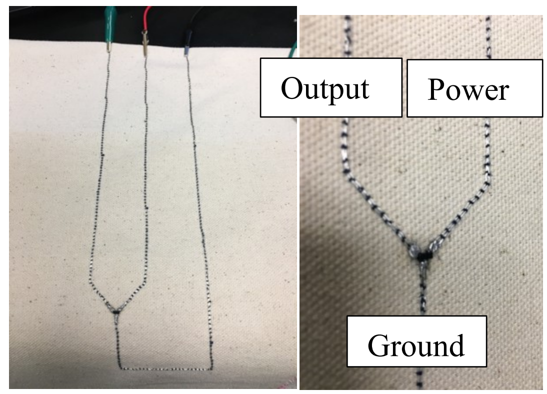
Step 1: Check connection.

- Check if there is any broken connection both visually and using a microscope.
- Check if the traces are touching each other (if there is any short)
- Check if the solder is broken

- Check if the solder connection is weak
- Check if the trace connection is broken

Step 2: Check sensor connection using a digital multimeter.

- The voltage difference between power and ground should be ~5V
- The voltage difference between ground and power should be ~ 0.72V
- If the voltage is different then check the connection and perform a visual inspection.



Check if there is any short using a digital multimeter.

Make sure all three traces (power, ground, and output) should not touch each other.

Step 4: Fix failed connection. Re-solder if needed.

Step 5: Repeat step 1 to 3 until the sensor gives the desired value. If it's still not working, then leave it is as it is. Put a label on the defected connection/sensor.

Step 5: Repeat the same process for all the sensors.

Step 6: Put the garment piece into a box once rework is completed.

Task 15: Insulate traces and sensor components

Step 1: Use a Hand Iron (Setting: 3 out of 5, for 5-6 seconds)

Step 2: Cut seam tape (4")

Step 3: tape the component using the heat press

Task 16: Sew Conductive Traces Using Lock Stitch Machine (E-Textile Body)

Steps involved in this task:

Step 1: Sew traces using a lock stitch machine.

- Run conductive thread through lockstitch machine over marked lines to form traces
- Follow trace layout
- Leave 1" edge on shoulder seams
- Stitch traces on the wrong side of fabric and pulling thread through to other end and manually tying knots to intended connection points or use a hand needle to make connection between intended connection points.

Task 17: Solder and QA of Intended Connection Points

Step 1: Solder intended joints

Step 2: Test using a multimeter

Task 18: Attach Snaps on the Body (E-Textile Garment)

Step 1: Attach snaps (female) using a snap fastener machine.

Step 2: Perform a visual inspection to see if the thread is permanently snapped with the fabric.

Department D: E-Textile Garments Sewing

Task 19: Serge garment pieces with the Serger machine (E-Textile garment)

Step 1: Serge ¼" seam allowance.

- Hem
- Body bottom
- Sleeve cuff
- Front opening
- Neck
- Edges of pocket

Step 2: Underarm seam

Step 3: Armscye

Task 20: Sew Conductive Traces Using Lock Stitch Machine (Finished E-Textile Garment)

Steps involved in this task:

Step 1: Sew traces using a lock stitch machine.

- Run conductive thread through lockstitch machine over marked lines to form traces
- Follow trace layout
- Leave 1" edge on shoulder seams
- Stitch traces on the wrong side of fabric and pulling thread through to other end and manually tying knots to intended connection points or use a hand needle to make connection between intended connection points.

Task 21: Serging and assembling the garment (E-Textile Garment)

Step 1: Upper arm and shoulder seam

Step 2: Serge mitered corner

Task 22: Assemble zippers (E-Textile Garment)

Step 1: Attach zipper.

- **1" seam allowance**

Task 23: Assemble pocket (E-Textile Garment)

Step 1: Crease pocket (sewing)

Step 3: Attach pocket to body

- **1/16" seam allowance**
- **Leave one side of the pocket open**

Task 24: Assemble Velcro straps (E-Textile Garment)

Step 1: Attach 3 2-inch Velcro straps on the neck (see picture attached)

Task 25: Hemming (E-Textile Garment)

Step 1: Fold serged edges (1/2” on the body and sleeves; ¼” by the zipper)

Step 2: Stitch the corner

Department E: Quality Assessment of the Finished Garments

Task 26: Quality Assessment of the Finished Garments-Garment Level

- Step 1: Trim all serge tails/loose threads
- Step 2: Quality assessment.

Part name	**Length (inch)**	**Tolerance (inch)**
Body Length	31 ¼	± ¼
Body width	28 ¼	± ¼
Sleeve length (outside seam)	27 ¾	± ¼
Sleeve length (inside seam)	24	± ¼
Sleeve width	6 ¾	± ¼
Zipper length	64	± ¼
Pocket	6” x 5”	± ¼

Task 27: Testing, Troubleshooting, and Reworking of the E-Textiles Garments

Step 1: Attach external hardware to snaps in pocket. (E-Textiles)

- **Snap the male snaps onto the female snaps (pocket).**

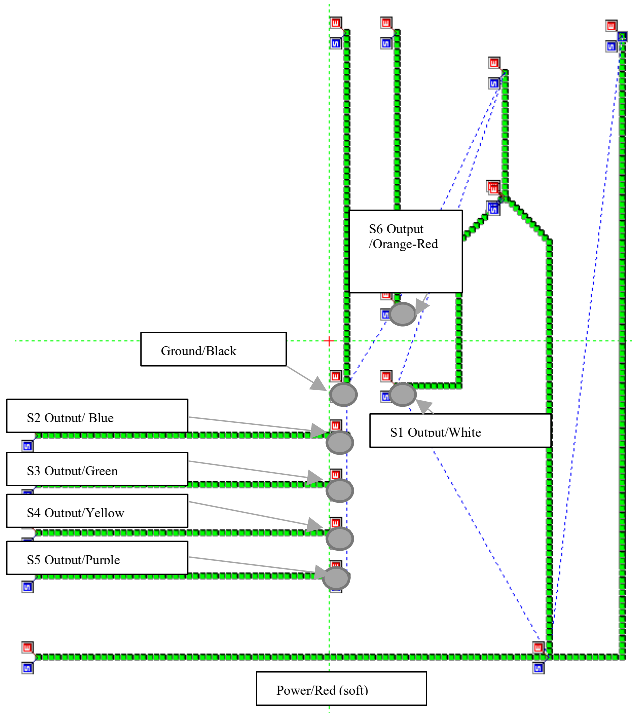
Step 2: Check if all the sensor circuits is still working.

Step 3: Check Open/short-doesn't show any value in the power supply.

Step 4: Check electricity continuity- show any value in the power supply.

Step 5: Check resistance measurement- measure the resistance at all the points of measures of the system.

Step 6: Check voltage test- check if the voltage gives correct reading. One way to figure this out is to check the voltage level at room temperature and crosscheck with the datasheet. Voltage can be measured using a power supply and a Digital Multimeter.



Step 7: Check incorrect orientation of the sensor-check the voltage

-If there is a small voltage (~45 mV) passing through the terminals, there is problem with the sensor or the connections.

- If there is no change in the voltage level (~5v), there might be a short in the circuit. Check the connection.

- If the voltage is less than 5V but close to 5V (~4.2v), that means ground is not connected.

5V-Problem with ground

0V-problem with power

1.5-2.5V-problem with output

Step 8: Perform rework.

Step 9: Put the fabric piece into a designated box once done.

Step 9: Repeat the above steps

APPENDIX C: QUALITY ASSESSMENT EQUIPMENT AND TOOLS

Equipment/Tool	Things to measure	Troubleshooting Parameters
Visual inspection of the individual connection	Broken connections	-Solder joint is broken -Trace connection is broken
Inspection using Microscope	Broken connections, alignment of the chip	-Solder joint is broken -Trace connection is broken -Wrong alignment of the chip
Comparing pictures of actual joints against true joints	Weak connections	- “Cold” solder joint - Improper amount of solder
Flying probe with a power source	Opens and shorts on the boards, Electricity continuity, resistance measurement, voltage test, incorrect orientation of the sensor	Open/short-Doesn’t show any value in the power supply Electricity continuity-show any value in the power supply

		Resistance measurement-Measure the resistance at different location of the system Voltage test-Check the voltage level at room temperature and crosscheck with technical sheet Incorrect orientation of the sensor-Check the voltage
Inspection using a hardware set up with a prototype board and Arduino code	Check the actual temperature of the sensors in Arduino serial monitor and compare with a reference thermometer temperature	If the sensor temperature is similar to the reference thermometer temperature with ±2.5 accuracy

APPENDIX D: TECHNICAL DATA PACKAGE

Technical Data Package for Regular Garment

Product: Firefighter turnout coat liner

Size: Medium

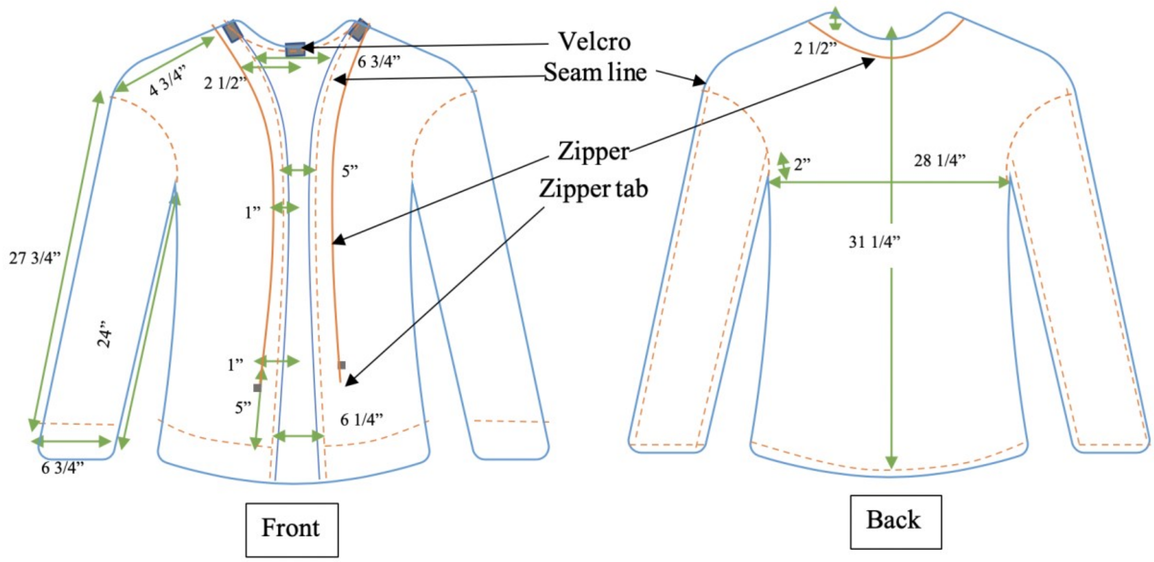
Number of pieces: 40

Material Details:

Material	Description	Color	Figure
Fabric	100% cotton canvas twill fabric	Grey/Natural	
Zipper chain	Brass zipper, size #5	Beige	
Zipper slider	Size#5	Brass	

Zipper top stop	Size#5	Brass	
Zipper bottom stop	Size#5	Brass	
Velcro strap	Sew on Velcro strap, ¾ inch width and 2 inch long strap	Beige	
Sewing thread	100% Spun Polyester sewing thread	Beige	

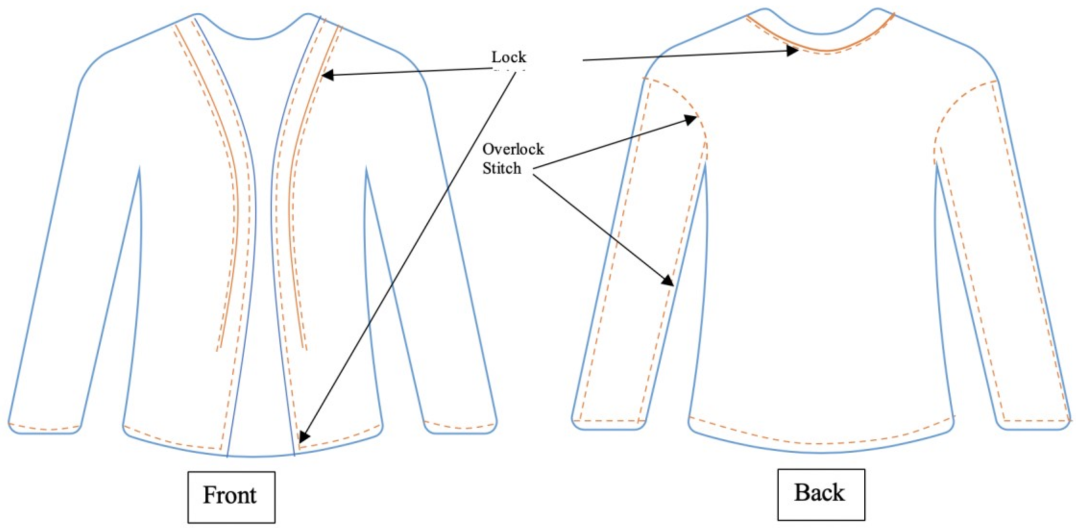
Garment sketches:



Spec sheet:

Part name	Length (inch)
Body Length	31 ¼"
Body width	28 ¼"
Sleeve length (outside seam)	27 ¾ "
Sleeve length (inside seam)	24"
Sleeve width	6 ¾ "
Zipper length	64"

Seam indicator lines:



Instructions on zipper assembly: Cut the zipper with a length of 64 inch. Assemble the zipper into the garment. See point of measurement for the exact location of the zipper onto the garment.

Stitch Instructions: Overlock stitch on the shoulder seam and sleeve joints. Lockstitch in rest of the seamline.

Technical Data Package for Sensor-Integrated Liner Garment

Garment description: Temperature sensing firefighter turnout coat liner

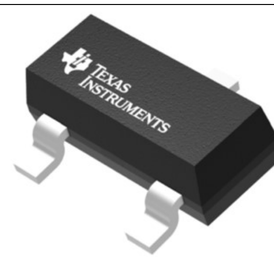
Size: Medium

Number of pieces: 40

Material Details

Material	Description	Color	Figure
Fabric	100% cotton canvas twill fabric	Grey/Natural	

Zipper chain	Brass zipper, size #5	Beige	
Zipper slider	Size#5	Brass	
Zipper top stop	Size#5	Brass	
Zipper bottom stop	Size#5	Brass	
Velcro strap	Sew on Velcro strap, ¾ inch width and 2 inch long strap	Beige	
Sewing thread	100% Spun Polyester sewing thread	Beige	

Sewing thread	100% spun Polyester sewing thread	Black	
Female snap buttons	Size #15 (3/8 inch)	Silver	
Male snap buttons	Size #15 (3/8 inch)	Silver	
Ring snap backs	Size #15 (3/8 inch)	Silver	
TMP 235 sensor	Analog temperature sensor, 3.04 x 2.64 mm	Black	
Solder paste	Chip quick solder paste		

Conductive yarn	Silver coated vectran thread Conductivity- 1 Ohm/ft	Silver	
Electrical wire	Silicone electrical wire 18 gauge (1/20 inch)	Blue, green, black, red, yellow, orange, light blue, light green	
Insulation material	Melco seam sealing tape (0.50 inch)	clear	
PLA	3mm Polylite PLA	Various	

Bill of materials

Bill of materials for regular thermal liner garment

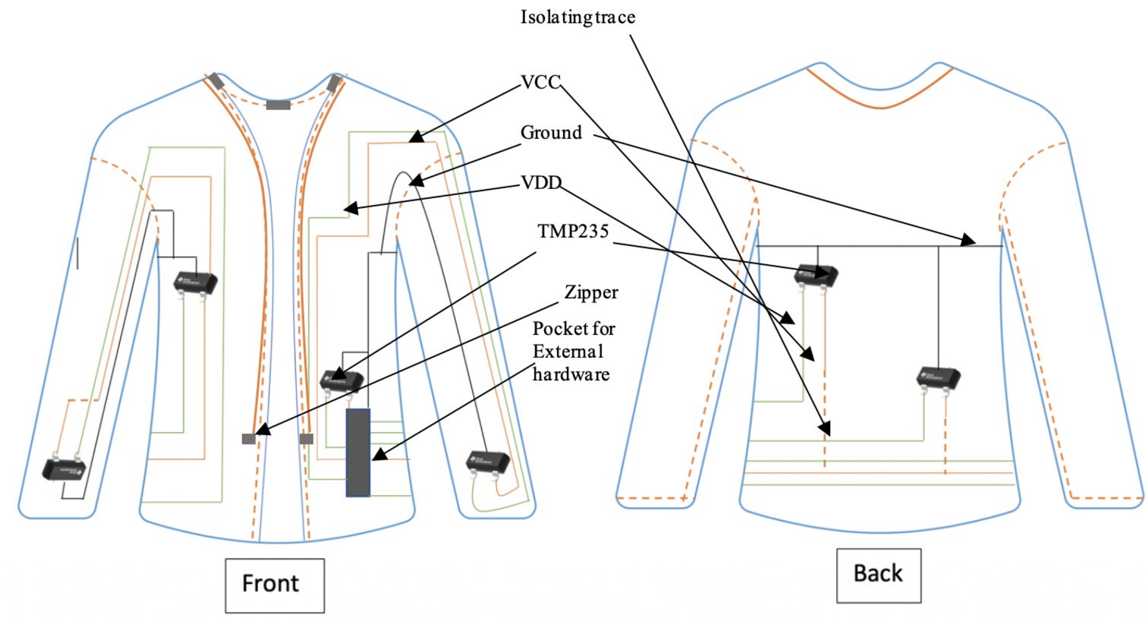
Component	Details	color	Amount/ Garment	Unit	Total amount (40 Garment)	Allowance (25%)	Price Per Unit	Unit	Price Per Garment	price for 40 Garments
Softgoods										
Canvas Fabric		Beige	1.58	Yards	63.2	79	$3.40	1	$5.37	$214.88
Sewing Thread	Polyester thread (yards)	Beige	160	Yards	6400	8000	$13.89	24,000	$0.09	$3.70
Zipper Chain	Size #5	Beige	0.88	Yards	35.2	44	$3.99	1	$3.51	$140.45
Zipper Slider	Size #5	Brass	1	Each	40	50	$0.89	1	$0.89	$35.60
Zipper Top Stop	Size #5	Brass	1	Each	40	50	$6.49	100	$0.06	$2.60
Zipper Bottom Stop	Size #5	Brass	1	Each	40	50	$6.49	100	$0.06	$2.60
Velcro	3/4" width and 2 inch long strap	Beige	0.16	Yards	6.4	8	$24.20	10	$0.39	$15.49

Bill of materials for sensor-integrated thermal liner garment

Component	Details	Color	Amount/ Garment	Unit	Total amount (40	Allowance (25%)	Price Per Package	Package Quantity	Price Per Garment	Price For Forty Garments
Softgoods										
Canvas Fabric	Canvas Fabric	Natural	1.58	Yards	63.2	79	$3.40	1	$5.37	$214.88
Sewing Thread	Polyester thread (yards)	Beige	160	Yards	6400	8000	$13.89	24,000	$0.09	$3.70
Sewing Thread	Polyester thread (yards)	Black	24	Yards	960	1200	$13.95	12,000	$0.03	$1.12
Zipper Chain	Size #5	Beige	0.88	Yards	35.2	44	$3.99	1	$3.51	$140.45
Zipper Slider	Size #5	Brass	1	Each	40	50	$0.89	1	$0.89	$35.60
Zipper Top Stop	Size #5	Brass	1	Each	40	50	$6.49	100	$0.06	$2.60
Zipper Bottom Stop	Size #5	Brass	1	Each	40	50	$6.49	100	$0.06	$2.60
Velcro	3/4" width and 2 inch long strap	Beige	0.16	Yards	6.4	8	$24.20	10	$0.39	$15.49
Total									$10.41	$416.43
Electronics										
Arduino Nano	Standard		1	Each	5		$12.86	3	$4.29	$171.47

TMP235 sensor	Temperatu re sensor		6	Each	240	400	$0.35	1	$2.08	$83.16
Solder paste	34.93g		1.3	Gram s	10	10	$18.8 6	35	$0.70	$28.02
Silicone Wire	26AWG	Variou s	3.33	Feet	133. 2	166. 5	$10.8 8	108	$0.34	$13.42
Conductive yarn	Vectran Thread (yards)		72	Feet	2880	3600	$0.22	1	$15.8 4	$633.60
Seam Sealing Tape	Melco seam tape		1	Yard	40	50	$1.05	1	$1.05	$42.00
Female Snaps	Size 15 (3/8")	Silver	8	Each	320	400	$2.50	50	$0.40	$16.00
Male Snaps	Size 15 (3/8")	Silver	8	Each	40	50	$2.50	50	$0.40	$16.00
Ring Snap Backs	Size 15 (3/8")	Silver	16	Each	360	360	$1.75	50	$0.56	$22.40
PLA	3mm Polylite PLA	Variou s	52	gram s	2080	2600	24.99	1000	$1.30	$51.98
Total									$26.9 5	$1,666.0 5
Final Total									$37.3 6	$2,082.4 8

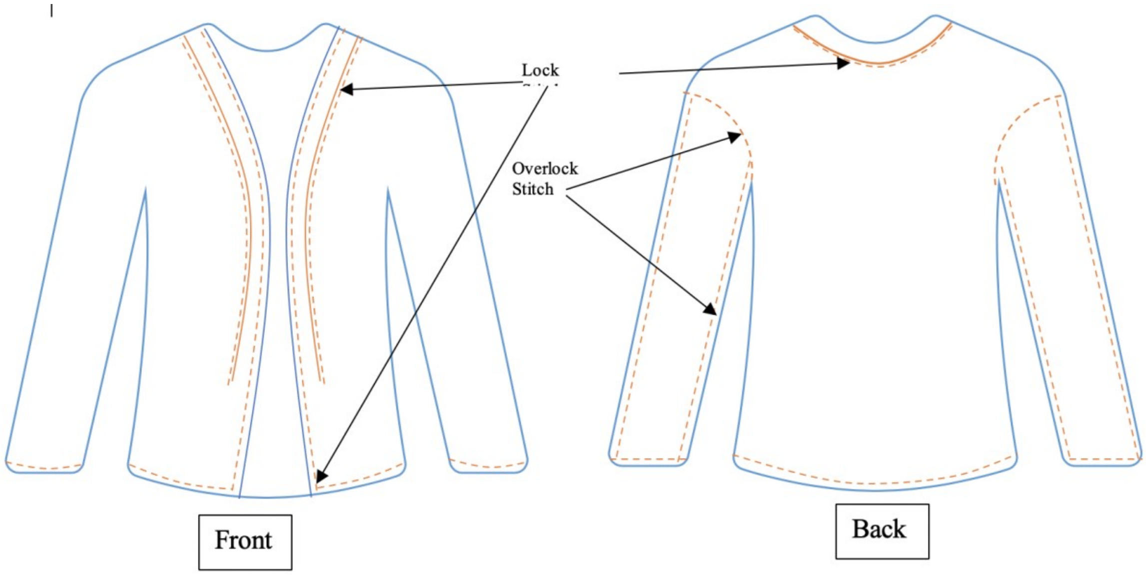
Garment sketches & location of sensors:



Spec sheet:

Part name	Length (inch)
Body Length	31 ¼”
Body width	28 ¼”
Sleeve length (outside seam)	27 ¾ “
Sleeve length (inside seam)	24”
Sleeve width	6 ¾ “
Zipper length	64”

Seam indicator lines:



Location of sensors:

Sensor 1: Front right chest

Sensor 2: Front left abdomen

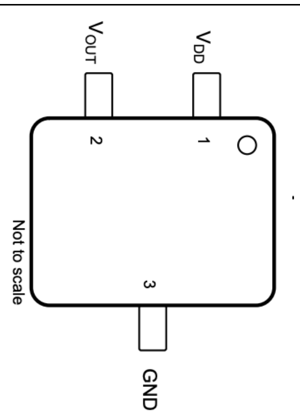
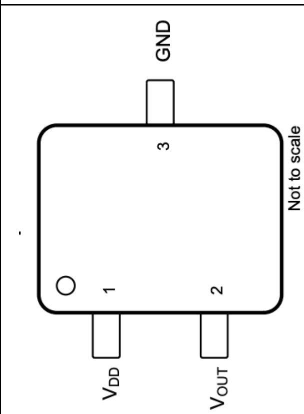
Sensor 3: Back left waist

Sensor 4: Back right armpit

Sensor 5: Left wrist

Sensor 6: Right wrist

Orientation of sensors:

Right wrist	**Other Location**
	

Instructions on zipper assembly: Cut the zipper with a length of 64 inch. Assemble the zipper into the garment. See point of measurement for the exact location of the zipper onto the garment.

Location of the pocket for the removable electronics: Create the pocket at the front right abdomen of the garment.

Instruction about trace layout:

Location of the removable electronics: Inside the pocket

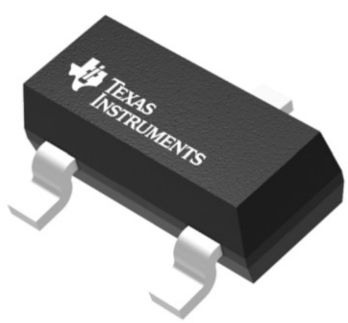
Creating connections between traces: Use solder paste and heat gun

Techniques for Isolating traces: Stitch the opposite side of the fabric layer

Insulation application: Cut insulation material into small pieces. Use the t-shirt press to affix the insulation material onto fabric.

Stitch Instructions: Overlock stitch on the shoulder seam and sleeve joints. Lockstitch in rest of the seamline.

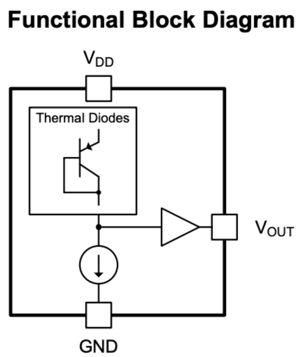
TMP235 sensor:

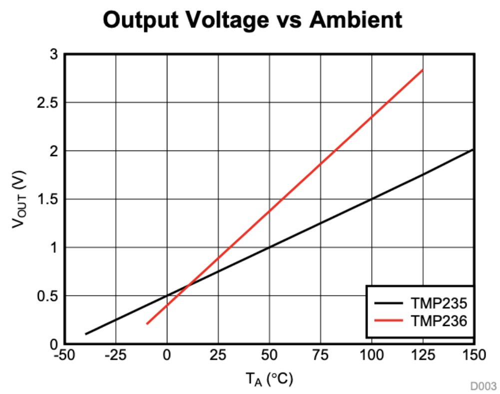


Features:

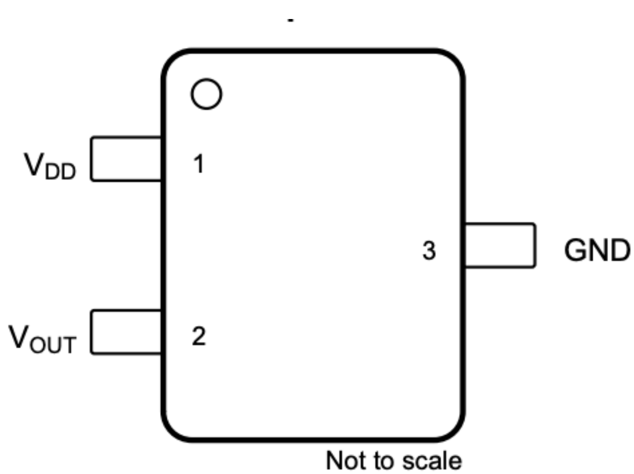
- Temperature range: – ±2.5°C (maximum): –40°C to +150°C
- Operating supply voltage range: – 2.3 V to 5.5 V

- Power: 9 µA (typical)
- Output for driving loads up to 1000 pF
- 3-pin SOT-23 (DBZ) surface mount





Pin Configuration and function:



Name	Pin	Type	Description
GND	3	Ground	Power supply ground.
VOUT	2	Output	Outputs voltage proportional to temperature

V_{DD}	1	Input	Positive supply input

Transfer Table:

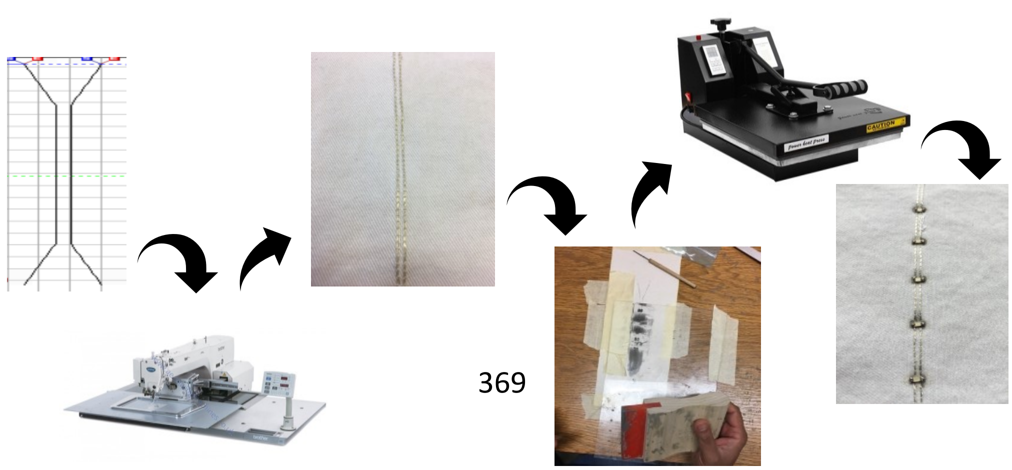
TEMPERATURE (°C)	V_{OUT} (mV) IDEAL LINEAR VALUES	V_{OUT} (mV) PIECEWISE LINEAR VALUES
–40	100	100
–35	150	150
–30	200	200
–25	250	250
–20	300	300
–15	350	350
–10	400	400
–5	450	450
0	500	500
5	550	550
10	600	600
15	650	650
20	700	700
25	750	750
30	800	800
35	850	850
40	900	900
45	950	950
50	1000	1000
55	1050	1050
60	1100	1100
65	1150	1150
70	1200	1200
75	1250	1250
80	1300	1300
85	1350	1350
90	1400	1400
95	1450	1450
100	1500	1500
105	1550	1550.5
110	1600	1601
115	1650	1651.5
120	1700	1702
125	1750	1752.5
130	1800	1805.5
135	1850	1858.5
140	1900	1911.5
145	1950	1964.5
150	2000	2017.5

See TMP235 datasheet for additional information.

Soldering technique:

- Stitch conductive traces using the pattern stitcher on the fabric pieces

- Place the fabric piece onto a flat surface e.g. table
- Use tape to temporarily attach the fabric onto the table (to avoid movement during solder application)
- Put a solder stencil on top of the fabric
- Use tape to temporarily attach the fabric onto the table (to avoid movement during solder application)
- Put solder paste on thesolder stencil and use a squeezee to squeezee solder onto the traces.
- Remove the stencil
- Place the TMP235 sensor using a tweezer
- Start heat press and set the temperature at 230^{0}C and time 60 seconds
- Wait untile the temperature move to 230^{0}C
- Remove the fabric piece from the table and place it onto the heat press
- Place the top surface onto the sensor and keep it for 60 seconds
- Remobe the tope surface after 60 seconds
- Wait 30 seconds to cool down the circuit
- Remove it from the troubleshooting
- Perform QA and troubleshooting



APPENDIX E: A LIST OF OPERATION, PARTICIPANTS, AND MACHINE/TOOLS USED DURING THE MANUFACTURING STUDY

Operation No.	**Operation Name**	**Department**	**Immediate Preceding**	**Operator**	**Machine/ Tools Used**
1	Cut press cloth	Department A: Cutting (Sensor-integrated and regular thermal liner garment)	**-**	**P5**	Scissors
2	Cut fabric pieces using the paper marker		**-**	P3, P4, P5, P6, P7, & P8	Paper marker, rotary knife, scissors
3	Cut zippers and assemble zipper teeth		**-**	**P5, P7, & P8**	Scissors, measurement tape, pliers
4	Sorting/dividing cut pieces		**2**	P3, P4, P5, P6, P7, & P8	**-**
5	Quality Assessment		**4**	**P3, P7, &P8**	Measurement tape, pattern template
6	Draw location of the sensors (E-Textiles)		**5**	**P5, P7, & P8**	Marker pen, paper template
7	Draw starting points for zippers and pockets (E-Textiles)		**5**	**P5, P7, & P8**	Marker pen, paper template

8	Draw starting points for zippers and pockets (Regular)		**5**	**P5, P7, & P8**	Marker pen, paper template
9	Serging-sleeves inseam	Department B: Regular thermal liner assembly	**8**	**P1, P2, & P3**	Serger machine
10	Serging-Armscye, shoulder seam, and upper arm		**9**	**P1, P2, & P3**	Serger machine
11	Serging-sleeves and body hem		**10**	**P1, P2, & P3**	Serger machine
12	Assembling zipper		**8**	**P1, P2, P3, & P4**	Lockstitch machine
13	Serging pocket edges		**8**	**P1, P2, & P3**	Serger machine
14	Sewing pocket edges		**12**	**P1, P2, & P3**	Lockstitch machine
15	Stitching pocket to the body		**13**	**P1, P2, & P3**	Lockstitch machine
16	Hemming-Body and sleeve		**11**	**P1, P2, P3, & P4**	Lockstitch machine
17	Assembling Velcro straps		**12**	**P1, P2, P3, & P4**	Measurement tape, scissors, Lockstitch machine
18	Stitch trace layouts using pattern stitcher		**7**	**P1, P2 & P10**	Pattern stitcher

19	Solder and mount sensor	Department C: Sensor Development	**18**	**P3, P4 & P8**	Solder paste, awl
20	Heat press and affix sensor onto traces		**19**	**P7, P9, & P10**	Heat press
21	QA, Troubleshoot, and Rework		**20**	**P6 & P8**	Arduino-Uno set up, computer, digital multimeter
22	Insulate sensor components		**21**	**P9 & P10**	Melco seam sealing tape
23	Sew conductive traces on the body using lock stitch machine		**22**	**P1, P2, & P3**	Lockstitch machine
24	Solder and QA of intended connection points		**23**	**P9**	Digital multimeter, solder paste
25	Attach snaps on the body		**7**	**P9 & P10**	Snapping tool
26	Serging-sleeves inseam	Department D: Sensor-integrated thermal liner garment assembly	**25**	**P2 & P3**	Serger machine
27	Serging-Sewing on sleeves (upper arm) to body		**26**	**P2, P3**	serger
28	Sewing conductive traces from the body to the sleeves using lock stitch machine		**27**	**P2 & P3**	Lockstitch machine
29	Serging-Armscye, shoulder seam, and lower arm		**28**	**P2, P3**	Serger machine

30	Serging-sleeves and body hem		**29**	**P2, P3, P9**	Serger machine
31	Assembling zipper		**7**	**P2, P3, P5**	Lockstitch machine
32	Serging pocket edges		**7**	**P2, & P3**	Serger machine
33	Sewing pocket edges		**33**	**P2, P3, & P5**	Lockstitch machine
34	Stitching pocket to the body		**34**	**P2 & P3**	Lockstitch machine
35	Hemming-Body and sleeve		**31**	**P1 & P3**	Lockstitch machine
36	Assembling Velcro straps		**35**	**P3**	Measurement tape, scissors, Lockstitch machine