5-2020

Smart Textiles as the Digital Interface of the Future

Audra Beneux

Smart Textiles as the Digital Interface of the Future

A thesis submitted in partial fulfillment
of the requirements for the degree of
Bachelor of Science in Electrical Engineering

by

Audra Beneux

May 2020
University of Arkansas

This thesis is approved for recommendation to the Honors College.

[redacted]

Robert Saunders, P.E.
Honors Thesis Advisor

Abstract

The growing field of smart textiles could change everyday life, adding an element of interactivity to commonly used items such as clothing and furniture. Smart textiles measure then respond to external stimuli. For scalability in the future, smart textiles must be produced using conventional textile manufacturing craftsmanship. The resulting textile must be durable and comfortable while retaining electrical capabilities. Smart textiles can be fabricating through embroidery, weaving, and knitting using conductive threads. Electronics can also be printed onto textiles. Researchers are also creating higher-order electronics, such as the transistor, on the fiber-level to make the technology in smart textiles as discreet as possible. A variety of sensors can be produced with smart textile technology, and these sensors can be utilized in medical and protective applications. Smart textiles can then communicate a response through output devices such as lighting displays. As smart textiles develop, the ethics of manufacturing must be considered. Lightweight sources of power generation besides batteries are needed to make textiles systems more robust. As the smart textile market continues to grow, there are several obstacles in the way of smart textiles entering everyday life. Two traditionally different sectors—textiles and electronics—must converge. Consumers must also be motivated to trade up to smart textile products through increased electronic functions. As smart textiles continue to mature, more applications will be accepted by society and begin impacting day to day life.

Acknowledgments

The encouragement and support of family, friends, and mentors made this thesis possible. A special thanks to Robert Saunders for providing advice and guidance in times of uncertainty.

Table of Contents

Chapter 1: Introduction

As electronics have integrated into life over the past century, the way people interact with their world has drastically changed. Many objects besides clothing are constructed using textiles as well such as furniture. The growing field of smart textiles could change the fiber of everyday life, adding an element of interactivity to items humans already understand. Everyone uses clothing, and billions of garments are produced each year. Many other objects, such as furniture, are constructed using textiles as well. Without the confines of traditional electronic packaging, the seamless integration of electronics into fabric extends the possibilities of personal computing, making everyday objects into computer interfaces.

The term *smart textile* applies to a range of fabrics with functionality beyond the purpose of traditional fabric. They can be defined as materials that sense and respond to external stimuli [1]. Smart textiles can be divided into two categories. The first is passive smart textiles, which change properties according to the environment, including hydrophobic, hydrophilic textiles, and shape-memory materials. This is achieved through how the fabric is constructed such as applying additives or coatings [2]. The second is active smart textiles that convert measured parameters to an electrical signal using integrated sensors and actuators [1]. The sensors detect signals from the environment, and the signal is processed locally by an embedded microchip or transmitted the cloud for analysis on another device, therein connecting to the Internet of Things [1]. The actuators in the textile such as light-emitting diodes and vibrating devices then give light and haptic feedback according to the results of the signal analysis.

The development of active smart textiles is an emerging but active field. The first wearable computer—created to predict roulette—was completed in 1961 [3]. However, in wearable computers, there was no integration between the electronics and textiles. The first research related to smart textiles with electronics began in the late 1990s with the first textile semiconductive components being produced in the early 2000s [1]. Over the last two decades, the trend in smart textile research has been integrating more electronics, including transistors, on the fiber level.

This paper covers fabrication processes used to create smart textiles that must adhere to traditional textile craftsmanship for scalability in the future. Then, the possible sensors and actuators that can be realized using smart textiles are discussed with supporting examples. Currently, there are many practical applications in the field of medicine and protection, but not as many commercial developments. With the development of smart textiles, problems arise such as the ethics behind smart textile production, sustainability, and power generation. Finally, while it is ideal for smart textiles to eventually blend into daily life, this may not be possible in the current textile market until there are more advancements in smart textile technology.

Chapter 2: Fabrication Processes

With the integration of electronics into clothing, the constraints of traditional textile production must be considered, and the final textile must retain its electrical properties while functioning like the raw materials tailors are accustomed to. The resulting fabric must be durable and flexible to withstand the mechanical stresses of everyday use including washing and sweat. The comfort and breathability of the textile are paramount to appeal to the wearer. Smart textiles can be produced using multiple traditional textile processes: embroidery, weaving, knitting, and printing.

A. Embroidery

A common process to implement active smart textiles is embroidery. Numerically controlled embroidery using conductive thread is both time-efficient and precise, enabling the creation of circuit traces, component pads, and sensing surfaces [4]. The conductive thread must be strong and flexible enough for use in high-speed sewing machinery. Otherwise, the thread will break, creating electronic discontinuities. The yarns used in this process may vary in electrical properties like resistance, and yarn variety and stitching patterns make it possible to implement discrete components on traditional textile substrates [4]. Conductive yarn is created using stainless steel as a conductor spun with a variety of synthetic and natural fibers. This yarn can be made in any color to suit the needs of clothing designers. Stainless steel is inert, and the embroidered electronics are resistant to the effects of sweating and washing and thus ideal for daily usage. For high-speed embroidery, the yarn should be spun from segments of stainless steel instead of continuous threads that are unable to stretch and handle tension. Aracon™ metal-clad aramid fibers, produced by the DuPont company, exhibit mechanical and electrical stability over repeated changes in radiation exposure and temperature. Its ability to withstand high temperature means it can be soldered like normal wires. It is expensive and preferred for aerospace applications, but it will likely emerge as the preferred choice for fabric circuitry as availability increases [4].

Traces created using embroidery make high impedance interconnections between components, so embroidery is not ideal for designs with high current and thus large power consumption such as lighting applications. Fortunately, engineers can introduce this constraint on the front end of the design where interconnections are modeled as transmission lines. Composite threads with shorter fibers of stainless steel are typically more resistive but easier to use in standard sewing machines and maintain electrical continuity. The shorter steel fibers extend from the thread, causing short circuits between traces, but this can be fixed by brushing a magnet against the fabric [4]. However, the loose fibers make ideal contact surfaces for sensors and pads. The conductive yarn can be insulated by polymer coating or wrapped by an insulating yarn such as polyester. This makes the yarn more resistant to washing, but it is necessary to remove the insulation to make electrical connections to components [2]. Insulation fabric can be inserted between layers of embroidered textiles connected by stitched vias to realize multilayer circuits. The design of multilayer circuits yields more electronic capabilities and gives designers control of the outward appearance of the textile. For example, only threads relevant to the user for interaction could be shown on the fabric.

B. Weaving and Knitting

Smart textiles can be created through traditional weaving and knitting. During the weaving process, two sets of yarn—the weft and warp—are interlaced perpendicularly to form a tightly packed grid. Metallic silk organza is finely woven silk where each thread running along the weft is wrapped by a thin gold foil helix [4]. Because the conductive threads run parallel to each other, the fabric functions like a ribbon cable as the threads can be individually addressed. The conducting fibers in metallic silk organza will always stay parallel no matter what direction the textile is stretched. This textile can be easily folded, but the flexibility of metallic silk organza could also cause components to short if the textile folds in on itself. To prevent components from accidentally coming in contact, an insulating layer of cloth needs to be attached to the metallic silk organza. Components can be soldered directly onto the textile, but it is difficult to machine sew without breaking the fragile foil and causing electrical discontinuity. As a result, working with metallic organza as more than just a substrate is labor-intensive and time-consuming [4].

While metallic silk organza is a two-dimensional textile, it is also possible to weave in three-dimensions on special looms. In three-dimensional weaving, there are more possible yarn spacing patterns to create as conductive yarns are interlaced vertically through layers of warp and weft. This technique was applied at Google on Project Jacquard to isolate the conductive yarn the user interacted with from the yarns individually addressed in the design. Instead, these pieces of yarn floated freely in a layer where they could be easily stripped of insulation and connected to electronics as seen in Figure 1. Before individual yarns had to be plucked out of the textile, leading to errors, so three-dimensional weaving simplified the fabrication process [5]. As a result, the Project Jacquard textile could be made in a scalable textile manufacturing process which is ideal in commercial applications.

Figure 1. Sample touch sensor weaved by Google ATAP in Project Jacquard using conductive threads and 3D weaving [5].

In the process of knitting, yarns are arranged into rows of consecutive loops. It is possible to create more complex patterns by changing the sequence of individual stitches. Industrial knitting machines can produce three-dimensional textile architectures as well on circular weft-knitting machines [6]. One of the major advantages of weaving and knitting processes is the ability to make large-area textiles quickly and autonomously. Industrial weaving machines can make more than ten million square meters of fabric in a year [7]. Woven fabrics and knitted textiles are comfortable too as they are breathable and lightweight. Woven and knitted textiles both have distinct characteristics though. Woven textiles are durable and maintain their designated shape better than knits. As a result, the placement of conductive yarns can be more precise, and the yarns can be placed more densely together, creating more integrated components in a set area. On the other hand, knitted fabrics can be easily stretched, so they are more suitable in environments where the textile is under more mechanical stress. Knitted fabrics have better air permeability and thermal retention as well [2]. The process of weaving or knitting is chosen depending on the requirements of the final design.

C. Printing

Printing on fabric can also create highly conductive interconnects by selectively coating a textile in ink. However, commercially available metallic inks designed for planar substrates contain hydrophobic polymer binders, resulting in hydrophobic electrodes. One binder-free printing process uses a Silicon ink to print circuits instead. First, a water-based Si particle ink is created, and it acts as a precursor. Then, a wax layer is printed on fabric in the negative space of the pattern of the electrical design. The Si precursor is cast onto the fabric, and metals such as gold, silver, and platinum are deposited onto the Si ink autocatalytically at room temperature. The resulting textile has a low electrical resistance ($3.5\ \Omega\ sq^{-1}$), flexible, electrocatalytic, hydrophilic, porous, and low-cost [8]. This method also preserves the 3D structure of the fabric. The method of printing highly conductive, hydrophilic patches is ideal for creating sensors on human skin. Other successful printing methods include using inkjet printing to deposit silver interconnections and small conducting polymer sensors such as PEDOT (poly(3,4-ethylenedioxythiophene) polystyrene sulfonate) [9]. This method maintains low resistance conducting lines while highly conductive, hydrophilic electrode sensors. When printing circuits onto textiles, the ink must be equally flexible as the fabric substrate it is applied to. If not, mechanical stress could cause cracks in the printed design, potentially causing a disconnect between components.

D. Placing Electronic Packages

In most applications today, both smart textile devices and traditionally packaged electronics are used in smart textile design. Traditional components can be mounted onto textile substrates through soldering or bonding with an adhesive. The leads can also be attached to the traces on the textile through mechanical means such as crimping, stapling, or using metallics clasps and snaps. The mounting of traditional electronics packaged in hard plastics results in an uncomfortable and stiff textile, so integrating components into the fabric is preferred for comfort. However, this is not possible for all electronics, including but not limited to microprocessors. Instead, alternative packaging must be considered for these more complex electronics. First, the packaging needs waterproofing or insulation to protect the inside electronics from damaging conditions such as washing. In some cases, the electronics are simply physically removed if the textile needs to be washed. There is a drive to develop round packages for textile substrates to balance the forces of the threads emanating from the component, making the final system more durable [4].

E. Fibertronics

Researchers in smart textiles are even trying to make all electronics seemingly disappear into the textile by creating higher-order fiber-level electronics. The first research to create complicated fiber-electronics began in the early 2000s, and this field of research is often called "fibertronics" [2]. This developing technology allows smart textile systems to be constructed from the fiber upwards instead of the traditional from the components downwards approach. The transistor is one of the most essential components in the design of conventional electrical devices. However, standard transistors require a defined geometry. This is more difficult to achieve on a textile substrate than a planar substrate. The cylindrical topology of the fiber introduces surface curvature and torsion effects which complicate the processing of electronic textiles [10].

Transistors may be implemented on the fiber-level using several different methods. Thin-film transistors of amorphous silicon made on a flexible polyimide foil substrate can be woven with conductive and inert fibers. These simple thin-film transistors successfully created a woven textile inverter [11]. However, this method still requires the attachment of thin electrical components to the fibers of the textile. The construction of organic wire electrochemical transistors (WECT) devices implements transistors deeper on the fiber level. To make WECT devices on a single fiber, textile monofilaments are coated in a continuous thin film of conducting PEDOT [12]. The advantages of using an organic electronic material, such as conducting polymers, are its high elasticity and mechanical flexibility, making the final textile smart more rugged. Electrochemical transistor operation relies on switching the conductivity of the PEDOT channel through a reversible redox process in PEDOT films that share an electrolyte [12]. Figure 2 illustrates ECTs made on a planar substrate versus on a non-planar fiber substrate. ECTs have been made on flat substrates such as glass, plastic, and paper (Figure 2a). Patterns of PEDOT film are created through photolithography followed by a layer of solid polymer electrolyte (Figure 2c). ECTs can be realized on a fiber-level by using cylindrical PEDOT films to cover fibers with an electrolyte contact where the fibers cross (Figure 2b and 2d).

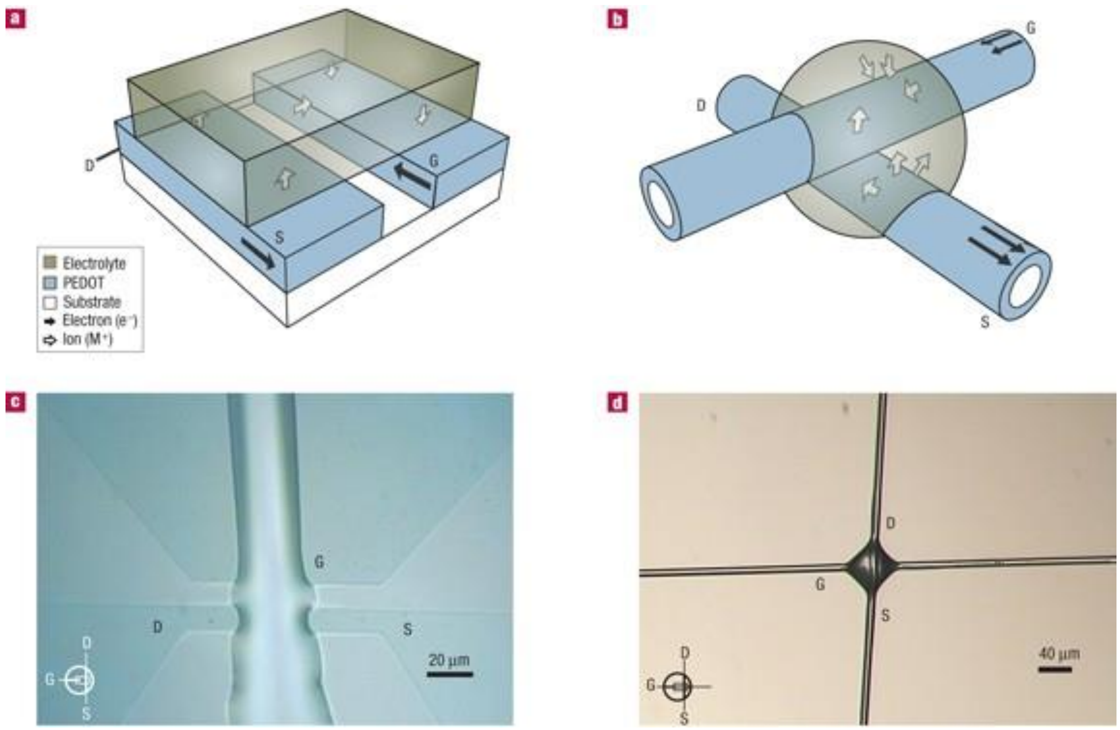

Figure 2: Planar and cylindrical electrochemical transistors (ECTs). a. Planar ECT b. Wire ECT c. Optical micrograph of planar micro-ECT made through photolithography d. Optical micrograph of wire ECT constructed at the crossing of PEDOT coated filaments [12].

To create a large piece of textile, PEDOT coated monofilaments can be woven into the fabric, and electrolyte junctions are placed where transistors are needed. The PEDOT film used to cover the fibers can withstand the mechanical strain of industrial knitting and weaving. The final textile made from this technology has several electrical advantages as well for large-scale electronic design. Wire ECTs are symmetrical as any of the four connections can be chosen as the gate with corresponding connections on the opposite fiber selected as the source and drain. Also, the local geometry and patterns of the electrolyte junctions do not majorly impact the function of the device [12]. As a result, the shape and amount of electrolyte at each transistor does not need to be as precisely controlled as that of traditional transistors. Thus, in a large-scale production setting, there is a smaller chance of error and faulty devices. This method is more cost-efficient for electronic textiles than lithography patterning [12]. This is essential if fiber-level transistors and devices are going to be produced for commercialization in the future. Inverters and multiplexers have been created using this process, demonstrating the ability of a smart textile to complete universal logic operations. With the symmetry and ease of production of ECTs, circuits can be integrated directly into the architecture of the textile. In combination with techniques such as three-dimensional weaving, there are endless combinations of smart textile topologies. However, researchers are still far from being able to integrate microcontrollers, memory units, and wireless links into a purely textile device.

Chapter 3: Smart Textile Devices and Applications

When smart textiles were first developed, the smart textile used a means for creating interconnections between standard traditional components, following the vision of simply wearing already existing computers. The methods of embroidery, weaving, knitting, and printing can all produce interconnections with a single functionality like conductivity. These methods can also create a variety of textile integrated input and output devices. These textiles become an essential part of the electrical design, serving a greater purpose than a carrier for conductive yarn and standard electronics.

A. Input Devices

One of the most important smart textile devices for creating a purposeful application is the sensor. Sensors can monitor an individual and their environment, providing an efficient way for users to stay healthy and protected while still being comfortable. Sensors measure physical quantities, such as pressure and light intensity, and convert these values into a signal to be analyzed locally with a processor or transmitted to a cloud.

As textiles are most often used to make clothing, many of the sensors developed thus far are made to measure different aspects of human health such as heart rate and temperature. A change in the wearer's temperature could signal an underlying health problem, and even if one's temperature is not dangerously high or low, being too hot or cold is uncomfortable. Thin-film temperature sensors attached to a Kapton E stripe can be woven with standard textile yarns to create temperature sensing fibers [13]. Various pressure sensors are easily constructed smart textiles too. Purely textile capacitive pressure sensors are made by inserting a foam or textile spacer between electrodes embroidered by silver-coated yarn [14]. Pressure sensors can measure muscle activity for detailed motion tracking. They can detect breathing patterns or even indicate possible pressure sores, a common problem for those who are bedridden. Pressure sensors are also used in commercial applications as they allow user feedback through textile keyboards, which could be used on clothes as well as furniture. Like pressure sensors, strain sensors can measure the articulations of the human body. Strain sensors can be made by knitting elastomeric and conductive yarns [15]. Chemical and humidity sensors are utilized to detect the presence of biological fluids in sweat. Electrochemical sensors can be screen printed directly onto textiles [16]. Cotton threads can be made into biosensing fibers by using a polyelectrolyte-based coating with carbon nanotubes. The carbon nanotube cotton threads, sense humidity as well as albumin, the key protein of blood [17].

These textile sensors are combined to make comfortable and lightweight biomonitoring systems that can monitor data efficiently and promptly. For example, the Georgia tech Wearable Motherboard™ (Figure 3) was the first piece of clothing to incorporate optical sensors and other "special sensors" to detect bullet wounds and monitor vital signs unobtrusively [18]. Other biomedical smart clothes use embedded textile systems for measuring respiration, body posture, blood oxygen saturation, and electrocardiogram. These clothes also have pockets for additional sensors such as ECG electrodes and accelerometers connected to a processor through the conductive textile [19]. Health applications are currently the most valuable application of smart textiles as they can be used to regulate and mitigate health risks especially for the diseased and disabled.

Figure 3. Georgia Tech Wearable Motherboard [18].

Before clothing became a means for self-expression, it protected its wearer from the hazards of the surrounding environment by providing a barrier between the skin and the elements. Traditional clothing is restrained to protecting the wearer from weather, but with the development of smart textiles, the protection capabilities of clothing expand as sensors can detect changes in the wearer's surroundings that result in danger. Sensors made by plastic fiber optics have been used in soldier uniforms to detect chemical and biological threats, above-normal temperatures, and other hazards [20]. Optical sensors operate by measuring changes in light intensity at the end of the fibers. When the light is less intense, the fiber has been deformed. For chemical optical sensors, the fibers are coated in layers that react with specified chemicals, the reaction causes the fibers to degrade, changing the intensity of light transmission.

B. Output Devices

After signals from the input device have been captured and analyzed, the system can either store the input data or react to it. One reaction is using output devices to communicate with the user and their surroundings. Textile systems can communicate with the wearer through haptic and lighting devices. The response may be as small as a blinking indicator light or a short vibration to warn the user of a change in their environment.

Lighting displays are the most common textile output device, and smart textiles can interact with a variety of displays from a woven LED matrix to fiber optics. Textile lighting can be applied in many applications ranging from art installations to automotive lighting. One application is photodynamic light therapy which is commonly used in oncology, gastroenterology, and dermatology. A uniform light source is crucial for photodynamic therapy, and a flexible textile-based light source improves light delivery to curved surfaces. The most efficient way to achieve this is by integrating side-emitting optical fibers into a flexible structure [21]. This same textile woven with optical fibers has been used in a variety of fashion designs. Over time, lighting applications will be used more often in fashion as they offer wearers an added aesthetic element to control their self-expression. Smart textile lighting products will become more common in everyday items as integrated textile systems become more robust, durable, and discreet.

Chapter 4: Concerns

As with any developing technology, there are concerns with the ethics of smart textiles. In contemporary society, consumers are increasingly concerned with how their clothes are produced as well as their environmental impact. The processes used to create electronics are precise and expensive, sometimes requiring micrometer precision to optimize electrical behavior. On the other hand, textile processes are low cost but less accurate in terms of dimensions and thread placement as the focus is producing large textile surfaces. Even though many textile manufacturing processes are automated, the precision needed to create smart textiles is still labor-intensive even when using industrial machines [2]. Textile production remains concentrated in countries where labor costs are low in comparison to countries such as the United States. Another common ethical concern today is data security. Many people would probably hesitate to purchase smart textiles that transmitted physiological data to another device for fear of the data being taken or manipulated. For example, manipulated health data could lead to a misdiagnosis.

Two major environmental risks within the production of smart textiles are the consumption of scarce raw materials and creating electronic waste that is difficult to recycle. The textile industry is responsible for many environmental problems as raw materials such as cotton are consumed, and textile production causes improper waste disposal and excessive use of water, energy, insecticides, and chemical treatments [22]. The microelectronic industry pollutes the environment with heavy metals and toxic chemical compounds, and fabricating electronics requires the use of rare metals such as coltan or gallium. Companies and researchers can minimize the impact of smart textile production by reducing waste, energy consumption, and material usage. These efforts support the environment and have a positive effect on business

[22]. The overall sustainability of a smart textile is dependent on the sustainability of the individual parts of the device as these components come from different supply chains.

A smart textile product should be durable, extending its lifetime, but once one of these projects loses its electrical functionality or tears, how is it disposed of? Ideally, electrical components could be replaced. For example, the smart textiles could be isolated to the collar of a shirt, and if the smart shirt is damaged and loses its functionality, a new collar may be sewn on. If the product must be thrown out, it should be recycled to preserve resources. Textiles are generally well suited for recycling. The ability to recycle smart textiles depends on the amount of integration between the textile and electronic elements. If most devices on the smart textile are standard electronics, they can be physically removed and recycled separately. Even so, electrical hardware is difficult to recycle as packages contain very small quantities of various materials. With conductive textile yarns used in most seamless integrated textiles, the deposition of metals throughout the fabric makes recycling textiles even more difficult [22]. The further the electrical components are integrated into the fiber-level, the more difficult it is to dispose of smart textiles responsibly. This contradicts the progress of research in smart textiles towards fiber-level electronics, so there is a trade-off between sustainability and further innovation.

It must also be considered how smart textiles are powered. Ideally, the power supplies are lightweight but have a large capacity to ensure the target application is powered for several hours. It is most common to use rechargeable batteries to power smart textiles, but batteries are impossible to fully integrate into the architecture of the textile [2]. Consequently, there is a drive to find lightweight alternative power generation or storage. One possibility is ultrathin, flexible energy storage devices based on supercapacitors and batteries created by sheets of nanocomposite that can adapt to strict shape and space requirements [23]. Another approach is building all-carbon solid-state yarn supercapacitors using commercially available carbon fiber yarns with the carbon fibers acting as current collectors [24]. These yarns demonstrate mechanical flexibility with minor changes in capacitance. As the carbon materials used are safe and already commercially available, yarn supercapacitors are ideal for scaling up textile-based power alternatives in the future.

There is also research in harvesting solar energy using thin-film photovoltaics. Photovoltaic cells can be made on lightweight and flexible substrates. Efficient solar cells made with organic semiconductors are less expensive and easily manufactured as well [25]. Individual photovoltaic fibers made of nano-layers of organic polymers on polypropylene tape can be woven into a textile [26]. The power conversion efficiency of the photovoltaic tapes was increased by adding a layer of gold underneath the layers of electrode making the photovoltaic cell [27]. Solar cells are more expensive than rechargeable batteries to produce, but they avoid dependence on electricity which could be produced by polluting fossil fuels such as coal.

Power can be generated by the human body as well. Heat dissipation, joint rotation, bodyweight enforcement, and displacement of mass centers are a viable source of power [28]. A smart textile user could charge their device by simply going through their daily activities. Mechanical energy could be harvested in shoes through the piezoelectric effect [28]. Smart textiles could even be self-powered using the electrostatic energy generated by motion through triboelectric nanogenerators fabricated using textile-mounted electronics, embroidery, deposition of salinizing agents [29]. Nevertheless, these approaches do not have a better capacity of maximum current value than traditional batteries while being relatively low cost [30]. Textile compatible power is still needed for future applications to continue expanding the capabilities of smart textiles and to make computers seemingly disappear into everyday objects.

Chapter 5: Market Viability and the Future of Smart Textiles

The smart textile market is currently driven by applications for healthcare and personal protection as there are few examples of smart textiles used in everyday clothing and commercial applications. Possible commercial applications vary from sports and wellness to telecommunications to augmented reality gaming, and commercial products will most likely depend on sensing (health monitoring), heating, and lighting applications. The consumer wearables market continues to grow, resulting in investment in new smart textiles and their associated manufacturing technologies [2]. The developing new market of smart textiles allows smaller traditional textile manufacturers to enter a technological niche. As a result, the small textile manufacturer has a new edge competing against large textile manufacturers who offer lower prices due to cheap labor overseas. The following graph in Figure 4 illustrates the forecast of the possible growth in the market of smart textiles. The market demand for smart textiles in 2021 is projected to be 2.9 billion dollars.

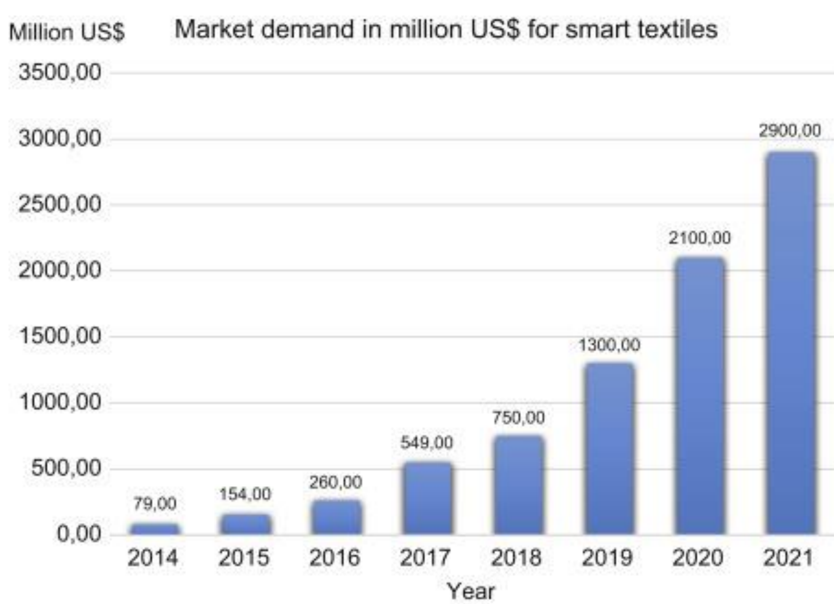

Figure 4. Evolution of the smart textiles market [31].

Nevertheless, there are still several barriers in the way of smart textiles entering the mainstream and transforming everyday life. The development of smart textiles requires the convergence of the fields of electronics and textiles, two contrasting industries. Currently, smart textile research is driven by research in electronics. Consequently, product development focuses on technical aspects of design such as integrating microchips into clothing and overcoming wash-and-care problems. Developments centered on the clothing industry are uncommon from a lack of knowledge about new textile technology or simply the lack of motivation to use smart textiles in clothing products [32]. For large-scale, automated production to be successful, the fabrication process of smart textiles must be compatible with traditional industrial textile production processes, so researchers in technology, textile scientists, and fashion designers must combine their experience in different backgrounds to manufacture smart textile products.

Other disciplines must be involved in this process as well such as polymer scientists to make conductive coating and inks. For the design of physiological sensors, biomedical engineers must be involved in the collaboration. Each field has its jargon, which can make communication difficult. Those involved in this collaboration can expand their knowledge, developing new skill sets in vastly different fields. This collaboration between people of different specialties offers an opportunity for diversity of thought, resulting in innovation and new solutions. The integration of technology into textiles would also make the textile industry more competitive and knowledge-driven, rejuvenating an established commercial sector for the twenty-first century.

Additionally, as smart textile development is an emerging field, there is little standardization and regulation for new products. Smart textile production is costly, so businesses must risk supporting research and development financially. This emerging technology must also be accepted by the general public to be commercially viable. The electrical capabilities of smart clothing and smart furniture must add tangible value to the product to justify a large price tag. These electrical capabilities must differentiate themselves both from the conventional clothing and existing electronic devices users already own to motivate buyers to purchase these products, even trading up the sensorless goods they already own. The general public who is uneducated in the field of smart textiles will also be concerned about how the products affect their safety and how the electronics can be washed. Due to better healthcare, the mean age of the population around the world has risen, and smart textiles would offer a convenient, efficient way to keep the elderly stronger, safer, and healthier. Ironically, this demographic is typically the most opposed and questioning of advancements in technology.

Smart textiles are held to the same judgments made when consumers are considering buying traditional textiles, so smart textiles must be comfortable and stylish as well. The more sensors placed on the garment, the less breathable the clothing becomes. Designers must avoid placing electronics in areas that are prone to chafing or experience a higher degree of mechanical flexion. For example, electronics should not be placed under the armpit. The smart clothing designs currently available are classic styles. There is little room for self-expression outside of these classic garments though. Lighting displays offer an avenue for unique styling, but this is unpractical for everyday wear as lighting designs usually require a large amount of power. As smart textiles continue to mature, their nature will mirror normal clothing in style, comfort, and durability. In modern society, many shoppers who can afford smart textiles and new gadgetry consider the ethics and sustainability of a product as well. Environmental and ethical responsibility positively impacts business revenue [22]. Consumers must consider how often their smart clothing must be replaced to due wear and tear or damage from wash-and-care. Ideally, smart textiles would be self-cleaning and stain-resistant, and consumers shift from the habit of washing clothes for freshness to only doing laundry when the smart clothing is truly dirty. Even so, the product will eventually meet the end of its life, but as electronics are further integrated into the textile, the more difficult it is to recycle. This is contrary to the goal of smart textile research to integrate as many electrical functions into smart textiles as possible.

Despite these drawbacks, an advantage of smart clothing is the opportunity to be connected to technology without being tethered to the screen of a mobile phone. This was one of the main goals with the high-profile Project Jacquard jacket made in partnership by Google and Levi's which was designed to keep cyclists safer on their commute while still giving the wearer access to information. Project Jacquard has made it possible to implement touch and gesture interactivity into any textile using industrial weaving looms. The Jacquard jacket has self-capacitive sensors made by weaving custom conductive yarn on the sleeve cuff, and it responds to brushing up the sleeve, down the sleeve, covering, and tapping on the cuff [5]. Because there are only four controlling gestures, there is a limited number of responses and technological capabilities at a given moment. The jacket may be washed using the same care instruction for a regular Levi's jacket if the small Jacquard computer tag holding the higher-order electronics is removed. The jacket is currently selling for $200 to $250, which is more than most of the general public is willing to pay for a denim jacket with limited technological functions. For smart textiles to make a significant impact on the future, a large-scale, low-cost manufacturing process must be developed to make cheaper products that are more accessible to the average consumer. Finally, because of the limited functionality and expensive price tag, the question for consumers is "What is the point?" Consumers will prefer a cheaper, conventional jacket. The

Jacquard jacket, while interesting, is a solution to a problem that did not exist. Even so, updates are still being released to the Jacquard computer, expanding its functionality, and the small Jacquard device can be inserted into compatible goods like shoes and backpacks. As functionality improves, Project Jacquard will lead the way for commercial applications of smart textiles.

While it seems smart textile development could be fruitless, consumers will be driven to buy more smart textile products as electrical functionality improves and the textiles feel and look more like conventional textiles. There are clear gaps to fill in the design and fabrication of smart textiles as the fields of electronics and textiles converge, but as smart textiles mature, computers will be seamlessly integrated into everyday objects. As digital interfaces become invisible, society is one step closer to achieving the world depicted in science fiction.

References

[1] V. Koncar, Ed., *Smart Textiles and Their Applications*. Duxford: Woodhead Publishing, 2016.

[2] K. Cherenack and L. V. Pieterson, "Smart textiles: Challenges and opportunities," *Journal of Applied Physics*, vol. 112, no. 9, Nov. 2012

[3] E. O. Thorp, "The invention of the first wearable computer," Digest of Papers. Second International Symposium on Wearable Computers (Cat. No.98EX215), Pittsburgh, PA, USA, 1998, pp. 4-8.

[4] E. R. Post, M. Orth, P. R. Russo and N. Gershenfeld, "E-broidery: Design and fabrication of textile-based computing," in IBM Systems Journal, vol. 39, no. 3.4, pp. 840-860, 2000.

[5] I. Poupyrev, N.-W. Gong, S. Fukuhara, M. E. Karagozler, C. Schwesig, and K. E. Robinson, "Project Jacquard," *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pp. 4216–4227, May 2016.

[6] J. Krauledaitė, K. Ancutienė, V. Urbelis, S. Krauledas, and V. Sacevičienė, "Development and evaluation of 3D knitted fabrics to protect against mechanical risk," *Journal of Industrial Textiles*, Vol. 49, no. 3, pp. 383–401, Jun. 2018.

[7] J. L. Dorrity and G. Vachtsevanos, " On-line defect detection for weaving systems," in Proceedings of IEEE 1996 Annual Textile, Fiber and Thin Film Industry Technical Conference, 15–16 May 1996, pp. 1–6

[8] M. Grell, C. Dincer, T. Le, A. Lauri, E. N. Bajo, M. Kasimatis, G. Barandun, S. A. Maier, A. E. G. Cass, and F. Güder, "Autocatalytic Metallization of Fabrics Using Si Ink, for Biosensors, Batteries and Energy Harvesting," *Advanced Functional Materials*, vol. 29, no. 1, Sep. 2018.

[9] P. Calvert, P. Patra, T.-C. Lo, C. H. Chen, A. Sawhney, and A. Agrawal, "Piezoresistive sensors for smart textiles," *Electroactive Polymer Actuators and Devices (EAPAD) 2007*, Apr. 2007.

[10] J. B. Lee and V. Subramanian, "Weave patterned organic transistors on fiber for E textiles," in IEEE Transactions on Electron Devices, vol. 52, no. 2, pp. 269-275, Feb. 2005.

[11] E. Bonderover and S. Wagner, "A Woven Inverter Circuit for e-Textile Applications," *IEEE Electron Device Letters*, vol. 25, no. 5, pp. 295–297, May 2004.

[12] M. Hamedi, R. Forchheimer, and O. Inganäs, "Towards woven logic from organic Electronic fibres," *Nature Materials*, vol. 6, no. 5, pp. 357–362, Apr. 2007.

[13] K. Cherenack, C. Zysset, T. Kinkeldei, N. Münzenrieder, and G. Tröster, “Woven Electronic Fibers with Sensing and Display Functions for Smart Textiles,” *Advanced Materials*, vol. 22, no. 45, pp. 5178–5182, Oct. 2010.

[14] J. Meyer, P. Lukowicz and G. Troster, "Textile Pressure Sensor for Muscle Activity and Motion Detection," 2006 10th IEEE International Symposium on Wearable Computers, Montreux, 2006, pp. 69-72.

[15] O. Atalay, W. Kennon, and M. Husain, “Textile-Based Weft Knitted Strain Sensors: Effect of Fabric Parameters on Sensor Properties,” *Sensors*, vol. 13, no. 8, pp. 11114 11127, Aug. 2013.

[16] Y.-L. Yang, M.-C. Chuang, S.-L. Lou, and J. Wang, “Thick-film textile-based amperometric sensors and biosensors,” *The Analyst*, vol. 135, no. 6, p. 1230, 2010.

[17] B. S. Shim, W. Chen, C. Doty, C. Xu, and N. A. Kotov, “Smart Electronic Yarns and Wearable Fabrics for Human Biomonitoring made by Carbon Nanotube Coating with Polyelectrolytes,” *Nano Letters*, vol. 8, no. 12, pp. 4151–4157, Nov. 2008.

[18] S. Park, K. Mackenzie, and S. Jayaraman, “The wearable motherboard: a framework for personalized mobile information processing (PMIP),” *Proceedings 2002 Design Automation Conference (IEEE Cat. No.02CH37324)*, 2002.

[19] Fabrice Axisa, P. M. Schmitt, C. Gehin, G. Delhomme, E. McAdams and A. Dittmar, "Flexible technologies and smart clothing for citizen medicine, home healthcare, and disease prevention," in IEEE Transactions on Information Technology in Biomedicine, vol. 9, no. 3, pp. 325-336, Sept. 2005.

[20] M. A. El-Sherif, J. Yuan, and A. Macdiarmid, “Fiber Optic Sensors and Smart Fabrics,” *Journal of Intelligent Material Systems and Structures*, vol. 11, no. 5, pp. 407 414.

[21] J. B. Tylcz, C. Vicentini, and S. Mordon, “Light emitting textiles for a photodynamic therapy,” in *Smart textiles and their applications*, V. Koncar, Ed. Duxford: Woodhead Pub., 2016.

[22] S. Ossevoort, “Improving the sustainability of smart textiles,” *Multidisciplinary Know How for Smart-Textiles Developers*, pp. 399–419, 2013.

[23] V. L. Pushparaj, M. M. Shaijumon, A. Kumar, S. Murugesan, L. Ci, R. Vajtai, R. J. Lindhardt, O. Nalamasu, and P. M. Ajayan, “Flexible energy storage devices based on nanocomposite paper,” *Proceedings of the National Academy of Sciences*, vol. 104, no. 34, pp. 13574–13577, Aug. 2007.

[24] S. Zhai, W. Jiang, L. Wei, H. E. Karahan, Y. Yuan, A. K. Ng, and Y. Chen, “All-carbon

solid-state yarn supercapacitors from activated carbon and carbon fibers for smart textiles," *Materials Horizons*, vol. 2, no. 6, pp. 598–605, Jul. 2015.

[25] M. Pagliaro, G. Palmisano, and R. Criminna, *Flexible Solar Cells*. John Wiley & Sons, Ltd, 2008.

[26] A. C. Bedeloglu, A. Demir, Y. Bozkurt, and N. S. Sariciftci, "A Photovoltaic Fiber Design for Smart Textiles," *Textile Research Journal*, vol. 80, no. 11, pp. 1065–1074, Oct. 2009.

[27] A. C. Bedeloglu, R. Koeppe, A. Demir, Y. Bozkurt, and N. S. Sariciftci, "Development of energy generating photovoltaic textile structures for smart applications," *Fibers and Polymers*, vol. 11, no. 3, pp. 378–383, Jun. 2010.

[28] D. Jia and J. Liu, "Human power-based energy harvesting strategies for mobile electronic devices," *Frontiers of Energy and Power Engineering in China*, vol. 3, no. 1, pp. 27–46, Jan. 2009.

[29] M. S. D. Medeiros, D. Chanci, C. Moreno, D. Goswami, and R. V. Martinez, "Electronic Textiles: Waterproof, Breathable, and Antibacterial Self-Powered e-Textiles Based on Omniphobic Triboelectric Nanogenerators (Adv. Funct. Mater. 42/2019)," *Advanced Functional Materials*, vol. 29, no. 42, Jul. 2019.

[30] M. Frydrysiak, "Textronics-Electrical and electronic textiles. Sensors for breathing frequency measurement," *Fibers and Textiles in Eastern Europe*, vol. 14, no. 5, 2006.

[31] V. Koncar, Ed., *Smart Textiles for In Situ Monitoring of Composites*. Duxford: Woodhead Publishing, 2019.

[32] B. Ariyatum and R. Holland, "A strategic approach to new product development in smart clothing," *Journal of Asian Design International Conference*, pp. 70–80, 2003.