Inclusion of Fabric Properties in the E-Textile Design Process

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Abstract

This paper considers the impact of fabric properties on the e-textile design process. Specifically, properties such as weave pattern, drape, and weight are evaluated as physical aspects of an e-textile system within an expanded design flow. Results from woven e-textile samples are reported and analyzed, with a more detailed analysis on sensors as fibers in simple and more complex double weave patterns.

1 Introduction

Much of the work in electronic textiles (e-textiles) has concentrated on the basic electronic and electrical systems, but in order for a garment to be wearable, comfortable, and manufacturable, e-textile design must ultimately consider the fabric properties and the physical environment in which it will be used and constructed. This paper makes two main contributions: First, it provides an overview of an e-textile design methodology that considers both the fabric and the electronic aspects of an e-textile. Second, the paper explores the interplay between the spacing of electrical conductors in the fabric and the fabric's physical properties.

An e-textile is an electronic system incorporated into fabric that is woven, knit, or a composite. An e-textile differs from conventional electronic systems in that the electrical and physical features operate symbiotically and can affect the operating functions and properties of each other. Therefore, designs for e-textiles must move into a comprehensive strategy that considers both the physical fabric and electronic function.

For example, merely specifying a fabric weight and construction for an application (as is done in conventional textile design) does not answer the question of how best to place wires for optimal sensor placement or if the sensor is a fiber, how the weave might affect the sensor's response. Conversely, assuming an e-textile is just an electronic system tends to provide a micro-perspective. A circuit in fabric tends to be physically larger than a printed circuit board, and thus power and bus problems emerge in the e-textile that would not be encountered with a typical circuit.

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Finally, e-textile design must consider manufacturability, wearability and cost. Custom fabric for a single person or a single use is too expensive: the comprehensive design must plan for multiple applications on one system, such as monitoring heart beat and listening to an iPod simultaneously.

Unlike previous research that concentrated on the properties of printed circuits [4] for a more wearable e-textile, this paper provides a case study of the interaction between the weave pattern and the physical properties of an e-textile fabric. The layout of this paper is as follows: an overview of the methodology, and design flow in Section 2, followed by an introduction to the fabric properties in Section 3, and an example of the use the methodology and properties with sensors as fibers in Section 4.

2 Methodology

The creation of an e-textile is application driven. The materials and sensors that work for one application may not be optimal for another application as each application has specific and general requirements that need to be addressed to create an accurate prototype. Following a design flow for an e-textile allows these aspects of an e-textile to be considered and evaluated in light of the final application.

Design Flow: The e-textile design flow is a multiple-step process involving simulation and software design as well as incorporating a fabric substrate into the final design process. A previous description of the e-textile design flow [7] details the basic process from the application overview to the final design, shown in the left (unshaded) side of Figure 1. However, this process does not consider 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 combination of the left and right side of Figure 1.

Fabric Synthesis: Synthesizing the e-textile substrate means considering the manufacturing constraints and the materials that will work best for the application. The main parts of the fabric synthesis are wire spacing, cost, weight, weaves, sensor placement, and other electronic material integration. In fabric synthesis the communication/power bus, sensor placement and sensors as fibers use textile properties

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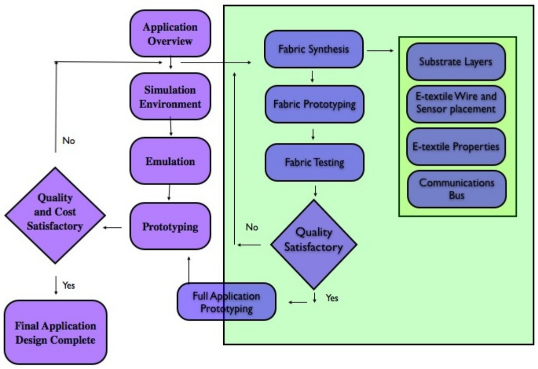


Figure 1. Expanded E-textile design flow

to determine layout, functionality and weave.

Fabric Prototyping: To determine the actual aspects of an e-textile substrate, a physical prototype must be made and evaluated. An AVL 40 inch, 24 harness Industrial Dobby Loom was used for the construction of all prototypes considered in this paper.

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 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.

3 Fabric Property Analysis/Synthesis

The primary e-textile properties this papers considers are material weight and cost, wire grid spacing, fabric weaves and drape. Derived analysis of these properties gives an estimate of potential sensor placement and weight-cost analysis. This paper does not differentiate between specific weaves of the fabrics, only a comparison of the number of ends and picks in relation to the cost and weight. Although the amount of yardage will change in relation to the number of interlacings in a particular fabric, this can be measured by determining a fabric's crimp factor. An example of the analysis centers on a resistive circuit in the fabric to show how the materials and weave interact in the substrate.

Materials: The materials used for calculating the synthesized and actual fabrics within this section are shown in Table 1. This table shows the cost per unit, the source and the weight of the material. Table 2 depicts the fabrics that will be used in both the weight and cost analysis. Picks denote the number of yarns in the weft direction, the width of the fabric, while ends refers to the count in the warp direction, the length of the fabric. EPI and PPI refer to one standard in textile engineering for describing the fabric density by inch, which is then replicated throughout the fabric. 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 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 2, 3, and 4 is the baseline fabric without any electronic material woven in the substrate.

Material Type	Tex g/1000m	Cost $/lb	Manufacturer or material source
10/2 Pearl Cotton	124	13.75	halcyonyarn.com
20/2 Pearl Cotton	62	13.75	halcyonyarn.com
16/2 Newport Linen	207	29.95	halcyonyarn.com
Tinsel Wire	662	150	newenglandwire
12/2 Bekinox® Stainless Steel	500	120	Bekaert Fibre Tech
Elastic	30	19	Ctsusa.com

Table 1. Materials for calculations and fabrics

Fabric	Yarn Type	EPI	PPI	Warp Wire Wire Runs	Weft Wire Wire Runs
Sample 1	10/2 Cotton	36	24	0	0
Sample 2	10/2 Cotton	36	24	8	12
Sample 3	20/2 Cotton	36	24	8	12
Sample 4	20/2 Cotton	36	24	9	24
Sample 5	16/2 Linen	20	20	8	12

Table 2. Parameters for 36 in $\times$ 36 in samples

Weight: 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 an average pair of men's khaki's 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.

Table 3 shows two fabrics with identical wire and yarn density, Sample 2 and Sample 3, weight per square yard is decreased 13% by simply changing the substrate fabric from a 10/2 Cotton to a less dense 20/2 Cotton. Similarly, increasing the number of wire runs within fabrics, Sample 3 and Sample 4, increases the fabric's overall weight by 11%. To further illustrate this point, the choice of using a 20/2 Cotton in fabric (Sample 3) results in a fabric that weighs less per square yard than the base fabric (Sample 1) with no wires, showing the connection between the weight of the e-textile and the materials used in manufacturing. In these instances, the wire and stainless steel weight are most of the weight of the e-textile. Therefore, weight cuts can be made by reducing the amount used; however, weight can also be reduced by changing the substrate material.

Cost: 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 conductive material. Determining the best placement of these materials may reduce the cost per yard. Table 4 uses the same fabrics as in the weight analysis, where the base fabric, Sample 1, shows the cost of a square

Fabric	Material	lb/yard	lbs/Sq yd	%of sq yard	Tot Calc Wght
Sample 1	warp - cotton 10/2	0.00025	0.324	60	
EPI: 36 PPI: 24	weft - cotton 10/2	0.00025	0.216	40	
	Tinsel Wire	0	0	0	
	12/2 Stainless Steel	0	0	0	0.54
Sample 2	warp - cotton 10/2	0.00025	0.324	47	
EPI: 36 PPI: 24	weft - cotton 10/2	0.00025	0.216	31	
	Tinsel Wire	0.00133	0.107	16	
	12/2 Stainless Steel	0.00101	0.0403	6	0.687
Sample 3	warp - cotton 20/2	0.000125	0.162	39	
EPI: 36 PPI: 24	weft - cotton 20/2	0.000125	0.108	26	
	Tinsel Wire	0.00133	0.107	26	
	12/2 Stainless Steel	0.00101	0.0403	10	0.417
Sample 4	warp - cotton 20/2	0.000125	0.162	32	
EPI: 36 PPI: 24	weft - cotton 20/2	0.000125	0.108	21	
	Tinsel Wire	0.00133	0.176	34	
	12/2 Stainless Steel	0.00101	0.0665	13	0.513
Sample 5	warp - linen 16/2	0.00042	0.3	40	
EPI: 20 PPI: 20	weft - linen 16/2	0.00042	0.3	40	
	Tinsel Wire	0.00133	0.107	14	
	12/2 Stainless Steel	0.00101	0.0403	5	0.747

Table 3. Calculated fabric weights

yard of the material before adding 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 shows the overall cost of one square yard of fabric Sample 2 is $12.60 where 73% of the cost is due to the stainless steel and wire bus. 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 with fabric Sample 3 where an increase in wire consumption results in a 68% increase in the cost of the fabric. Some of this increase can be mitigated by a lower price point for the materials and buying in bulk. However, optimal wire placement in the e-textile balances not only its weight but its cost.

Fabric	Warp yards/cost	Weft yards/cost	Tinsel Wire yards/cost	12/2 SS yards/cost	Total Cost per SQ yard
Sample 1 EPI: 36 PPI: 24	1296 / $3.24	864 / $2.16	0	0	$5.40
Sample 2 EPI: 36 PPI: 24	1296 / $3.24	864 / $2.16	80 / $5.60	40 / $1.60	$12.60
Sample 3 EPI: 36 PPI: 24	1296 / $1.62	864 / $1.08	80 / $5.60	40 / $1.60	$9.90
Sample 4 EPI: 36 PPI: 24	1296 / $1.62	864 / $1.08	132 / $9.24	66 / $2.64	$14.58
Sample 5 EPI: 20 PPI: 20	720 / $4.50	720 / $4.50	80 / $5.60	40 / $1.60	$16.20

Table 4. Costs per square yard of sample

Drape: The measurement of the drape of a fabric shows how a fabric will act once deformed on an object or body [5]. This is important when proper analysis requires that the sensor either not move on the body, be placed at a particular point for accurate measurements and for wearability. The interplay of how a fabric drapes for wearability with the addition of electronic components is touched on in [6], however, this section describes how different materials, different weaves and wire spacing specifically effects the e-textile's drape. A low drape coefficient shows a more drapeable or object-formable fabric, while a higher drape coefficient shows a more stiff fabric. The weights for the drape coefficient were measured using the FRL Drapemeter and a Mettler-Toledo Model PG 503-S Delta Range scale.

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, due to the fact that 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 5. Comparing both control fabrics with tinsel wire at a 4-inch interval in the warp resulted in a difference of a drape coefficient of 5%, showing that the tinsel wire dominates the drape property of the fabric. However, the fabric with 2-inch tinsel wire spacing interlaced in the weft direction and 4-inch spacing in the warp resulted in a 10% lower coefficient than the 4-inch spacing in both directions. The drape test shows that the weight of the wire overcomes the stiffness of the tinsel wire in the 2-inch weft wire spacing resulted in a lower coefficient shows that overall weight will overcome the stiffness of the tinsel wire.

By adding elastic in the weave, the same Broken Twill fabric with tinsel wire grid of 4-inches 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 elastic will be much more form fitting and comfortable with fewer wire runs than the similar drape coefficient Broken Twill fabric with 2-inch weft wire spacing. This effectively reduces the cost and weight of the fabric and the size of the communication power grid without altering the 4-inch wire configuration or compromising on comfort.

Fabric	warp wire spacing	weft wire spacing	F
Basket Weave	ss only	no wire	69%
Broken Twill	ss only	no wire	53%
Basket Weave	4 inch	no wire	74%
Broken Twill	4 inch	no wire	70%
Broken Twill	4 inch	4 inch	78%
Broken Twill	4 inch	2 inch	69%
Broken Twill w/elastic	4 inch	4 inch	50%

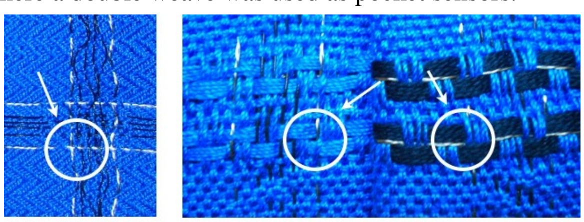
Table 5. Drape coefficient of sample fabrics measured on face side only of 10/2 pearl cotton substrate with EPI:36 and PPI:24

Wire spacing and sensor placement: The placement of the wire grid determines where the sensors can be placed on the e-textile garment. If too fine of a grid is woven in the fabric, the cost, weight and drape of the fabric is affected. More sensor placement is available with this scenario, however, optimal spacing and placement of the wire bus will establish the necessary power and communication grid and reduce the overall cost and weight of the e-textile.

4 Sensors as fibers

Experimenting with a stainless steel resistive network within the e-textile highlights the use of the expanded design flow by incorporating different weave patterns into the electronic design. An e-textile that effectively allows the sensor to be a material within the fabric, as opposed to just a circuit board attached to the wires on the grid, shows how the textile and sensors interplay. Previous research using fibers as sensors includes [2], a system which uses an entire sheet as the e-textile sensor, and [3] which used the resistive network as a dynamically changing network. This work is differentiated by its focus on specific sensor placement and resistance measurements within a fabric.

Creating a dynamic resistive network in the substrate allows for sensors to be placed on a garment where circuit boards can not be comfortably attached on a body, for example, using a resistive sensor on the backside of the garment in place of a board where a connection is determined once the circuit is closed if the subject contacts an external surface. If the fiber sensor is woven properly, only pressure against the node will activate the node. The sensors, Bekinox® Stainless Steel yarn woven alongside the tinsel wires, are interlaced perpendicularly creating a node, and attached to centralized boards. Each node creates a closed circuit upon connection of the two sensors, where, ideally, the resistive network is only activated by external pressure. 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 2 shows two variations of an e-textile resistive network, Figure 2(a) where the stainless steel wires were floated to create the resistive sensor, and Figure 2(b), where a double weave was used as pocket sensors.



a.) b.)

Figure 2. Stainless steel as sensor by floating wires (a) and double weave, (b)

The two resistive networks depicted in Figure 2 show the design flow progression of the e-textile property of weave type. In the original single weave, yarns float over each other, while in the double pocket weave, the yarns are separated by two layers of fabric. Each network was designed for different e-textile applications. The single weave [3] used in the large surface e-textile was designed to use a variable resistance change in the network, while the newer double weave circuit is designed to be either open or closed.

The reverse side of the double weave is woven in a darker yarn to emphasize the difference in the weave. A double weave is two fabrics woven in unison on the same loom, that do not have interlaced warp and weft ends. This particular double weave is woven by using the existing warp setup on the loom while creating small pocket double weaves within the weft direction then returning to a single layered weave until the next sensor placement. Having stainless steel on separate layers allows for an open circuit until the node is depressed, when the stainless steel sensors connect to close the circuit within the two fabric layers. This dynamic resistive network within a narrow double weave band in the e-textile was a change from the single weave's resistive network and shows how the electronics and mechanical aspects of the e-textiles are intertwined and symbiotic.

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 make 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, and 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.

5 Concluding Remarks

This paper has provided an overview of an e-textile design methodology that considers the physical properties of the textile as well as the properties of the hardware and software. The analysis of the textile's physical properties is important for creating e-textiles that look and feel like normal clothing and thus are truly wearable. The fabric weave in the design of an e-textile alters the electronic capabilities of an e-textile when using sensors as fibers. Thus the expanded design flow and fabric synthesis are design tools to help create an e-textile that considers the fabric substrate as an integral part of the whole e-textile application.

An analysis of potential wire placement in relation to body sizes and standardized garment patterns is a next step in this research project. 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.

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