Inclusion of Fabric Properties in the Design of Electronic Textiles

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(Abstract)

This thesis considers the impact of fabric properties on the electronic textile (e-textile) design process. Specifically, properties such as weave pattern, drape, tinsel wire placement and weight are evaluated as physical aspects of an e-textile system within an expanded design flow and fabric synthesis. A textile's physical properties are important for creating e-textiles that look and feel like normal clothing and thus are truly wearable. A more detailed assessment of the weave of an e-textile and its effect on the electrical resistance of networks of uninsulated conductive fibers is also considered in both single weaves and complex pocket double weaves.

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Publications

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Chapter 1

Introduction

Just as the design of any embedded computing application must consider its hardware platform, so must an electronic textile (e-textile) design consider its own platform requirements and challenges. For as fabrics vary from garment to garment, so too will e-textiles need to vary from garment to garment and application to application. A major design challenge involves creating an e-textile with mechanical and electrical properties that do not interfere with the application's software and hardware, but enhance its overall performance. In essence, the substrate of the e-textile just becomes another piece of hardware.

E-textiles are applications that use the mechanics of how the materials interlace and connect, along with how the material is used and what it is used for, plus the software and hardware, to help route and sense the desired inputs. E-textiles could even be considered embedded networks. Understanding every aspect of an application would require the designer of a fully integrated e-textile to be a student of textile engineering, mechanical engineering, computer engineering, industrial and systems engineering, along with other application-specific engineering and non-engineering disciplines. Therefore, defining how the e-textiles are put together will help the e-textile designer combat potential issues with components and the end application. This thesis will explore a design space that addresses this concept and provides examples of how the e-textile's properties effect the application.

1.1 Motivation

While designing prototypes for the Intel-agent Rug [8] for a Virginia Tech E-textile Lab project, we encountered a number of design issues that would effect the function of the proposed project. Of what material should the substrate be composed? What was the best weave to use? What was the best wire spacing to monitor a user walking across the surface? How would we weave piezoelectric and electro-luminescent wires in the rug? How would we weave the Bekinox® Stainless Steel as a variably resistive network?

These questions and the process of answering them formed the basis of the expanded design flow that will be presented in Chapter 3 as many of these questions returned in subsequent prototypes and projects. A process to define and answer the questions and parameters was needed for future projects and materials. The expanded design flow is a method of design that considers the substrate and electronic materials' properties part of the application. The primary motivation of this thesis, an integrated design, relates to how an e-textile is designed for usability and the challenges of how the fabrics properties interrelate to the application.

1.2 Contributions

The main emphasis of this thesis is to consider the whole e-textile as a symbiotic platform composed of electronics and materials that are interconnected and rely on an integrated design process. The e-textile design be more than electronics and sensors that are attached to a piece of fabric, it must also consider the properties of the e-textile as a variable in the design specifications. This thesis also provides the designer a view of the design space of an e-textile that enables more robust applications.

To illustrate this approach, a sensor was integrated into the weave of a fabric in varying weave designs to produce different results. One weave resulted in a variably resistive network and another a resistive switch, both within similar fabrics, but by simply adjusting a single property of the e-textile, a different electrical characteristic of the sensor was emphasized.

This thesis makes two main contributions to the field of e-textiles. First, it provides a design methodology that considers both the fabric and electronic properties of an e-textile in a design platform. Second, it provides an example of an e-textile's fabric properties effecting the electrical characteristics of an e-textile with a fiber used as a sensor.

1.3 Thesis organization

This thesis first presents a brief background in Chapter 2 on weaving to familiarize the reader with the textile engineering to better understand the information presented in the paper. The second half of Chapter 2 presents a literature review on related e-textile topics. A design flow is presented and expanded on in Chapter 3 to include the design space of the textile substrate and its properties. An analysis of the synthesis portion of the design flow for a few e-textile properties is shown in Chapter 4. Finally, Chapter 5 takes a detailed look at using a fiber as a sensor and how an e-textile's weave can vary the sensor's behavior.

Chapter 2

Background

The nomenclature that will be used in this thesis to define e-textiles is the standard nomenclature used in textile engineering to describe the construction and categorization of woven fabrics. The main categories of fabrics are woven, knitted, composites, non-wovens, and braids, however, for the purpose of this thesis we will discuss only woven e-fabrics because the Virginia Tech E-textile Lab's prototyping capabilities are limited to only woven materials. Basic definitions of woven fabric terms, such as EPC, PPC, warp and weft, are necessary for this thesis. As such, the first part of this chapter will focus on a brief background on textiles. Then the second part will define a subset of knowledge of other work in the area of e-textile design and simulation and wearable computing.

2.1 What is an e-textile?

An electronic textile, e-textile, is an application built within a textile using materials and sensors that communicate, power or respond as required while a part of the structure. These materials may be woven, knit or layered into the fabric to create the application. The pieces of an e-textile can be viewed as independent, however, as the e-textile layers are all interwoven, each piece depends on the other to work properly and relates to the challenges of wearable and pervasive computing.

2.2 Textile terms

Defining a fabric's construction is implicit to understanding the expanded design flow and an e-textile's properties. Construction of a textile entails the weave density, the size of the repeat pattern, the weave pattern, and the fabric direction. Each of these terms defines a specific property in a fabric's construction. As such, a woven e-textile also incorporates the same construction principles and terms.

A woven fabric is directional in that there are two axes that the yarns interlace, the warp and weft directions. The **warp** direction of a fabric refers to the yarns that are placed on the loom during setup. The **weft** yarns are inserted in the fabric perpendicular to the warp during the weaving process and are called **picks**. The two directions of the fabric are shown in Figure 2.1 on a sample fabric. In an alternate way of viewing the axes, for some purposes of this thesis, the warp can be considered the y-axis and the weft the x-axis of the fabric.

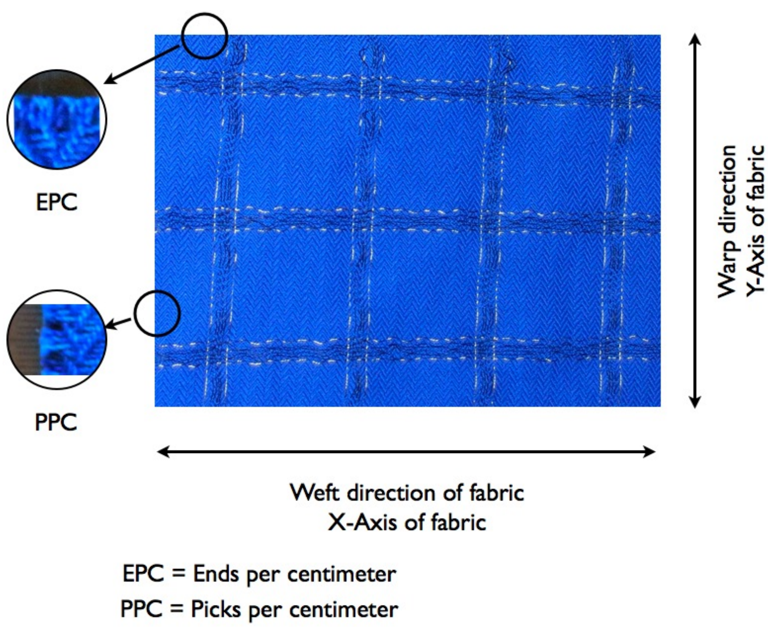


Figure 2.1: Fabric Terminology

The **weave density** of a fabric is determined by how many yarns are in one centimeter of fabric. As a fabric has two directions of interlacement, warp and weft, each direction has its own yarn count, **ends per centimeter** (EPC), and **picks per centimeter** (PPC). A close-up of both the EPC and PPC for a sample fabric is shown in Figure 2.1.

A repeat pattern is tied to the weave of the fabric. A fabric's warp repeat size can be anywhere from a repeat of two to however many ends are in the warp on the loom. A minimum of a two repeat is needed for interlacement to work and create a fabric, otherwise a pattern would not alternate and form a weave. The pattern also has a weft pattern repeat in that the weft yarns can alter the pattern as well. Creating repeats and patterns is as simple as a plain weave or can be as complex as a multilayered weave pattern. Further discussion on this topic and weave patterns will be covered in Section 2.3.1 and Chapter 5.

2.3 Weaving

Weaving a fabric involves interlacing material at an angle to another piece of material on a loom. Two common types of industrialized looms are the jacquard and dobby loom. On a **jacquard loom** every warp yarn is controlled individually for a pattern, while on a **dobby loom** the yarns are controlled in sets to create repeated pattern across the fabric. The loom used for prototyping e-textiles in the Virginia Tech E-textile Lab is a 24-harness AVL Industrial Dobby Loom, which is pictured in Figure 2.2

Figure 2.2: 40-inch wide AVL 24-harness Industrial Dobby Loom

In the construction of a woven fabric, first the loom is set up with the material that comprises the warp. Each warp yarn is threaded through a heddle on a shaft, harness, and then threaded through the reed and tied on to the warp beam. The order that the warp yarns are placed in the harness is called the **draw pattern** of the weave. For the purpose of the prototypes for the Virginia Tech E-textile Lab, the draw pattern is a straight draw, which means that the warp yarns are placed on the harnesses in order. For example, warp yarn one is placed on harness one, warp yarn two is placed on harness two, etcetera, until the last harness. Then the next warp yarn is placed on harness one again to repeat the pattern.

The weft yarns, picks, are placed in the warp in varying patterns by how the harnesses are lifted. A set of harnesses controls a set of warp yarns as decided in the loom's draw. The repeat chooses which harnesses are lifted, and in turn lifts the warp yarns that are controlled by those particular harnesses. This creates a separation of the warp yarns, a **shed**, through which the weft yarns are run in the order determined by the repeat pattern. Figure 2.3 shows a sample repeat pattern with the picks and harness identified along with the draw and the resultant fabric.

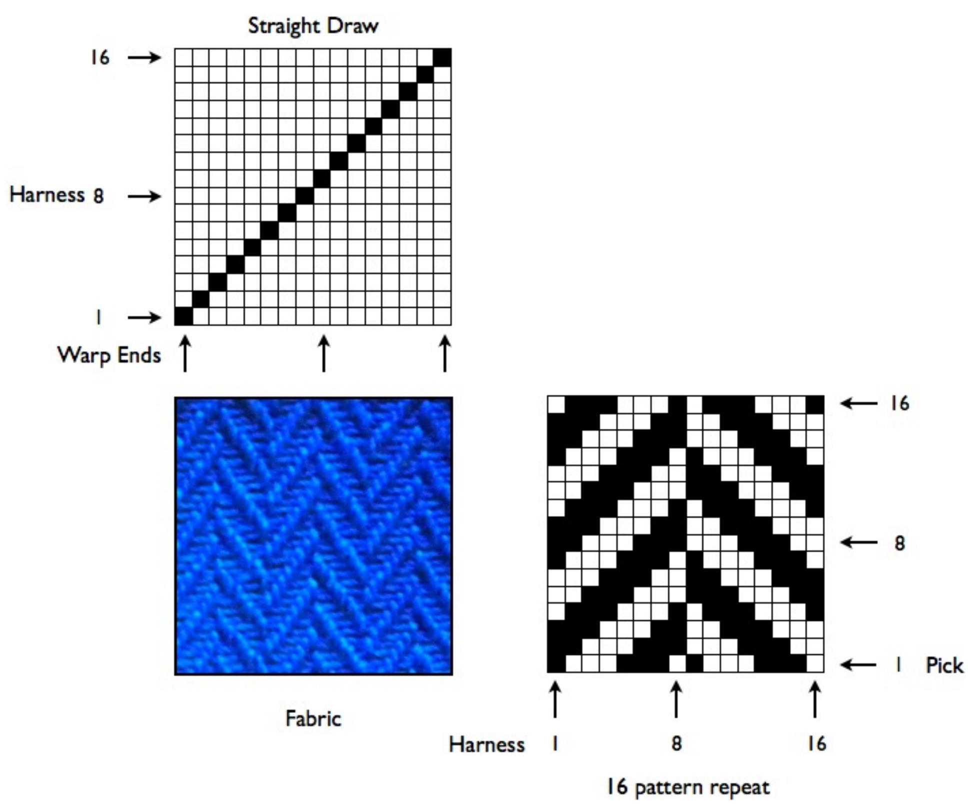


Figure 2.3: Repeat pattern and draw with picks and harnesses identified

Design versatility is tied to the harness count available on the loom as the fabric variations or repeat size is dependent on the number of harnesses and how the warp is threaded in the loom. The more harnesses a loom has, the more versatile a design can be. A loom with only four harnesses will give a much smaller repeat size than a 24-harness loom, and less than a jacquard loom, which has no repeat since each yarn is controlled independently.

2.3.1 Specific weaves

The four main weaves that will be used in this thesis, plain, basket, twill and broken twill, are shown in Figure 2.4. Each of these weaves is similar in that two sets of yarns are interlaced at 90-degree angles, however their differences lie in how often the yarns are interlaced or float over each other. Figure 2.4 depicts the various weaves with their repeat patterns where each square in the repeat pattern denotes whether the yarn is on top of the other yarn or below. A black square depicts that the warp yarn is on top and the white squares shows that the weft yarn is on top.

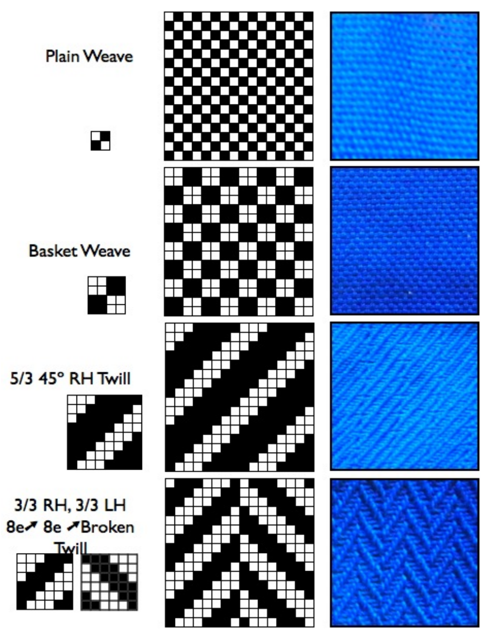


Figure 2.4: Weaves used in thesis showing repeat pattern and fabric with a 16 warp and weft repeat

The plain weave, as shown in Figure 2.4, equally alternates warp and weft yarn interlacings, which creates a checkerboard weave effect. In other words, the warp yarn passes under the weft yarn then over the weft yarn in a repeated pattern, or, using the other way to look at it, the weft yarn passes under a warp yarn then over the next warp yarn in a repeating pattern. The characteristics of this weave can be changed through the types of yarns used in the warp or weft. If a bulkier weft (filler) yarn is used, as in a taffeta fabric, the warp yarns are hidden only showing the weft yarns making this a warp weave.

Comparing the plain weave to the basket weave, in Figure 2.4, a larger or thicker checkerboard pattern emerges as a basket weave is a plain weave with two warp and weft yarns interlaced instead of one. Both the basket and plain weaves only require a two-harness loom. Looking at the twill repeat, one sees that the twill weave has a pronounced diagonal pattern in place of the checkerboard pattern of the plain and basket weaves. This diagonal is a result of the float pattern of yarns that is inherent in the design of a twill, which are patterned off a preset float increment with an angle of incline. For example, the twill shown in Figure 2.4 states that it is a 5/3 45-degree Right Hand Twill. This means that a warp yarn is raised for five weft yarns and then floated under three weft yarns, and repeated in a stepped pattern to form a 45-degree inclined diagonal pattern. The diagonal patterns of twills are set at an angle, and can run straight across the fabric or be broken into variegated patterns as in a herringbone or broken twill weave. The broken twill is a regular twill that has set alternate pattern and breaks with another twill pattern.

2.3.2 Wire repeat patterns

The high number of harnesses on the 24-harness AVL Industrial Dobby Loom allows for a versatile approach to weaving the prototypes for Virginia Tech's E-textile Lab. In addition to the 16 repeat patterns described in Section 2.3.1, the remaining eight harnesses available on the IDL were used for secondary patterns to be woven alongside the main weave pattern. Harnesses one through 16 were dedicated to a main fabric pattern, harnesses 17 and 22 for stainless steel, harnesses 18 through 21 for tinsel wire, and the final two harnesses, 23 and 24 for the fabric selvages.

Figure 2.5 shows the delineation of the repeat pattern that includes the selvage, tinsel, and stainless steel repeats. The adaptability of this approach is seen only when placing the secondary pattern yarns incrementally in the warp. This allows for multiple patterns to be woven for different materials simultaneously; a plain weave pattern for the selvage, and a variable twill pattern with intermittent floats for the weft and warp wire intersections and for connectors.

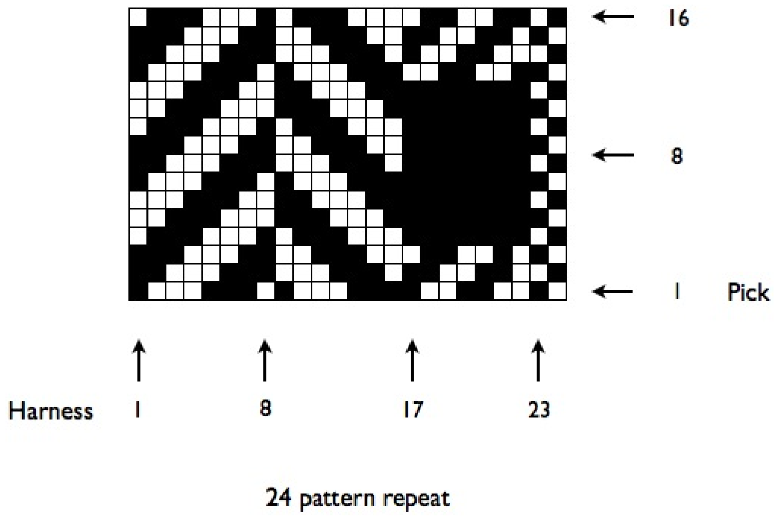


Figure 2.5: Repeat pattern shown for tinsel wire and stainless steel placement

2.4 E-textile design

This section provides a background of prior related research and how the work presented in this thesis fits in the e-textile field. The topic include weaves as related to e-textiles, comfort of an e-textile, circuits in an e-textile, related design flows, and a building-block approach to e-textiles. Each of these areas is an important aspect to e-textiles and to the research presented here.

2.4.1 Building blocks

A primary focus in Virginia Tech's E-textile Lab is to create a set of building blocks of hardware, networking and sensor simulation that are used in the creation of an e-textile. The goal is to give e-textile designers a set of building blocks that creates a foundation of hardware and simulation in e-textile design to reduce the amount of work required in the life cycle of an e-textile application. The use of simulation in training an e-textile for gait analysis and simulation of sensors has been proven to be a viable approach by Virginia Tech's E-textile Lab [6] [7] [16] [20].

The expanded design flow and fabric synthesis presented in this thesis fits with the building block approach in that it helps the designer break down the e-textile into useable physical property building blocks as the simulation of sensors and movement analysis does for the software.

2.4.2 Design flows

A critical design path for multiple disciplines to understand the detailed process of making a technical garment from fabric production and pattern cutting, to the end of life of an e-textile, was presented at the International Symposium on Wearable Computing conference, (ISWC) in 2005 [14]. A previous review of a design flow within Virginia Tech E-textile Lab [19] focused on the design of the application with an acknowledgment that the textile process was important, but did not fully consider the physical properties of the e-textile.

2.4.3 Comfort

A paper on the comfort of wearable computers by Knight, et al. [11], discusses how wearable computers are and what the limits are in considering the design of applications for users. This can be extrapolated to not just wearable computers but also the use of e-textiles as wearable computers. As part of the wearability of a garment is dependent on the comfort of the material used in the manufacture of the clothing, the wearability of an e-textile is in part determined by the comfort of the fabric, if the e-textile is not comfortable it will not be worn.

2.4.4 Use of resistive yarns or yarns as sensors

The creation of a rug that tracks a user's movements as they move across an e-textile was the subject matter of a previous project in the E-textile Lab at Virginia Tech [8]. Weaving electro-luminescent wires, tinsel wire, piezo cables and stainless steel yarn into a large-scale rug the stainless steel and piezo cables acted as motion sensors embedded in the fabric of the rug. The use of a resistive yarn sensor for monitoring respiration [9] in infants to reduce Sudden Infant Death Syndrome was developed as a knit fabric belt that wraps around the infants stomach and lungs. A characterization of conductive yarns for use as textile electrodes using both textile and electrode theory [18] measured the impedance of three types of resistive yarns under tension, of three different lengths and with three different forces to determine how the different yarns function as sensors. Banaszczyk et al. [5] modeled the current in a full resistive sheet woven with resistive yarns.

2.4.5 Circuits in textiles

Placing circuits in e-textiles is fundamental in the design of an e-textile and has been discussed in many areas of e-textile research. A 2003 dissertation by Zahi Nakad [16] from Virginia Tech's E-textile Lab considers use of an x-y communication and power grid of tinsel wires woven into the fabric with floats for the sensors to connect easily to the wire grid. An overview of circuits on e-textiles by Locher et al. [13] focuses on the interconnections of wires on the x and y-axes, vias, and use of connector boards. Karaguzel et al. [10] discuss printed circuits on fabrics for comfort and durability.

2.4.6 Weaving and e-textiles

Using the construction of an e-textile to affect the properties of the application has been the subject of previous research, namely the Georgia Tech Wearable Motherboard™ project. The Wearable Motherboard™ [4][17] research resulted in a novel weaving process to produce a fully formed garment directly on the loom that allows for materials to be spirally woven into the garment for uncut garment manufacturing. This reduces the need to connect wires after the conventional garment manufacturing process of fabric production and pattern cutting and sewing.

Chapter 3

Design Flow

The weave of an e-textile fabric is analogous to routing a printed circuit board. Where and how is it best to lay the routes? Do we need vias? What sort of packaged connectors are to be used? How can we separate the analog and digital signals? Since we cannot autoroute with a CAD program, how do we set the weave to get our desired layout? As such, this is a mechanically and electrically oriented problem, which will be able to be synthesized once the initial conditions are evaluated and quantifiable. However, the first step is to define the layers and evaluate the conditions on which the platform is built. As the end goal of Virginia Tech's E-textile Lab is not to create the fabrics, but the sensors, simulation, and software to create an e-textile, a design flow as the basis of how the substrate will affect the e-textile application needs to be considered by the engineer.

As the creation of an e-textile is application-driven, the materials and sensors that work for one application may not be optimal for the specific and general requirements of another application. Following a design flow for an e-textile allows the entire e-textile to be considered and evaluated in light of the final application.

3.1 Design flow

The design flow of an e-textile is a multiple-step process that involves simulation, software and hardware design, plus the incorporation of a fabric substrate into the final design process. A previous description of the e-textile design flow [19] details the basic process from the application overview to the final design, as shown in Figure 3.1.

In this design flow, the application is first evaluated for desired results and a simulation environment is built to test and refine the ideas for the application, which limits costs in the overall design process. Then, after an emulation of the e-textile application with programmed sensors, a prototype is built to the simulation and emulation specifications. At this point, the prototype will either work as expected or be reevaluated to determine the potential points of failure.

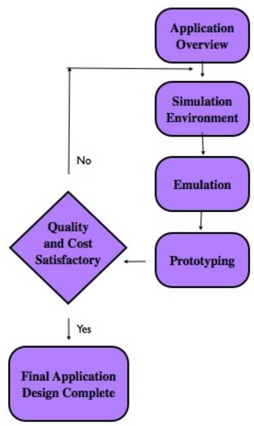


Figure 3.1: Design flow

This is a good design cycle, but, this design flow considers neither the substrate materials and properties, nor how the application is built. A more accurate design flow requires an integration of both the sensor and construction sides of the process, which is the shown in Figure 3.2 as an expanded design flow integrating the substrate prototyping and design. An e-textile is better evaluated when considering not only the sensors, but also the layer of materials within the e-textile.

This expanded design flow includes determining the fabric construction in detail from the substrate materials and wire and sensor placement to the communication bus, to prototyping and testing. The expanded design flow runs parallel to the original design flow to the final prototyping stage. The expanded design flow, however, highlights the integration of both sides of an e-textile with both the substrate and the sensors. By including the substrate materials and their mechanical and electrical properties, a more robust e-textile design will result.

Creating an e-textile substrate platform involves three processes: fabric synthesis, prototyping, and testing as described below. The following subsections concentrate on the particular constraints

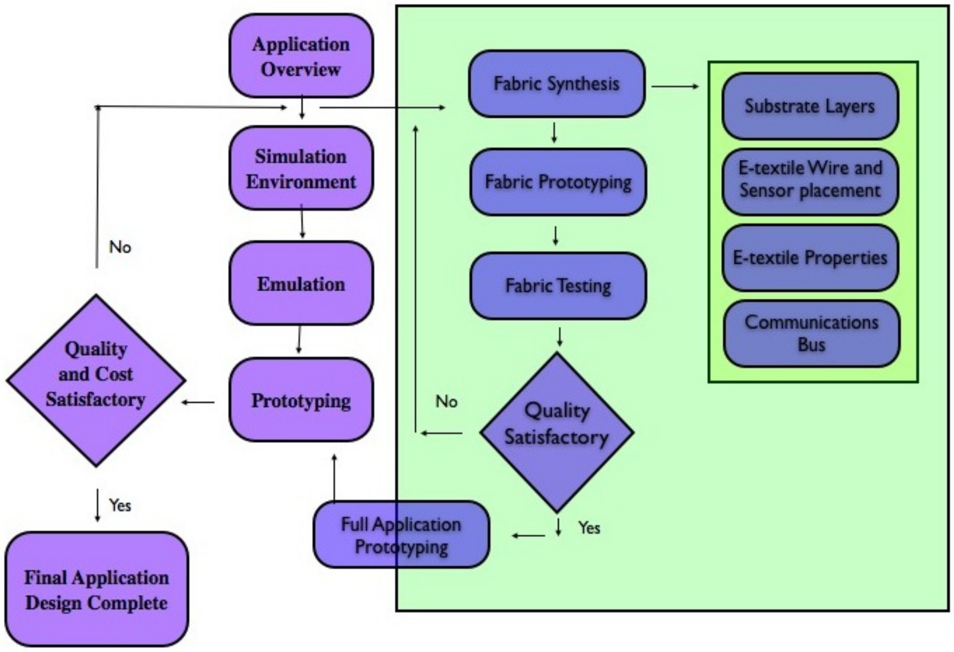


Figure 3.2: Expanded E-textile design flow

of past and future work within Virginia Tech's E-textile Lab, however, the general aspects of the expanded design flow have many practical design applications with other e-textiles as well.

3.1.1 Fabric synthesis

Fabric synthesis involves wire spacing, cost, weight, weaves, sensor placement, and other electronic material integration. Under this synthesis umbrella, the communication/power bus, sensor placement and sensors-as-fibers are based on textile properties determining layout, functionality and weave. Each of these elements of the synthesis is both a deciding factor in the final application and prototype and interrelated to the other areas within the synthesis.

Substrate layer

Synthesizing the substrate of an e-textile involves considering the manufacturing constraints and possibilities as well as the materials and weaves that will work best for the desired application.

One could consider the substrate as a large PCB that potentially has faults in traces, the wires, layers and can be flexible or not. The substrate layer is composed of the materials used for the base fabric, which is then layered with the communication wires, sensors and other electronic materials.

Wire and sensor placement

This design element focuses on best placement of the communication grid and sensors, which is a necessary component for an operable network and sensor data collection. Overuse of the tinsel wire will alter the drape, weight and cost of the e-textile, which, in turn, may change the application's behavior. For example, a less drapeable fabric may respond to a user's motions differently than a more drapeable fabric. However, placement of the sensors at particular distances from each other or in specific spots on body is a necessary requirement in many e-textiles.

E-textile properties

The main e-textile properties considered are the materials used, weave, drape, weight and cost. As previously discussed in Chapter 2, the weave and material of a fabric determines strength, drape, weight and ultimate cost. By changing the variables, a different e-textile can be created with very different properties, but with little extra work on the software and sensor platforms.

Fabric drape and comfort of the fabric are necessary conditions due to wildly variable applications: the fabric may need great stability for a roadside acoustic beamformer or it may need enough flexibility to capture the wind as an e-textile flag. By disregarding these properties, a designer risks building an application that is so constrained it is unusable in certain situations. For example, if the application end use is a garment, the wearer's comfort is important, whereas wearability is not an issue in a carpet or a tent. Like medication that is not taken, a medical e-textile to monitor the gait of a user will only work if the user is willing to wear the e-textile for an extended time. An all-inclusive weave or e-textile design will not optimally work, but it may be possible to use existing fabrics designs if the e-textile designer is aware of the fabric's constraints.

Communication Bus

The Virginia Tech E-textile Lab has determined that a wired communications and power grid, I^2C, is the most efficient method for the group's projects. Therefore, all design space discussion in this thesis focuses on using this solution. The communication bus requires four wires, power, ground and two data transmission lines. This bus is woven into the fabric by using washable, medical-grade insulated tinsel wire, and is required for all sensor networks of all e-textiles produced in the laboratory. Uninsulated stainless steel as a communication grid will not work for garments, or other e-textiles, due to unexpected fabric folds such as sleeve or cuff rolling, which can cause electrical shorts, or an e-textile coming into unexpected contact with a conductive material.

3.1.2 Fabric prototyping

Prototyping the fabric is just as important as prototyping the sensor network of an e-textile. In creating a woven fabric, the loom is the deciding factor regarding the complexity and integration of different materials and will determine a portion of the boundaries of the e-textile fabric. For example, a simple two-harness loom will not yield the fabric complexity of a jacquard loom. However, a many-harnessed loom does allow for a more complex fabric to be created without the time and cost investment of using a jacquard loom. An AVL 40 inch, 24 harness Industrial Dobby Loom [2] was used for the construction of all prototypes considered in this thesis.

While the loom can limit options the materials incorporated into the substrate. Further discussion on how the fabric substrate materials, density, weave and electronic materials effect a fabric's drape, weight, and cost are discussed in detail in Chapter 4. Each of these e-textile properties can easily be altered to achieve a desired effect. A good useable prototype is determined by the fabric synthesis.

3.1.3 Fabric testing

Standard ASTM tests D2260-03 and D3776-96(2002) [1] procedures for conversion, weight and the drape coefficient procedures for the FRL Drapemeter [3] were followed. Other tests on e-textiles include finding electrical shorts, determining resistive properties, and testing functionality as a full e-textile platform with sensors. Additional ASTM fabric tests are recommended, such as washability and tearing, however, they were not performed on the prototypes discussed, because the tinsel wire used for the communication bus is insulated with a medical-grade plastic. ASTM and ISO standardized testing will be determined by the end use of each individual e-textile application.

3.2 Further discussion and examples

The expanded design flow will be characterized and used in the following two chapters. First, Chapter 4 will focus on the fabric synthesis to create a more robust e-textile. Then Chapter 5 will use sensors as fibers to demonstrate how the use of the expanded design flow helps create a alternate e-textile from the same fabrics by varying minor aspects of the e-textile properties.

The weaves and prototypes used for this thesis were discussed previously in Chapter 2, except for complex weaves that are discussed in Chapter 5.

Chapter 4

Fabric Synthesis and Analysis

As discussed in the previous chapter, the four elements of the fabric synthesis in the design flow are: the substrate layers, the communication bus, e-textile properties and wire and sensor placement. These areas are important because they determine how the e-textile will perform mechanically when combined onto one platform. They help answer questions such as: if the application needs to conform to an object, how much of a drape coefficient is needed for the e-textile to perform as desired? And, is the required sensor placement in line with the woven network? This chapter introduces and evaluates a few mechanical properties of an e-textile and emphasizes how a design flow that includes the consideration of the physical properties of the application creates a more robust e-textile.

This chapter first focuses on the materials and weaves used in the analysis, followed by material weight and cost, wire grid spacing, fabric weaves and their drape. Derived analysis of these properties gives an estimate of potential sensor placement and weight-cost analysis. In this chapter, there is no differentiation of specific weaves of the fabrics for the weight and cost synthesis, but rather a comparison of the number of ends and picks as they relate to the cost and weight. However, the amount of yardage will change in relation to the number of interlacings in a particular fabric, which can be measured by determining a fabric's crimp factor.

4.1 Substrate

The substrate of the e-textile is the base fabric where the electronics and communication and power bus are placed. The properties of the substrate layer take into account the material and weaves used to create the e-textile. With this information, a better evaluation of the finished e-textile can be made because it sets up a comparison of how the substrate effects the application. A more in-depth description of this topic is discussed in Section 3.1.1.

4.1.1 Materials used

The materials used in creating the calculated synthesized and actual fabrics discussed in this chapter are shown in table 4.1. This table shows the cost per unit, the source and the weight of the materials. In the case of the elastic and tinsel wire, textile weights were not available from the manufacturer so 10 one-meter samples of wire were weighed on a Mettler Toledo AB-135-S/Fact Classic Plus balance to find an average weight in grams, which was then converted to Tex following ASTM Test Method D 2260.

Material Type	Tex g/1000m	Cost $/kg	Manufacturer or material source
10/2 Pearl Cotton	124	30.56	halcyonyarn.com
20/2 Pearl Cotton	62	30.56	halcyonyarn.com
8/4 Cotton Carpet Warp	310	26.22	yarn.com
16/2 Newport Linen	207	65.56	halcyonyarn.com
Tinsel Wire	662	333.33	newenglandwire.com
12/2 Bekinox® Stainless Steel VN 12/2x275/175S316 L/HT	500	266.67	Bekaert Fibre Technologies
12/3 Bekinox® Stainless Steel VN 12/3x275/175S316 L/HT	750	266.67	Bekaert Fibre Technologies
Elastic	300	42.22	Ctsusa.com

Table 4.1: Materials used in caclulations and actual fabrics

Table 4.2 depicts the fabrics that will be used in both the weight and cost analysis. As described in Chapter 2, picks and ends refer to the number of yarns in the warp and weft, and EPC and PPC are the number of ends and picks per centimeter. Every wire run consists of four tinsel wires, a washable and bendable wire, and two Bekinox® Stainless Steel wires. Three types of yarns were used in the analysis, 10/2 Cotton, 20/2 Cotton and 16/2 Linen where each is a two ply of different weighted yarn. The fabrics listed in Table 4.2 were picked specifically to show how changing the material and density of the yarn effects the e-textile properties. The first fabric listed in Tables 4.2, 4.4, and 4.9 is the baseline fabric without any electronic material woven in the substrate.

Fabric	Warp Ends	Weft Picks	Wire Ends	Wire Picks	Warp & Weft Yarn	EPC	PPC	Wire Runs Warp/Weft
Sample 1	1400	900	0	0	10/2 Cotton	14	9	0
Sample 2	1400	900	48	72	10/2 Cotton	14	9	8 / 12
Sample 3	1400	900	48	72	20/2 Cotton	14	9	8 / 12
Sample 4	1400	900	54	144	20/2 Cotton	14	9	8 / 24
Sample 5	900	900	48	72	16/2 Linen	9	9	8 / 12

Table 4.2: Fabric parameters for a square meter sample

Table 4.3 shows the set of prototypes that were woven for drape and weight analysis. All of these fabrics were woven as a single run of fabric on a 40-inch-wide, AVL Industrial Dobby Loom, IDL, with 24 harnesses.

Fabric	Weave	Warp Wire Spacing	Weft Wire Spacing	Warp &Weft Yarn	EPC	PPC
Prototype 1	Basket Weave	9.5 cm	no wire	10/2 Cotton	14	12
Prototype 2	Broken Twill	9.5 cm	no wire	10/2 Cotton	14	11
Prototype 3	Broken Twill	9.5 cm	8.5 cm	10/2 Cotton	14	11
Prototype 4	Broken Twill	9.5 cm	4.5 cm	10/2 Cotton	14	11
Prototype 5	Broken Twill with elastic	9.5 cm	8.5 cm	10/2 Cotton	14	11

Table 4.3: Prototype fabric parameters woven on 40 inch wide AVL Industrial Dobby Loom

4.1.2 Weaves

The materials and weave design determines the fabric's drape, cost, weight and density. The fabric weave alters these properties as the length of the yarn floats in the fabric design determines how a fabric drapes [12], the amount of materials used, and how dense of a weave is possible. For the purpose of the weight and cost synthesis, the weave and resultant crimp of the fabric will not be part of the evaluation; only the weave density and materials are considered. However, an analysis of the weight of the prototypes used in the drape analysis and their different weaves as well as tested crimp factor will be shown using the same algorithm used in the original weight cost analysis while adjusting for crimp. The weaves evaluated are a broken twill and basket weave, which are defined in Chapter 2.

4.2 Communication bus

As previously described in Chapter 3, the I^2C communication and power grid is a requirement in all of the lab's prototypes and is used in all of the Virginia Tech E-textile Lab applications. A bus composed of four tinsel wires provides a low power grid throughout the application. The communication grid, as it is in a woven material, is laid out in an x-y orientation. A more detailed description of the x-y orientation of the communication grid can be found in Section 4.4.

4.3 E-textile properties

An e-textile's properties vary with the materials used. Whether an e-textile is a woven, a knit, a composite or even a non-woven, certain properties are universal. The weight of the material, drape and cost are universal properties in evaluating how comfortable an e-textile might be, or whether it is better for a non-wearable application. How the e-textile drapes, its density and the weight of the application all are valid properties no matter how it is constructed. The construction of the e-textile, though, will effect each of these properties in turn. As stated previously, this thesis will only be considering the properties of woven materials and a few specific weaves.

Using the parameters of the sample fabrics laid out in Table 4.2, a set of weight and cost calculations of possible fabrics are made in Tables 4.4 and 4.9. Weave differences are not taken into consideration as these calculations are only to show the relationship of weight and cost across a small sample of materials and fabric densities. However, different weaves do alter the amount of materials used within a fabric and therefore the weight of the fabric due to how the yarn interlaces, which is measurable by determining a fabric's crimp factor. The drape analysis will analyze actual woven fabrics cut from a single bolt of variably woven fabric. These fabrics are described in Table 4.3.

4.3.1 Weight calculations

A first step in the synthesis of an e-textile is determining the potential weight of the fabric as a heavy fabric might be more useful as a rug, while a lighter, more flexible fabric would be more suited for better ease in movement on a body. For example, if a fabric for a pair of pants weighs approximately one and a half pounds, an increase of just one-half pound would increase the weight of the garment by about 33%. Changing the fabric's parameters of materials, yarn count and wire count will affect the final weight for a more comfortable garment.

Calculating an e-textile's weight requires knowing the placement and types of non-substrate materials used, the number of yarns per centimeter in both the warp and weft directions of the substrate, and the substrate material. The first two steps, Equations 4.1 and 4.2, determine the number of warp ends and weft ends in the fabric area. This is then used to determine the warp and weft weight of the substrate by multiplying the number of ends by their respective yarn length and weight as shown in Equations 4.3 and 4.4. Similar calculations, Equation 4.5, for the tinsel wire and stainless steel weight are added together for a total e-textile weight.

$$number\ warp\ ends = EPC \times width\ of\ fabric\ in\ cm \tag{4.1}$$

$$number\ weft\ picks = PPC \times length\ of\ fabric\ in\ cm \tag{4.2}$$

$$warp\ weight = number\ warp\ ends \times length\ of\ fabric\ in\ cm \times \frac{1m}{100cm} \times \frac{yarn\ tex}{1000m} \tag{4.3}$$

$$weft\ weight = number\ weft\ picks \times width\ of\ fabric\ in\ cm \times \frac{1m}{100cm} \times \frac{yarn\ tex}{1000m} \tag{4.4}$$

$$\begin{aligned} other\ material\ weight = {} & number\ of\ material\ picks \times length\ of\ material \times weight \\ & + number\ of\ material\ ends \times length\ of\ material \times weight \end{aligned}$$

Table 4.4 shows the calculated weights of the sample fabrics listed in Table 4.2 using Equations 4.1 through 4.5. Each of these fabric calculations show the weight per meter of the material, the grams per square meter of material needed, the % of a square meter sample and a calculated weight of the proposed fabric for comparison.

Table 4.4 shows the relationship between the weight of the fabric and the choices of materials chosen for the e-textile application. Sample one, woven with a 10/2 cotton and a weave density of 14 ends and nine picks per centimeter, is the substrate of the e-textile without any additional materials or tinsel wire and has a calculated base weight of 286 grams for one square meter of the substrate with these parameters. Adding a wire grid to the substrate, as shown in sample 2, that equates to 12 weft wire runs and eight warp to the base substrate, increases the calculated weight by 35% to 359g/m^2 for the e-textile. Simply changing the substrate material from a 10/2 cotton to a 20/2 cotton, while maintaining the same wire grid and weave density, as seen in samples two and three, decreases the weight of the e-textile by 40%. Similarly, increasing the number of wire runs within fabrics, Sample 3 and Sample 4, increases the fabric's overall weight by 17%. Sample 5 shows using a different base material, 16/2 linen, than Samples 2 and 3, but using identical wire configurations and PPC results in a heavier calculated weight despite a reduction in the amount of ends per centimeter in the warp. To further illustrate this point, the choice of using a 20/2 Cotton fabric, Sample 3, results in a fabric that weighs less per square yard with a wire grid than the base fabric Sample 1 with no wires.

This analysis shows the obvious connection between the weight of the e-textile and the materials used in manufacturing. In these instances, the wire and stainless steel weight effect the weight of the e-textile, while the choice of a substrate material is also a factor in the overall weight of the e-textile. Therefore, weight cuts can be made by reducing the amount of materials by changing the wires; however a weight reduction can also be made by changing the substrate material.

The calculations in Table 4.4 were estimated by the materials' weights and sizes by their Tex weight, grams per 1000 meters, and weave density. To determine the accuracy of the fabric calculations, an evaluation of the weight of the prototypes woven for the drape tests, as previously shown in Table 4.3, was performed

Fabric	Material	g/m	g/m^2	%of m^2	Total Calculated Weight
Sample 1	warp - cotton 10/2	0.124	174	61	
EPC: 14 PPC: 9	weft - cotton 10/2	0.124	112	39	
	Tinsel Wire	0	0	0	
	12/2 Stainless Steel	0	0	0	286g
Sample 2	warp - cotton 10/2	0.124	174	48	
EPC: 14 PPC: 9	weft - cotton 10/2	0.124	112	31	
	Tinsel Wire	0.662	53	15	
	12/2 Stainless Steel	0.5	20	6	359g
Sample 3	warp - cotton 20/2	0.062	87	40	
EPC: 14 PPC: 9	weft - cotton 20/2	0.062	56	26	
	Tinsel Wire	0.662	53	25	
	12/2 Stainless Steel	0.5	20	9	216g
Sample 4	warp - cotton 20/2	0.062	87	33	
EPC: 14 PPC: 9	weft - cotton 20/2	0.062	56	22	
	Tinsel Wire	0.662	85	33	
	12/2 Stainless Steel	0.5	32	12	259g
Sample 5	warp - linen 16/2	0.207	186	42	
EPC: 9 PPC: 9	weft - linen 16/2	0.207	186	42	
	Tinsel Wire	0.662	53	12	
	12/2 Stainless Steel	0.5	20	5	446g

Table 4.4: One square meter calculated sample fabric weights with different materials and wire runs

using both the weight calculation algorithm and weighing samples of the prototypes on a MT balance. The results shown in Table 4.5, show a 9% difference of the actual fabrics versus the calculated fabrics. The difference is related to the weave of the fabric, as the initial weight calculations did not take into account the crimp of the materials due to the fabrics' weave.

Fabric	EPC/PPC	Weave	Sample Size warp x weft yarns	Weight	Calculated Weight	%Difference
Prototype 1	14 / 12	Basket Weave	32 x 76.5 cm	96.7g	88.3g	8.7%
Prototype 2	14 / 11	Broken Twill	30.5 x 75.5 cm	89.8g	80.2g	10.7%
Prototype 3	14 / 11	Broken Twill	32 x 76 cm	105.6g	95.8g	9.3%
Prototype 4	14 / 11	Broken Twill	31.5 x 75 cm	111.8g	101.5g	9.2%
Prototype 5	14 / 11	Broken Twill w/elastic	30.5 x 75 cm	98.6g	91.5g	7.2%

Table 4.5: Weight of fabric prototypes using Mettler Toledo AB-135-S/Fact Classic Plus

Adjusting the calculated weights of the prototypes for the percentage of yarn crimp results in a more accurate weight analysis and calculation than initially found in Table 4.5. The fabrics' crimp was determined by following manual method in Test Method D 3883 from the 2006 ASTM Manual. Briefly, the manual method involves cutting 300-mm-length samples in both the fabrics' warp and weft directions and marking two benchmark lines perpendicular to the yarns being measured 250 mm apart, which is the in-fabric distance, F. For each sample, 10 unraveled samples of the yarns are then extended by hand across a ruler, without unnecessarily stretching the yarn, until the yarn is no longer undulating for a straightened yarn distance, Y. Equation 4.5 references the formula for determining the crimp percentage calculations found in Table 4.6 given in ASTM Test Method D3883. These results were not acquired in a properly humidified room, nor were the initial weight measurements, due lack of access to a 65% humidified room per normal ASTM specifications in Practice D 1776.

$$Yarn\,Crimp\;=\;\frac{straightened\,yarn\,distance(Y)-yarn\,in\,fabric\,distance(F)}{yarn\,in\,fabric\,distance(F)}\times 100 \qquad (4.5)$$

To recalculate the weights of the prototypes to reflect the crimp analysis, the length of the yarn samples are multiplied by the measured crimp factor. Adjusting Equations 4.3 and 4.4 for crimp simply multiplies the length of yarn by the crimp factor and is shown in Equation 4.6 for the warp weight. For example, Prototype 1's warp yarns are measured to be 32.5 cm, which when multiplied by the crimp factor adjusts to 37.4 cm. This factor is then used in the weight analysis.

Fabric	F in fabric distance	Y average of 10 sample yarns straightened	% Crimp
Prototype 1			
Warp	250 mm	288 mm	15%
Weft	250 mm	259 mm	4%
Prototype 2,3,4,5			
Warp	250 mm	287 mm	15%
Weft	250 mm	263 mm	5%

Table 4.6: Measured Crimp values of prototypes from Table 4.5 of 10/2 Cotton Yarn using the manual method in ASTM Test Method D3883

$$warp\ weight = number\ warp\ ends \times (length\ of\ fabric\ in\ cm * \%crimp) \times \frac{1m}{100cm} \times \frac{tex}{1000m} \quad (4.6)$$

Prototype 1	Calculated Weight	% Crimp	Recalculated Weight
Warp Yarns	42.5g	15%	48.9g
Weft Yarns	36.4g	4%	37.9g
Tinsel Wire	6.8g	15%/4%	7.8g
Stainless Steel	2.6g	15%/4%	2.9g
Total Weight	88.3g		97.5g
Actual Weight	96.7g		96.7g

Table 4.7: Prototypte 1 calculations with crimp factor analysis

Table 4.8 shows the recalculated weights of the prototypes using the results of the crimp analysis with the recalculations being less than one gram difference from the actual weights of the prototypes. ASTM Test Method D 3883 states that the measured precision of this yarn crimp test for a single-operator has been determined to be 4.7%.

Fabric	Weave	Sample Size in cm	Calculated Weight without crimp	% Crimp Warp/Weft	Re-calculated Weight	Actual Weight
Prototype 1	Basket Weave	32 x 76.5	88.3g	15 / 4	97.5g	96.7g
Prototype 2	Broken Twill	30.5 x 75.5	80.24g	15 / 5	89.1g	89.8g
Prototype 3	Broken Twill	32 x 76	95.82g	15 / 5	105.8g	105.6g
Prototype 4	Broken Twill	31.5 x 75	101.5g	15 / 5	111.6g	111.8g
Prototype 5	Broken Twill w/elastic	30.5 x 75	87.98g	15 / 5	97.24g	98.6g

Table 4.8: Weight of fabric samples using MT scale with crimp percentage analysis

4.3.2 Cost calculations

Due to the electronic materials, the cost of an e-textile can be greater than for non-technical textiles. Specifically, a wired communication and power grid within the fabric requires a conductive material. Determining the optimal placement of the more expensive materials will help reduce the cost per yard. Table 4.9 uses the same fabrics as in the previous weight analysis, where the base fabric, Sample 1, shows the cost of one square meter of the material prior to the addition of any e-textile components.

The cost of the tinsel wires and stainless steel will increase much more dramatically as more resources are used in relation to the cost of the base fabric. Table 4.9 shows the overall cost of one square meter of fabric Sample 2 is $31.45 where 73% of the cost is related to the stainless steel and wire bus in the fabric. As more wire runs are placed within the fabric, the cost of the wire increases in proportion to the number of runs placed in the fabric. This is illustrated when comparing fabric Samples 3 and 4 with identical warp and weft density but a 50% increase in weft wire density results in a 50% increase in the cost of the fabric. Fabric Sample 5, with a less dense weave but higher warp and weft cost, has a 53% price increase from Sample 2, which has the same wire density but less expensive substrate costs. Some of the increases in cost can be mitigated by a lower price point for the materials and buying in bulk. However, better wire placement in the e-textile easily balances not only the weight but the cost of an e-textile.

4.3.3 Drape

The measurement of the drape of a fabric shows how a fabric will act once deformed on an object or body [12]. This is important when proper analysis requires that the sensor either not move on the body, or be placed at a particular point for accurate measurements and for wearability. The interplay of how a fabric

Fabric	Warp meters/cost	Weft meters/cost	Tinsel Wire metersyards/cost	12/2 SS meters/cost	Total Cost per meter^2
Sample 1 EPC: 14 PPC: 9	1400 / $5.32	900 / $3.33	0	0	$8.65
Sample 2 EPC: 14 PPC: 9	1400 / $5.32	900 / $3.33	80 / $17.60	40/ $5.20	$31.45
Sample 3 EPC: 14 PPC: 9	1400 / $2.66	900 / $1.71	80 / $17.60	40 / $5.20	$27.17
Sample 4 EPC: 14 PPC: 9	1400 / $2.66	900 / $1.71	128 / $28.16	64 / $8.32	$40.85
Sample 5 EPC: 9 PPC: 9	900 / $12.60	900 / $12.60	80 / $17.60	40 / $5.20	$48.00

Table 4.9: Fabric costs per square meter of the five sample fabrics

drapes for wearability with the addition of electronic components is touched on in [13], however showing how the addition of different materials, different weaves and how the wire spacing specifically effects the e-textile's drape is shown in this section.

A low drape coefficient shows a more drapeable or object-formable fabric, while a higher drape coefficient shows a more stiff fabric. The fabrics used as test controls were chosen because the basket weave is common for a dress shirt, while the twill fabric is common in jeans and suit jackets, thus providing a commonality to understand the analysis of the drape coefficient.

The weights for the drape coefficient were measured using the FRL Drapemeter [3] and a Mettler-Toledo Model PG 503-S Delta Range scale [15]. Briefly, the method involves placing a fabric sample on a pedestal on a light table and weighing paper traces of the shadow of the fabric to calculate a drape coefficient. Specifically, a 4-inch and a 10-inch paper circle are cut from the same piece of tracing paper and weighed. A fabric sample is cut using the same 10-inch die as the paper circle and placed on a 4-inch circular pedestal on a light table. The shadow of the draped fabric is then traced onto the 10-inch paper circle on a glass top above the pedestal. A final weight is taken of the 10-inch paper circle after the fabric shadow relief is cut from the paper. An illustration of this process is shown in Figure 4.1. From these weights, the drape coefficient can be calculated.

$$Drape\ Coefficient(F) = \frac{Weight\ cut\ circle - Weight\ 4\ in\ circle}{Weight\ 10\ in\ circle - Weight\ 4\ in\ circle} \times 100$$

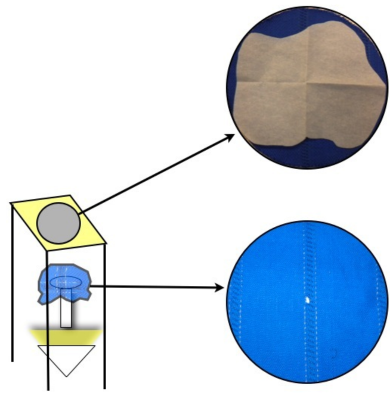


Figure 4.1: Illustration of FRL Drapemeter®

Two control fabrics with the same fabric density and material, but different weaves, a basket and broken twill, were analyzed for their drape coefficient. As expected, because a fabric with more floats and fewer interlacings will drape more easily, the broken twill was more drapeable than the basket weave by 16%, as shown in Table 4.10. Comparing both control fabrics with tinsel wire at a 9.5-cm interval in the warp resulted in a difference of a drape coefficient of only 5%, showing that the tinsel wire dominates the drape property of the fabric. However, Prototype 4, the broken twill fabric with 4.5-cm tinsel wire spacing interlaced in the weft direction and 9.5-cm spacing in the warp, resulted in a 10% lower coefficient than Prototype 3, a broken twill with 9.5-cm by 8.5-cm wire spacing. The drape test shows that the weight of the wire overrides the stiffness of the tinsel wire in the 4.5-cm weft wire spacing. This resulted in a lower coefficient showing that the accumulated wire weight from the greater wire density will overcome the stiffness of the tinsel wire.

Fabric	Weave	warp wire spacing	weft wire spacing	drape coefficient F
Prototype 1a	Basket Weave	ss only	no wire	69%
Prototype 2a	Broken Twill	ss only	no wire	53%
Prototype 1	Basket Weave	9.5 cm	no wire	74%
Prototype 2	Broken Twill	9.5 cm	no wire	70%
Prototype 3	Broken Twill	9.5 cm	8.5 cm	78%
Prototype 4	Broken Twill	9.5 cm	4.5 cm	69%
Prototype 5	Broken Twill w/elastic	9.5 cm	8.5 cm	50%

Table 4.10: Drape coefficient of sample fabrics measured - face side only of 10/2 cotton substrate

With the addition of elastic in the weave, the same Broken Twill fabric with tinsel wire grid of about 9-cm reduces the stiffness of the fabric by 28%. Thus, this shows that the mechanical properties of the materials affect the e-textile and are easily adjustable for different applications. A woven garment with the addition of elastic will be much more form fitting and comfortable with fewer wire runs than the similar drape coefficient Broken Twill fabric with 4.5-cm weft wire spacing. This effectively reduces the cost and weight of the fabric e-textile and the size of the communication power grid without altering the wire configuration or compromising on comfort.

Basically, our results show that making the garment heavier with greater wire or yarn density makes the fabric more drapeable and more comfortable for a clothing application. But, the added weight may cancel out the comfort from the greater drapeability. Adding elastic, however, reduces weight, while increasing wearability.

4.4 Wire and sensor placement

For a woven e-textile, the wire runs may be placed in both the weft and warp directions in a variety of spacing configurations. Properly determining the wire grid spacing requires analyzing the distances a sensor or contact could be placed on the fabric. The two ways that the spacing requirements are analyzed in this section are the maximum distance a desired placement of a sensor may be placed from both the weft and warp direction and an area measurement of how many wire runs are available within a certain space.

The maximum distance a point on the fabric might be to a wire run is related to sensor placement. If a sensor needs to be placed a specific distance or at a specific point, such as on a garment for shape sensing, how close to the desired spot can we place the sensor with different wire grid configurations? The consideration of one point on the fabric is easily adjusted as the garment pieces can be shifted across the e-textile before cutting to accommodate a particular placement of a sensor. Requiring multiple points on the wire grid within a predetermined acceptable error range, however, needs a properly configured grid.

To show the grid placement in the fabric, figure 4.2 depicts how the wires are placed within the fabric. Each of the three sections in the figure shows the base fabric in white and blue with the wire runs in red. Looking at figure 4.2 (a.), the maximum distance that a point on the fabric to the wire grid is half the width of the weft wire run along the warp yarns and no intersection along the weft yarn unless already on the wire grid, as shown by the green line. The same holds true with figure 4.2 (b.), however in the warp direction. A more redundant fabric has wire runs in both directions as shown in figure 4.2 (c.) where any point on the fabric is a maximum of half the smallest width wire run in either direction.

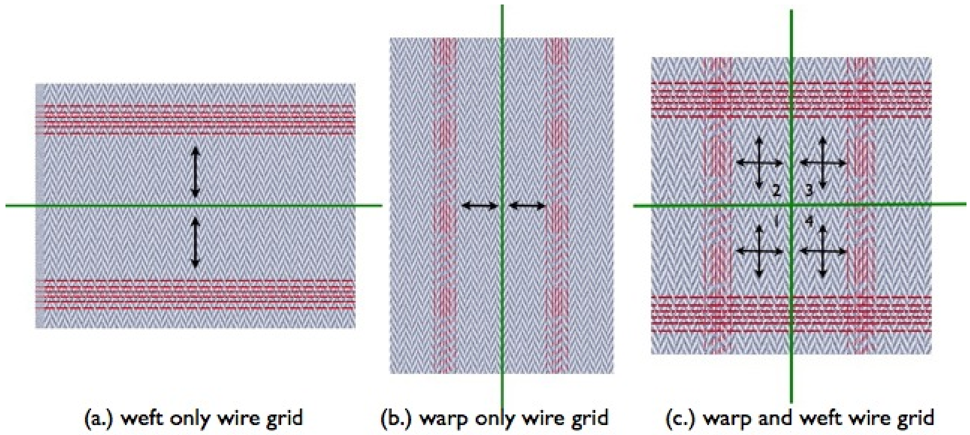


Figure 4.2: Wire placement in relation to the fabrics warp and weft

One-point selection of the wire grid selection allows that one wire run be placed exactly on the point that the sensor should be best placed. Multiple point selection of wire runs on the e-textile, unless a straight line, requires adjusting the grid placement or size to best fit necessary points.

A major challenge in wire placement is being able to use the same fabric to make different-sized garments where the sensors are placed within an acceptable error range of a particular point on a wearer's body. Differently sized garments will not have the same sensor placement and will need slightly varied wire spacing to accommodate the garment sizes. Similarly, as the garment sizes change, so do the body types within a range of sizes. This aspect of altering the wire grid for on-body proper sensor placement is part of the future work.

The fabric synthesis elements described in this chapter are the main tools in the expanded design flow. These pieces of the e-textile are interrelated and have properties that are alterable for varied results. From the substrate materials to wire placement, each variable becomes an integral part of the whole e-textile application. With knowledge of these variables and how they are able to effect the mechanical and electrical aspects of the e-textile, an e-textile designer is able to better design a more robust application.

Chapter 5

Sensors as Fibers

Our experiments with a stainless steel resistive network within the e-textile highlights the use of the expanded design flow. This work shows how the textile and sensors interplay on an e-textile that allows the sensor to be a material within the fabric and not just an e-tag attached to the wires on the grid as a circuit board. The creation of a dynamic resistive network in the substrate allows for sensors to be placed on a garment where circuit boards cannot be comfortably attached on a body, such as on the backside of the garment. If the fiber sensor is woven properly, only pressure against the node will result in activation of the node.

Previous research in the Virginia Tech E-textiles Lab used a stainless steel resistive network incorporated into a rug application that tracked a person's location while walking across a rug as an example of a large-scale e-textile[8]. Woven in parallel with the tinsel wire bus, as described in Chapter 4, a network of Bekinox® stainless steel wires was connected to the e-tags as a distributed resistive network. Research into a resistive and thermal sheet by Banaszczyk et al. [5] considers an entire fabric composed of resistive material for use in antennas and derives how to determine the resistance for a large sheet of resistive material. This work is differentiated by its focus on specific sensor placement and resistance measurements within a fabric.

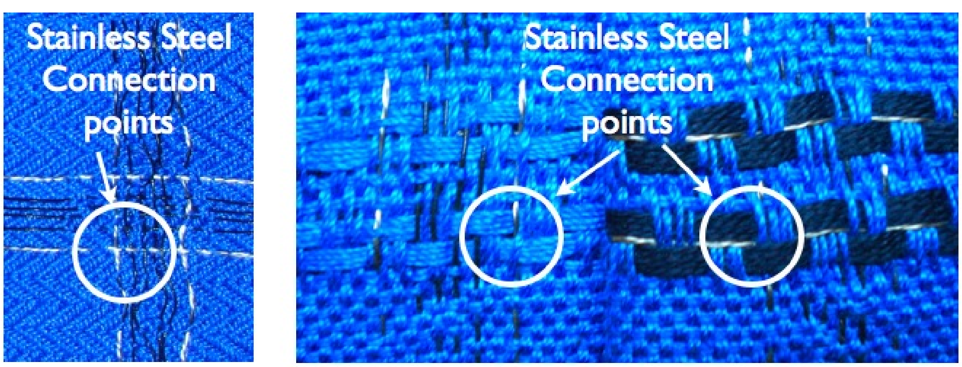
In this work, we considered a separate, useful dynamic resistance network that can be used in spot measurements as in textile electrodes [18] and resistive sensors. One such application for the Virginia Tech E-textile Lab is shape sensing, in which, placing the resistive e-textile nodes on the body may be useful in determining if a person is sitting or leaning, if a sleeve is rolled or if a limb is bent in conjunction with other sensor data.

In this chapter we consider the sensors as fibers in a resistive network in a variety of woven fabrics and configurations. We classify the different resistive fabrics and the evolution of e-textile prototypes and show how a resistive network activity of the e-textile was determined by the weave. A resistive network and its configurations are considered along with potential uses and finally, we test a number of e-textile prototypes using sensors as fibers.

5.1 Resistive fabrics

As we prototyped different e-textile applications, a series of sensors-as-fibers weaves evolved, resolving into two categories: single- and double-layered weaves. Single-weave sensors were used to create an overall resistive fabric, while double-weave sensors were developed for a more precise sensor node. This progression from various single weaves to more complex double weaves was a direct result of the electrical resistance of the Bekaert Bekinox® stainless steel as a sensor. Its mechanical properties were altered within the e-textile depending upon the application's weave. Each of these fabric's materials created for this research included Bekaert Bekinox® Stainless Steel, tinsel wire for a communication-power bus, and a fabric substrate made of cotton and/or wool.

The variations of different weaves explored for the sensors included floating the warp sensors on top of the weft sensors, inserting elastic around the sensors to separate the wires, inserting stuffer yarns between the wires, and double weave fabrics. Figure 5.1 shows two variations of an e-textile with a resistive network, Figure 5.1(a), where floating of the stainless steel wires was used to create the resistive sensor, and Figure 5.1(b), where a double weave was used for pocket sensors in the e-textile.



a.) b.)

Figure 5.1: Stainless steel as sensor by floating wires (a), and double weave (b).

5.1.1 Resistive properties of materials

The fabric is composed of both resistive and non-restive materials, of which the resistive material has specific electrical properties that are dependent upon its length, ply, insulation, tension, material and whether it is a filament or staple yarn. Table 5.1 shows the nominal electrical resistance by the manufacturer of the three types of resistive yarns and one resistive wire used in these experiments.

Material	ohms/meter	ply	insulation
12/2 Bekinox® Stainless Steel	14	staple	none
VN 12/2x275/175S316 L/HT		2 ply	
12/3 Bekinox® Stainless Steel	9	staple	none
VN 12/3x275/175S316 L/HT		3ply	

Table 5.1: Resistive material properties

Specifically, the resistance of a yarn is determined by the length of the yarn as the resistance of the stainless steel is variable depending upon its length and nominal resistance as in equation (5.1).

$$R_{yarn} = (length\ in\ meters) * (R\ of\ material\ per\ meter) \tag{5.1}$$

5.1.2 Single-layer weave

A single-layered weave consists of two sets of interlaced yarns, warp and weft, at 90 degree angles; some common fabrics that are easily recognizable as single layered weaves are tablecloths and jeans. Prior work in the Virginia Tech E-textile Lab [8] [19] using Bekinox® Stainless Steel used variations of a single layered weave, a broken twill and plain weave, respectively. Figure 5.2 depicts a cross section of a plain weave as a single layer fabric .

Figure 5.2: Single plain weave cross section

Using fibers as sensors as a variable resistive network to monitor movement, was the basis of weaving stainless steel into a large scale rug e-textile application, which was developed by Graumann et al. [8]. This resistive network, woven in a three-inch grid, was used as an adjunct to the piezo sensors to determine where a foot fell on the rug as a person walked across. The resistive network was only monitored for a change in resistance, as such no true open or closed state of the e-textile nodes was needed to monitor the movement. However, problems occurred due to the lack of variability in resistance in the application due to the tightness of the fabric's weave.

The first prototype for the large scale e-textile work [8] was a loose single-layered weave with the tinsel wires and stainless steel woven in the same heddle (eye in the harness that the yarn is threaded through) with a warp wire. The second weave, shown in Figure 5.3, which was the final large-scale prototype, separated the tinsel wire and steel onto their own harnesses to allow for the creation of more specific floats for the e-tags to be attached. In making this change, although a tighter weave was woven, the resistance of the large-scale textile did not change as much as desired for proper e-tag measurements.

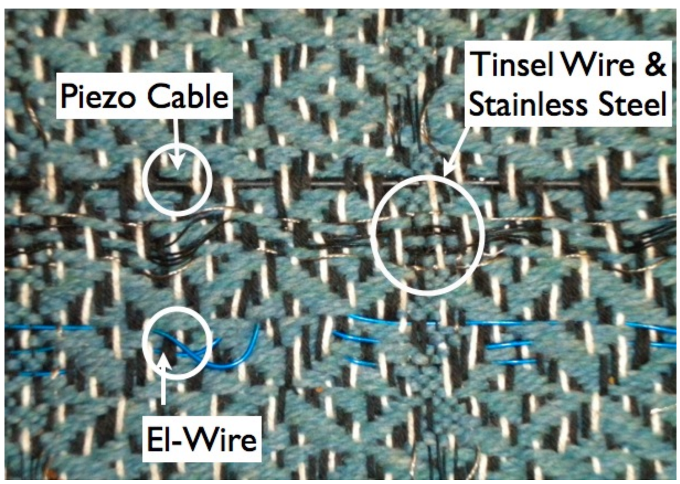


Figure 5.3: Intel Rug - Single layer broken twill weave

In order to mimic a looser weave for the resistive network, and therefore achieve more variability in resistance, a series of stuffer yarns was woven in by hand to separate the stainless steel warp and weft yarns. This solution allowed for a more open circuit, and when the stainless steel node was depressed, the change in resistance was of a greater magnitude than the original application. By only altering one property of the e-textile – the weave of the stainless steel – a more robust e-textile application was created without having to alter the application's electronics or the other layers of the substrate. The final prototype for the large-scale e-textile, shown in use in Figure 5.4, follows a person as they walk across the rug. Embedded in the rug, woven electroluminescent wires can be seen lighting small arrow patterns used to highlight the direction of the movement.

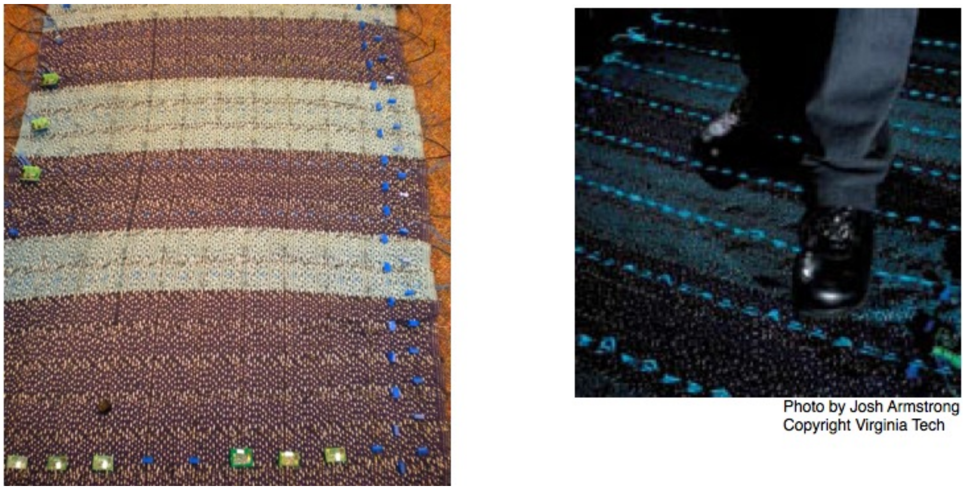


Figure 5.4: Intel Rug - Large scale e-textile application

The next set of prototypes focused on weaving a consistent variably resistive network. A number of alternate weaves were woven, including both stuffer yarns around the weft steel to lift the yarns apart and more of a float between the warp and weft steel yarns, mimicking the hand-woven stuffer yarns in the large scale prototype. Each of these variations did not result in a completely open circuit, but the expected results were a change in resistance not an open or closed circuit so the results were acceptable within the scope of the large scale e-textile application. This research, however, spawned a solution that might result in a closed circuit upon only external pressure; the double weave.

5.1.3 Double-weave or complex fabrics

A double weave is defined as two fabrics woven in unison on the same loom that do not have interlaced warp and weft ends, however, the two fabrics are stacked on top of one another in the warp [12]. In order to create a double weave, at least four harnesses are required, two for each layer, where each layer is woven in an alternating succession one weft yarn at a time. A visual representation of a cross section of a double weave in Figure 5.5 shows two distinct layers of fabric. Previous research in e-textiles using complex weaves can be seen in the wearable motherboard where the e-textile is woven as a tube on the loom [17].

Three uses of double-weave fabrics include weaves for wider width fabrics, pillows woven and stuffed on the loom, and tube fabrics commonly used for industrial conveyor belts. Each of these complex weave options results in a fabric with either two large distinct layers, as in the pillow, a circular effect, as in the tube fabric, or a wide width fabric, where the two layers do not interconnect at all. Unfortunately, these options do not

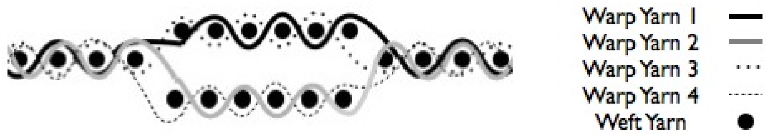


Figure 5.5: Double-weave cross section

result in a more precise sensor placement within the e-textile. As two separate stainless steel yarns in the warp and weft, each produces a fabric pattern that does not result in a particular yarn closing the circuit due to inadvertent slippage.

However, small areas of a double weave embedded within the e-textile do give the intended effect of two separate layers for the circuit, while maintaining the position of both pieces of fabric within the e-textile. In particular, the double weaves evaluated in this research were woven using the existing warp setup on the loom while creating small pocket double weaves within the weft direction, then returning to a single-layer weave. Essentially, this creates pockets of fiber sensors, or textile electrode nodes placed periodically through the e-textile.

Separating the stainless steel on different layers allows for an open circuit until the node is depressed where, within the layers of the two fabrics, the stainless steel sensors connect to close the circuit. This dynamic resistive network within a narrow double-weave band in the e-textile was a change from the single-weave resistive network, in Section 5.1.2, and shows how the electronic and mechanical aspects of the e-textiles are intertwined and symbiotic. This creation of the double-weave dynamic resistive network allows for sensors to be placed on a garment where circuit boards cannot be comfortably attached. For example, using a resistive fiber sensor on the posterior of the garment to help determine if a subject is sitting down versus squatting is a much more comfortable option than placing circuit boards on the backside of the garment. If the fiber sensor is woven properly, only a pressure against the node will result in activation of the node.

Five different double weaves were woven on the same warp to test this interplay. Each of these weaves was chosen to represent possible placement of the warp and weft yarn sensors in the double weave in relation to each other by alternating the resistive material from the top layer to the bottom layer. Two prototypes include elastic. A full description of the difference between the weaves is shown in Section 5.3.

5.2 Resistive network

As discussed previously in Section 5.1, embedded within the fabric substrate, the resistive network is the set of perpendicularly interlaced, woven, resistive material with each potential connection considered a node on the network, as seen in Figure 5.1. The nodes are activated and interconnected with pressure from outside the fabric as well as from within due to the fabric weave. Ideally, the nodes will only connect upon external pressure, realistically, the angle of the node contact and the fabric weaves may alter the expected resistance and create an unexpected measurement.

Basically, the nodes are resistive switches that are either in an open state when not activated and closed state when activated. A closed state occurs when the resistive materials only maintain contact during an external force, while the node will be considered open if any contact is made between the resistive materials.

5.2.1 Nodes and network configurations

As a single node is determined by two perpendicular resistive materials in potential contact, there must be a minimum of two resistive wires in any woven resistive network. The intersections are classified as dynamic or static nodes, where the dynamic nodes are activated from outside forces, while the static nodes are in contact due to the weave or permanent connections. Activating different nodes by alternating connections to power, ground and sensors will change how the fabric is used and the resistance of the fabric. There are five varieties of networks that can be distilled from the many possible node configurations: single and multiple nodes, with multiple activated nodes forming either a straight line, a grid-like structure or unconnected nodes within the grid.

5.2.2 One node

In a resistive, woven e-textile, a node is defined by where the warp and weft materials intersect as previously described in section 5.2. To calculate the equivalent resistance of a single node, one first determines the resistance value of the materials by finding the distance of the voltage source to the contact point and multiplying it by the nominal resistive value of the material as defined in Equation 5.1. To determine the value of two resistive yarns at one node, a simple resistors-in-series formula is used with the calculated R_{yarn} of the two resistors as shown in equation (5.2) and depicted in Figure 5.6. A secondary way to easily estimate the resistance of the simple circuit, for identical materials, is to calculate the total distance the node is from both the voltage source and ground, multiplied by the R_{yarn} value of the material. The closer the node is to the voltage source, the lower the R_{eq} value of the node. One-node resistance calculations work in both a grid and line-point scenario where only one node is activated.

$$R_{eq} = (R1_{yarn} + R2_{yarn}) \tag{5.2}$$

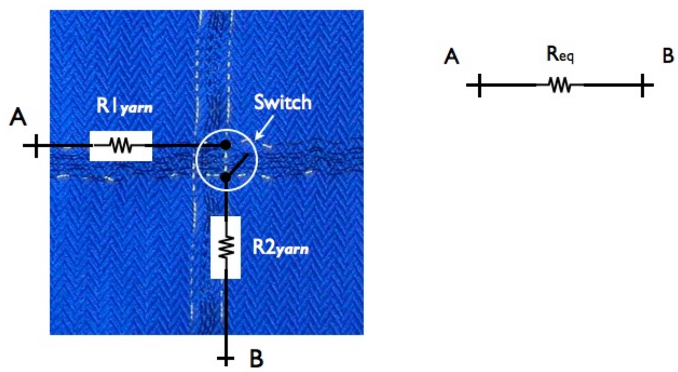


Figure 5.6: Simple one-node circuit and its equivalent resistance

Simply changing the distance the node is from the voltage source varies R_{eq}. One use of a one-node resistance measurement is on a line of single nodes where the R_{eq} of the circuit will determine the distance of the node that is depressed. Consider a series of resistors as shown in Table 5.2. The higher the resistance of R_{eq} for a particular node, the further it is from the voltage source.

Node	dist. R1	dist R2	$R1_{yarn}$	$R2_{yarn}$	R_{eq} of R1,R2
A	10.16cm	2.54cm	1.42	0.36	1.78
B	20.32cm	2.54cm	2.84	0.36	3.20
C	30.48cm	2.54cm	4.27	0.36	4.63
D	40.64cm	2.54cm	5.69	0.36	6.05
E	50.8cm	2.54cm	7.11	0.36	7.47
F	60.96cm	2.54cm	8.53	0.36	8.89
G	71.12cm	2.54cm	9.96	0.36	10.32
H	81.28cm	2.54cm	11.38	0.36	11.74

Table 5.2: Calculated R_{eq} of one node using Series Equation 5.2 for two wire spacing scenarios of 14 ohm/meter resistive yarn.

5.2.3 Line array

A line array is a collection of nodes along a single artery where the resistance is dependent upon the distance to the voltage source. Activating multiple nodes simultaneously will alter the total resistance measured. As stated previously, this may be used to measure the distance of the activated node, however, this may also be used to create a variable resistor, an inline resistor or even a potentiometer within the fabric.

A resistive network deployed on a single path with intersecting resistive materials shows how the resistive material spacing determines the relative accuracy of the network. If the spacing is too close, the R_{eq} values will be too close to accurately determine which node was activated. Figure 5.7 shows a typical line resistive network that might appear in an e-textile: one major artery where the resistance is dependent upon the distance to the voltage source with five potential connections. With no connections, there is not an active network. Accordingly, as the nodes are activated, the network changes its resistance value.

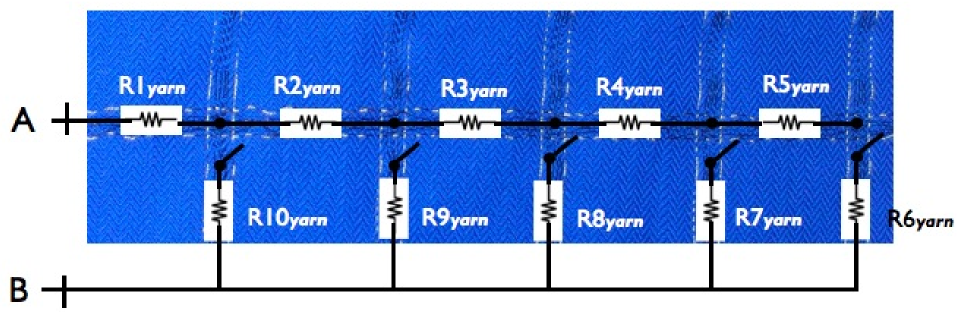


Figure 5.7: Nodes and grid line network configurations

5.3 Double-weave testing results

To determine if the double-pocket-weave e-textile best fits the properties of an open resistive switch, a series of pressure tests was performed on the e-textile prototypes listed in Table **??**. The e-textiles were woven with slight variations between the different prototypes by alternating how the resistive materials were placed within the layers. The variations chosen highlight the layers created in the double weave by placing the stainless steel in various combinations of layers, from opposing layers to the same layer. In addition, the use of elastic was woven in two fabrics to separate the stainless steel yarns more consistently through repeated use of the e-textile due to the higher nature of recovery of the weave.

The fabric prototypes consist of 10/2 pearl cotton in the warp and weft, stainless steel, tinsel wire, and two prototypes contain elastic. The main fabric design is a two-yarn basket weave, while the pocket double weave pattern is a four-yarn basket weave. A navy blue yarn was used in the weft for the bottom fabric to differentiate the two layers visually and the warp and weft tinsel wire runs are placed at four-inch intervals to intersect within the pocket weaves. With three weft and eight warp wire runs laid out in a grid, each prototype consists of 24 intersections to total 96 nodes for each pocket resistive e-textile for testing. Figure 5.8 shows a single sample node from the five prototypes showing both the front back face of the double weave. All of the pototypes were woven on a single warp run with a 24 harness AVL Industrial Dobby Loom.

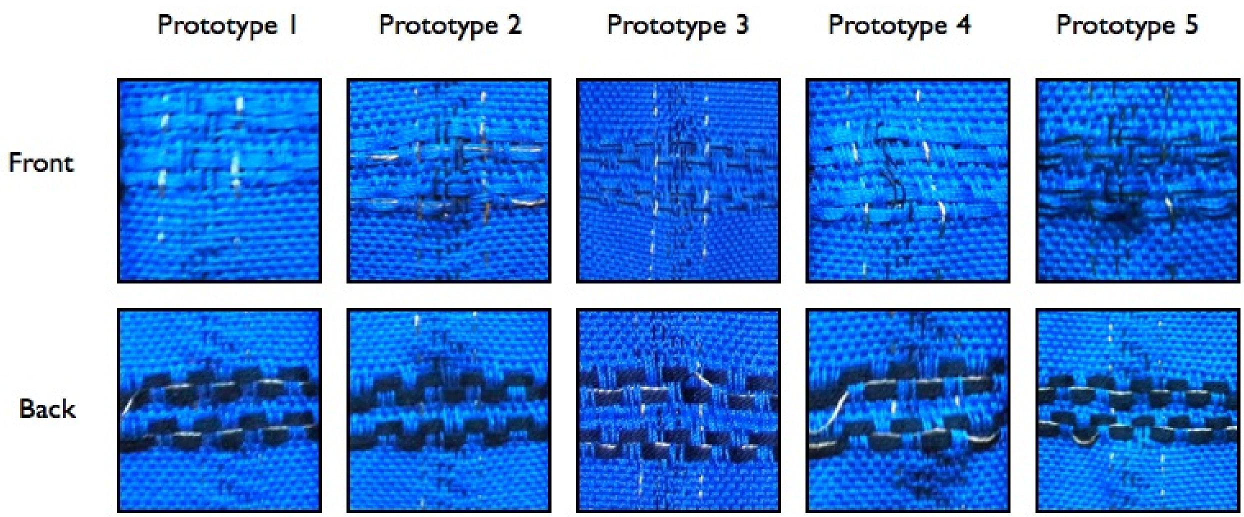


Figure 5.8: Double-weave prototype images of front (top row) and back face (bottom row) of the woven e-textiles

In addition to alternating the steel on different fabric layers, a secondary pattern was placed in the double-pocket weave to test slight differences in how yarn floats and placement effect the e-textile resistive prototypes. Each set of tinsel wires in the warp consists of two stainless steel yarns on opposing sides of the tinsel wires while the weft weave inserts two stainless steel yarns to create four resistive nodes in the one-half-square-inch wire intersection. The four-yarn basket double-weave allows for the conductive stainless steel yarns to intersect in a small pocket of fabric and is interspersed with a smaller single-weave two yarn basket weave. Figure 5.9 shows Prototype 3 with the four nodes, and weft and warp conductive yarns identified. Each prototype has 24 of each sensor node type – Node 1, Node 2, Node 3 and Node 4 – resulting in 96 total sensor nodes per tested e-textile.

Alternating the pattern of how the stainless steel floats in the warp and weft allows for variations of each pocket resistive e-textile by creating different nodes for testing. A visual representation and written description of the different types of conductive yarn placement is broken down in Table 5.3 into different conductive

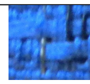
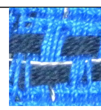
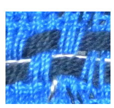
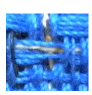
Warp/Weft	Type	Image	Description
warp	Type A		Warp yarn floats over 4 weft yarns, then under 4 weft yarns on the bottom of the top layer of the double weave. Intersection point for the conductive yarns is where the warp yarn passes under the top layer weft yarns.
warp	Type B		Warp yarn floats under 4 weft yarns, then over 4 weft yarns on the bottom of the top layer of the double weave. Intersection point for the conductive yarns is where the warp yarn passes under the top layer weft yarns.
weft	Type A		weft conductive yarn over 4 warp yarns then under 4 warp yarns on bottom layer of double weave fabric. The intersection point for the conductive yarns is where the weft conductive yarn switches from over the warp yarns to float under the warp yarns. This view is from the reverse side of the fabric so the perspective of the image is reversed.
weft	Type B		weft conductive yarn under 4 warp yarns then over 4 warp yarns on bottom layer of double weave fabric. The intersection point for the conductive yarns is where the weft conductive yarn switches from under the warp yarns to float over the warp yarns. This view is from the reverse side of the fabric so the perspective of the image is reversed.
weft	Type C		weft conductive yarn floats on top layer of fabric under warp conductive yarn
weft	Type D		weft conductive yarn floats on top layer of fabric over warp conductive yarn

Table 5.3: Warp and weft weave node types

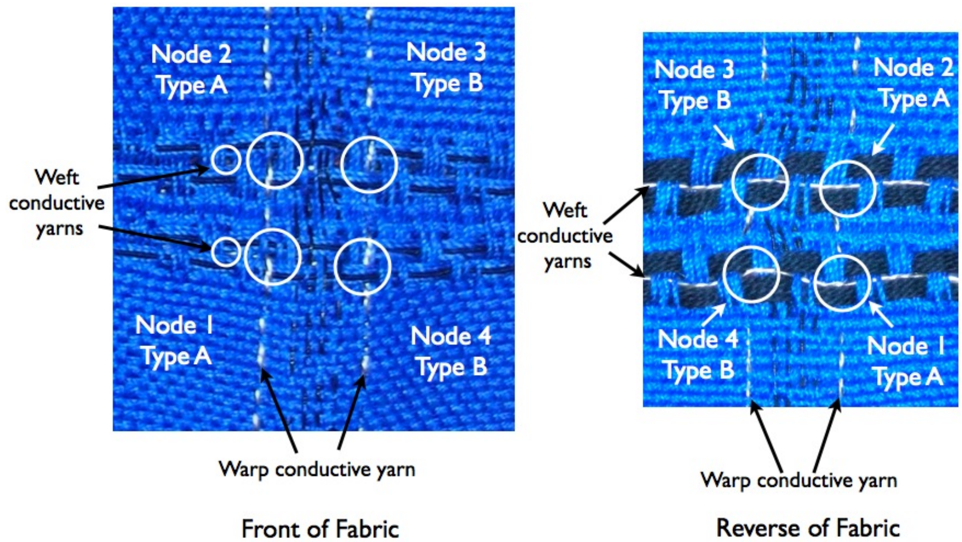


Figure 5.9: Double-weave node placement example – using Prototype 3

weave types for both the warp and weft. The two warp conductive weaves depict the two different ways the conductive yarns were floated in the double-weave basket pattern. Type A floats the conductive yarn over the first set of four weft substrate yarns and then under the next four substrate weft yarns, while Type B is woven opposite by floating the warp conductive yarn under the first four weft yarns and then over the next four weft yarns. Floating the conductive yarns in this manner allows for the yarn to interlace for stability yet float for a contact point with the other conductive yarn to create a sensor node.

Four weft yarn conductive yarn weaves were also used in the sensor node design. Weft Type A floats the weft conductive yarn over four warp substrate yarns, then under four warp substrate yarns, while weft Type B floats the weft conductive yarn under and then over four substrate yarns. Weft Types' C and D are on the top layer of the double weave where Type C floats under the warp conductive yarn and Type D floats over the warp conductive yarn. The sensor node variation combinations for the five prototypes with the different warp and weft conductive yarn weaves are detailed in Table 5.4, while images of the prototypes and Nodes are shown in Figure 5.8.

A close look at the weave pattern for Prototype 1 shows no difference between Nodes 1 and 2 which rest on the same warp wire where the warp stainless steel floats on the top layer of fabric over the intersection point, while Nodes 3 and 4 vary slightly from 1 and 2 in that the warp stainless steel floats at the bottom of the top fabric over the intersection point. Prototype 3 is the same weave pattern as Prototype 1 except for an elastic weft yarn added within two yarns from the intersection point. Prototypes 4 and 5 are similarly altered, with Prototype 5 being the elastic version of Prototype 4, although all four node warp stainless steel patterns

Fabric	Node 1 warp/weft type	Node 2 warp/weft type	Node 3 warp/weft type	Node 4 warp/weft type	Other Materials
Prototype 1	A/ A	A / A	B / B	B / B	
Prototype 2	A / C	A / C	B / D	B / D	
Prototype 3	A / A	A / A	B / B	B / B	Elastic
Prototype 4	A / A	A / A	A / B	A / B	
Prototype 5	A / A	A / A	A / B	A / B	Elastic

Table 5.4: Differentiation of sensor node intersection types of tested prototypes in double weaves

are identical. Prototype 2's weave pattern has both the warp and weft stainless steel on the top fabric layer mimicking a single layer weave.

All of the tests in this section used a Fluke Series 73 III multimeter with alligator clips connected to the resistive sensors along each node, thereby measuring the resistance of the two resistive materials in one node. The fabrics were placed on a hard surface with no tension to distort the resistance as tension of the stainless steel may alter the results. A workable weave pattern is judged by whether the nodes are active without contact, active with pressure contact, and how many nodes in each fabric worked successfully. Two sets of tests were done on the fabrics, the first, a series of pressure tests to determine which prototype resulted in the highest percentage of useable nodes, and the second, a more detailed analysis of the best fabric with different weight pressures.

The first set of tests was performed to determine if a connection is possible between the warp and weft sensors on the different nodes and whether the two sensors are able to create a closed circuit. The pressure tests were achieved by applying external pressure on the nodes with a series of different sized objects, from an index finger on the right hand of a right-handed person, to two plastic dowels of one-half and one-quarter inches. Each of these objects was applied with approximately two levels of pressure at about a perpendicular angle; light pressure where the object lightly rests on the node and heavy pressure where the object is heavily pressed on the node. Figure 5.10 depicts the results of the five prototypes tested and the percentage of active nodes for each object applied.

The results in Figure 5.10 show that Prototype 2 has 100% of workable nodes with activity a, no external pressure. However, there are no workable switches in Prototype 2's set of results shows as every node was active for every object whether there was external pressure applied or not. Therefore, this fabric will not work as a resistive switch as it is always a closed switch. Similarly, Prototype's 4 and 5 sensor node

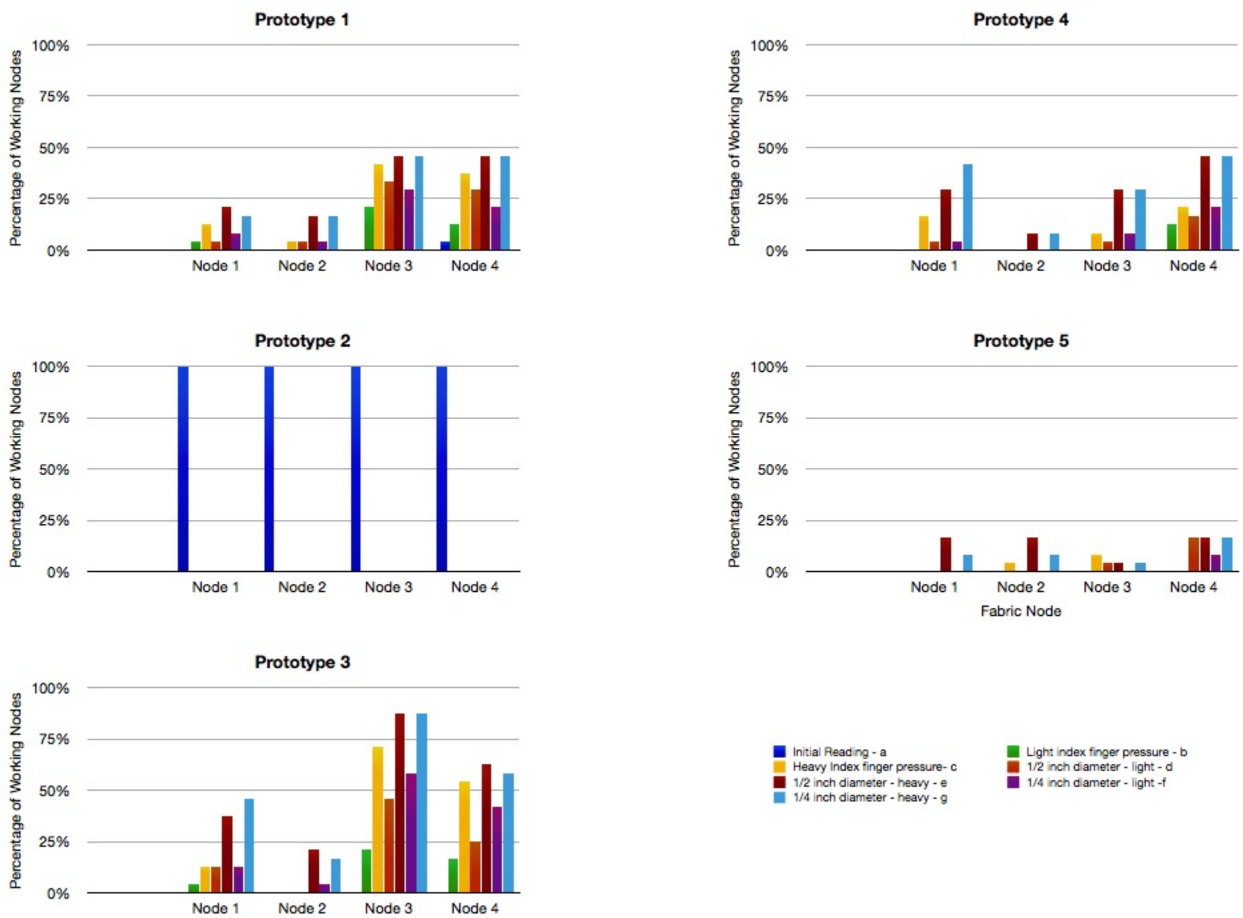


Figure 5.10: Percentage of working nodes out of 24 from double-weave prototypes from different types of pressure testing

combinations do not work as the majority of working sensor nodes for the pressure tests is below 25% for Prototype 4. The addition of elastic in Prototype 5 in the weave pattern of Prototype 4 instead of improving the number of working resistive nodes, instead lowers the percentage of working nodes to below 20% for all activities. Prototypes 2, 4 and 5, therefore do not work as resistive network e-textiles.

The e-textile with the most working nodes is Prototype 3, the elastic version of Prototype 1. Prototypes nodes three and four have the highest percentage of nodes that act as switches that are activate upon external pressure. Floating the warp stainless steel on the bottom of the top fabric over the weft stainless steel intersection point increases the number of useable nodes for a resistive network for these materials. Additionally, adding elastic to the weave improves the results by opening the weave pattern as more of a lattice or leno weave for more contact points between the two fabrics for the sensor nodes.

None of these combinations of conductive weaves and tests resulted in 100% functioning resistive pressure switches. However, examining the weaves of the two best e-textiles, Prototypes 1 and 3, a pattern discrepancy was found; a warp wire was placed in the wrong heddle, which resulted in an improper harness draw that propagated through the left half of the fabrics as they were woven. This resulted in the warp conductive yarn being offset in the nodes and not being able to make contact with the weft conductive yarn at the designed point.

Reexamining the results of the Prototypes 1 and 3, for the 12 nodes on the left hand side of the e-textile, Node 4 of Prototype 3 had a 100% workable nodes for two pressure tests: heavy pressure for the index finger and 1/2 diameter plastic dowel as shown in Figure 5.11. Prototype 1 did not have any nodes with a 100% workable switch test, however, one set of Nodes, in one weft grid line double-weave pocket, did have 100% workable sensor nodes for Nodes 3 and 4. Thus, showing that the initial weave design was a functional design if no errors in the fabric were made during the weaving process. Adding elastic to the weave design of Prototype 1 allowed for more workable sensor nodes, Prototype 3, when weave errors were present in the e-textile.

The SAS JMP v.8.0 software was used to statistically analyze the testing data for prototypes 1 and 3. The independent variables were prototype number, node number, pressure type, and pressure object. The dependent variable was the number of working switches. A generalized linear model was fitted to the data and effects were analyzed for significance ($p < 0.05$). The following effects were found at a statistically significant level. Node types 3 and 4 were better than node types 1 and 2. As expected, heavy pressure resulted in more successful tests than light pressure. Finally, node types 3 and 4 were significantly better on prototype 3 than on prototype 1.

Different materials will give different results, but the same principles of the e-textile properties effecting the end application apply. For example, all of the tests on the double-weave pocket resistive switches are

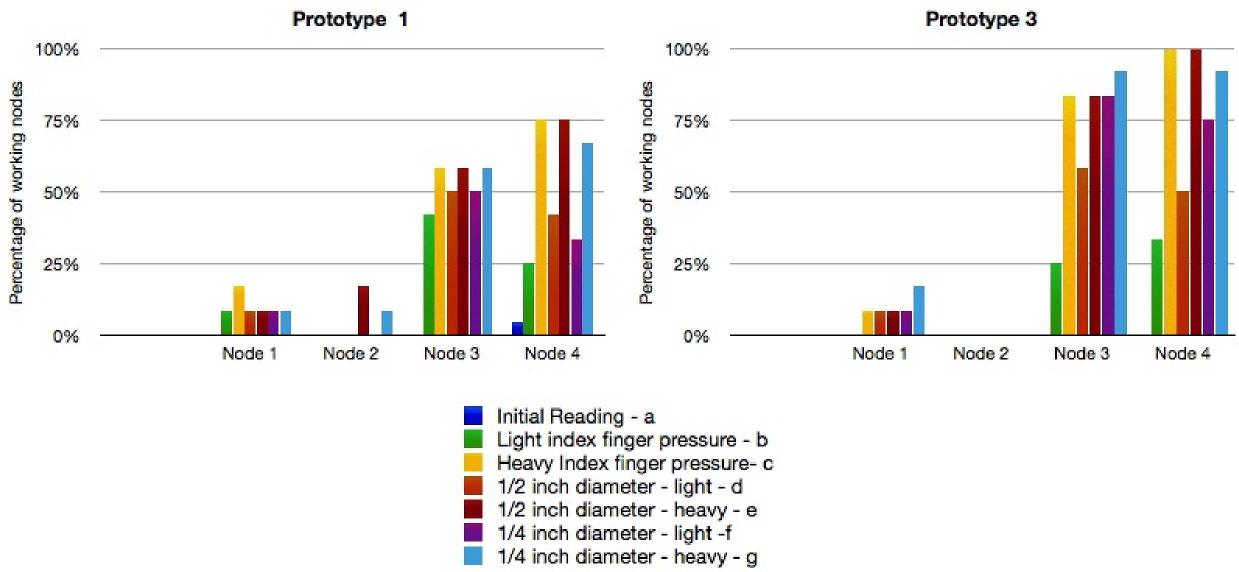


Figure 5.11: The percentage of working nodes out of 12 from the double-weave prototypes for the left hand side of the fabric only

dependent upon the thickness of the resistive and substrate yarns used. When changing the diameter yarn or stainless steel, it is necessary to return to the expanded design flow to see how this changes the synthesizing and prototyping of new e-textiles and the ultimate performance of the end application.

Along with the weave property considerations, the weight and drape e-textile properties of the double weave fabric should also be considered. Due to the weight of the stainless steel, adding too many sensor points will create a much heavier garment, however opportunely placed sensors-as-fibers will increase the functionality of the e-textile while limiting the weight worn by the subject, along with material costs. The drape of the fabric will determine how the garment sits on the wearer, if the e-textile is too stiff, the garment will not hold to the body for proper sensor placement.

Chapter 6

Conclusion

The purpose of this thesis has been to provide a framework for an e-textile design methodology that considers the physical properties of the textile as well as the properties of the hardware and software. This is established by explaining the design methodology of an e-textile, analyzing specific physical properties of an e-textile, and using a fiber as a sensor in a detailed analysis of a single physical property affecting the electrical properties of the e-textile. Combining knowledge of both textile and electrical engineering allows a more complete fabric to be created that considers both the e-textile's mechanical and electrical properties.

The design methodology shown in Chapter 3 is a tool to help create an e-textile that considers the fabric substrate as an integral part of the whole e-textile application. An expanded design flow is introduced that combines the application's design flow in parallel with the substrate's design flow to create a prototype. This design flow shows the aspects of an e-textile as part of a designer's toolbox to create a symbiotic e-textile by breaking the e-textile into layers. This analysis includes a fabric analysis of the substrate, the communication and power bus, wire and sensor placement and the e-textile's properties showing the interrelation of the e-textile parts as a whole.

An analysis of specific e-textile physical properties, as presented in Chapter 4, is important for creating e-textiles that look and feel like normal clothing and thus are truly wearable. The drape of a set of prototypes with different weaves and wire spacing is evaluated using a FRL Drapemeter. These drape tests shows that the choice and placement of the materials used in the e-textile affect the drape, weight, cost and function of the application. A more dense wire placement results in a lower drape coefficient, which translates as a more drapeable fabric. However, the higher density of wire results in a heavier fabric with a higher cost of materials than a fabric with the same weave and less wire density. The addition of elastic to a prototype with less wire density results in a lower drape coefficient.

In Chapter 5, the use of conductive yarn as a resistive sensor-as-fiber demonstrated how one specific property, the weave of the e-textile, can affect the function of the application. The weaves and prototypes tested show this relationship by altering the substrate of the e-textile to a pocket double-weave from a single-layer weave. The double weave shows that an open circuit could be woven using stainless steel yarn, and that the resistive nodes close the circuit upon external pressure to the sensor-node. This shows that the combination knowledge of both textile and electrical engineering allows for a more complete fabric to be created that considers both the e-textiles mechanical and electrical properties.

The expanded design flow, fabric synthesis and sensor-as-fibers presented in this thesis fit with the building-block approach of Virginia Tech's E-textile Lab in that they help the designer break down the e-textile into useable physical property building blocks as the simulation of sensors and movement analysis does for the software. Analyzing the drape, weight and cost of the e-textile for wearability, and use of a sensor-as-fiber node highlights the building block elements presented in this thesis.

6.1 Future research

This thesis provides a foundation for an expanded design flow to achieve functional, useable e-textiles. Further research is necessary, however, for e-textiles to achieve their promise. One issue for future research is better wire placement determination, specifically, an analysis of potential wire placement in relation to body sizes and standardized garment patterns. In determining the best wire-placement-to-garment sizing, a garment will have known wire and potential sensor placements for varying body types and sizes. This will enable the e-textile designer to determine in advance the use of a specific fabric for different applications and the potential error involved.

More research is also needed to further develop a more stable pocket double weave where the uninsulated resistive material is encapsulated within the weave. Limiting the resistive yarn exposure to within the pocket of the double weave reduces potential for off-fabric electrical shorts and skin contact for a garment. Potential weaves include placing the warp and weft resistive yarns as stuffer yarns or within rib weaves and then floating the warp and weft inside the double-weave pocket for contact. A secondary option is to attach resistive sensor node patches to the garment thus reducing the resistive material contact to the wearer's skin and enabling spot placement of sensor nodes for different applications and users. As this area of e-textile develops, additional issues in textile-as-substrate will arise.

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