ABSTRACT

MEOLI, DINA. Interactive Electronic Textiles: Technologies, Applications, Opportunities, and Market Potential. (Under the direction of Dr. Traci May-Plumlee.)

The developing area of interactive electronic textiles is generating an abundance of literature within the textile industry. Presently, researchers in this area are working toward the development of interactive touch and voice activated wireless electronic textiles. Potentially, these specialized textiles will integrate many communication, entertainment, and safety devices directly into traditional textile and apparel products.

The purpose of this research was to study the emerging area of interactive electronic textiles. First, available literature was used to examine interactive electronic technologies, the potential application areas for these technologies, and the potential market appeal for interactive electronic textiles. Hypotheses were developed regarding expert perceptions of the potential technologies appropriate for mass-producing these products at affordable price points. To test the hypotheses, expert opinions regarding future opportunities, applications, and market appeal for interactive electronic textiles were obtained via an Internet-based electronic survey. The results of the survey revealed that numerous viable technologies were being investigated for developing interactive electronic textiles; health and safety, communication, and entertainment were perceived as major growth areas for these specialized textiles; and that product attributes, operation difficulty levels, and user concerns were considered to have important implications for interactive electronic textiles market appeal.

INTERACTIVE ELECTRONIC TEXTILES: TECHNOLOGIES, APPLICATIONS, OPPORTUNITIES, AND MARKET POTENTIAL

by
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BIOGRAPHY

The author, Dina Meoli, was born on April 7, 1970, in Queens, New York. She moved to Florida in 1975 with her family where she received her primary and secondary education. In 1988, she graduated from Largo High School in Largo, Florida. While attending high school, she developed an interest in fashion and textiles. This led her to Saint Petersburg Vocational and Technical Institute where she studied the fundamentals of apparel construction and design during 1988-1990.

In 1993, she entered the Fashion Institute of Technology in New York City. She graduated Magna Cum Laude earning a Bachelor of Science degree in Textile Development and Marketing in 1997. In 2000, she moved to Raleigh, North Carolina to attend North Carolina State University. Currently, she is pursuing a Master of Science Degree in Textiles with a Management concentration.

ACKNOWLEDGMENTS

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CHAPTER ONE: INTRODUCTION

As electronics become smaller, less expensive, and require less power we have begun to adorn our bodies with personal information and communication devices. Such devices include cellular phones, personal stereos, pagers, personal digital assistants (PDA's), pocket video games, and notebook computers. As we move into an electronic future, many of these devices will be integrated into our apparel. Developing these wearable-computing products is emerging as an important research and technology area. Many different terms are being used to identify this new area. Examples include: "Wearable Computers", "Smart Garments", and "Intelligent Garments". However, these terms all fail to include the other numerous applications for the specialized textiles typical of this product category. Integrated intelligence has the potential to benefit many traditional textile applications such as medical, military, industrial, and commercial and residential textiles. For the purpose of addressing the entire area with one term, "Interactive Electronic Textiles" will be used throughout the remainder of this paper to identify this emerging area.

Since interactive electronic textile products are in the early stages of development, there are many questions and concerns about this emerging area. Many of these questions stem from the technologies being used to produce these products as well as the application areas and market potential. As new products enter the market that will affect our social and business culture, potential concerns such as privacy, security, and safety will also develop. This research provides an in-depth study of the interactive electronic textiles arena by reviewing literature, interviewing experts, and conducting surveys. Together these research methods provide understanding and insight into the area of interactive electronic textiles.

1.1 PURPOSE OF RESEARCH

The purpose of this research is to explore the emerging area of interactive electronic textiles. This research identifies and examines expert perceptions of the technologies, their potential application areas, and the market potential for interactive electronic textiles. The technologies range from the conductive materials used for product development, to the electronics used activate them. Many of these technologies are already used successfully outside the textile complex for other applications. Efforts are underway to modify and adapt them for interactive electronic textile development. Considering the production of electronic devices and textiles are two quite different areas, both industries must combine their expertise to successfully develop interactive electronic textile products. Therefore, understanding the product development efforts of each industry is vital to this new areas success. By understanding the development efforts for interactive electronic textiles we will have a better idea of which technologies will be the first to market within this new area. Expert perceptions of the applications, future opportunities, and the potential market appeal for interactive electronic textiles were also identified and examined. The available literature suggests there are many appropriate applications and markets for these specialized textiles. Potential applications and opportunities range from fashion and functional apparel to commercial and residential furnishings. An on-line electronic survey questionnaire was administered to industry experts presently researching and developing these specialized textiles to gather data on the specifics of interactive electronic textile development including the technologies, the applications, and the market potential for these products.

1.2 RELEVANCE OF PROPOSED RESEARCH

The interactive electronic textiles arena has generated an abundance of literature, especially trade literature. The literature suggests the merge of electronics and textiles will offer significant opportunities for both industries. These opportunities stem from increased consumer demand for lightweight mobile electronics. Technological advances have enabled electronics to become smaller and more powerful. Many industry experts are seeking to take this one step further by integrating electronics into textiles to increase user mobility and comfort. This involves understanding available technologies and how they can be used to develop interactive electronic textiles. The firms that understand how to incorporate these emerging technologies into their business strategy will establish and sustain financial and competitive advantages within their industry. This research provides a better understanding of the current work and foci in the interactive electronic textiles arena and may potentially open the area to new concepts and ideas. When a research study can provide information to assist industry with further understanding of a new emerging area it proves to be worthwhile and relevant.

1.3 RESEARCH QUESTIONS

The research questions for this project are significant to the emerging literature on interactive electronic textiles. They were developed to provide a better understanding of this new technological area within the textile industry and to address some of the questions that were unanswered. Considering that there are many different technologies being used to develop interactive electronic textiles, the potential of each individual technology is ambiguous. Therefore, the first research question to address is:

Question 1: Which technologies have the greatest potential in the area of interactive electronic textiles?

Determining the significant technologies will clarify the focus of research efforts and assist further development. Identifying and perfecting the significant technologies will enable both researchers and practitioners to have a better understanding of the future opportunities for interactive electronic textiles. Once the significant technologies have been identified, questions arise as to the most appropriate applications. This brings us to the second research question.

Question 2: Which application areas have the greatest potential for interactive electronic textiles?

Available literature suggests the main application areas for interactive electronic textiles are communication, entertainment, health, and safety. However, the significance of each application area is unclear. By determining which applications possess the greatest potential, researchers and practitioners will gain insight on the future market opportunities for interactive electronic textiles. This directly relates to the third research question.

Question 3: According to an industry expert perspective, what will be the potential market appeal for interactive electronic textile products?

Industry experts presently involved in interactive electronic textile research and development can provide valuable insight into the expected potential market appeal for interactive electronic textiles. There are many factors that can affect the market success for new technological products. Factors relating to the success of interactive electronic textile products include difficulty levels for use, care and maintenance, compatibility among products, and affordability. Considering this area is still developing, those presently advancing this area are the most appropriate to provide perceptions on the expected potential market appeal for these specialized textile products.

1.4 CONCLUSION

The preceding section provided an introduction to the emerging area of interactive electronic textiles and why it is an important topic to explore, the research relevancy, and the research questions at hand. The following chapters outline the research and report the results. Chapter two provides a review of the literature that serves as the foundation for this research. Chapter three converts the research questions into testable hypotheses. Chapter four outlines the research methodology used for conducting the survey. Chapters five and six examine the research results and chapter seven explores opportunities for future interactive electronic textiles research.

CHAPTER TWO: LITERATURE REVIEW

2.1 HISTORY OF WEARABLE COMPUTING

Wearable computing devices have been around for years. They can easily be defined as devices that become part of the users personal space and are operationally and interactionally controlled by the user, i.e. they are always on and accessible (Mann, 1998). Historical research suggests the first complete wearable computer, conceived in 1955, was designed to predict outcomes of the casino gambling game roulette. This wearable system was a cigarette-pack sized analog computer with four push buttons. A data taker would use the buttons to indicate the speed of the roulette wheel, then the computer would send tones via radio to a hearing aid worn by the bettor. This wearable was later prototyped in 1961 by Edward Thorp and Claude Shannon at the Massachusetts Institute of Technology. Thorp disclosed a similar system, featured in the March 27th 1964 issue of Life Magazine, for beating the Wheel of Fortune gambling game (Siewiorek, 1999).

Since then, many researchers have experimented with wearable concepts. One such researcher, Steve Mann, professor at the Massachusetts Institute of Technology (MIT), is considered a pioneer in the area of wearable computing. He has been designing and building wearable devices since the early 1980's. Early wearable computing systems developed by Mann consisted of head and waist mounted displays and cameras (Figure 1) (Mann, 1996). These apparatuses have proved to be cumbersome and awkward, therefore they are impractical for daily use. Today, Mann's wearables have shifted toward more comfortable and practical devices such as eyeglass based communication systems, 'smart shoes' that incorporate sensors to provide information on footstep force and velocity, and 'smart undergarments' that can monitor heart rate and respiration (Mann, 1996).

Figure 1: Wearable Computing Devices Developed By Steve Mann

A research group at Carnegie Mellon University coined the term ‘wearable computing’ in 1991. Today this term is used to define a wide assortment of wearable devices that incorporate electronics. Examples of these devices are pocket and wristwatches, portable cassettes and compact disk players, and notebook computers. These wearable electronic devices can either be strapped on the body or easily carried in a pocket for transferring, receiving, and storing information (Siewiorek, 1999).

Many of the wearable electronics developed to date are cumbersome and awkward due to the materials and processes used in their fabrication (Figure 2). As a result, most of these devices are only wearable in the sense that they can be strapped on the body or carried. Today interest in wearable computing is increasing and development is shifting toward more lightweight and practical wearable devices. The concept of textile-based computing is currently being explored, integrating electronic technologies directly into textiles and apparel to create truly wearable devices.

Figure 2: Head-Mounted Wearable Computers

2.2 ELECTRONIC TEXTILES

In the past, clothing containing electronics was only portrayed in the world of science fiction. The merging of textiles and technology has made electronic textiles an exciting new reality. The idea of integrating electronics into our textile and apparel products is no longer science fiction. Textile-based computing is currently being developed, allowing the wearer to easily move audio, data, and power around a garment or textile. These specialized textiles have the potential to keep us connected, informed, and entertained without the need to carry any electronic devices. Interactive touch, voice, and body heat activated wearable electronics are being developed and are gradually appearing on store shelves. The development of these items is fueled by the increasing desire for mobile devices that will allow us to access information anywhere and at anytime.

Interactive electronic textiles items on the market today use integrated wiring and carrying devices that add bulk and weight to the garments making them uncomfortable and impractical for daily use. Furthermore, these items are expensive and present issues relating to garment care, flexibility, and user safety. The first wired electronic apparel line was recently developed by two leading wearable technology developers, Levi Strauss & Co. and Philips Research Laboratories. In August of 2000, they were the first to introduce an outerwear line, ICD+ (Industrial Clothing Design Plus), comprised of four "wired" jackets that combined garment functionality with wearable electronics. One of the four jackets included in the ICD+ outerwear line is the Mooring (Figure 3).

Figure 3: The "Mooring" Jacket

These jackets incorporate a communications system that connects a mobile phone and MP3 player (Figure 4). The garment also has built-in speakers, a microphone and a display (Figure 5). A personal area network (PAN) provides the backbone for connecting these electronics. Concealed inner wiring and connectors in the fabric allow the devices to operate by remote control.

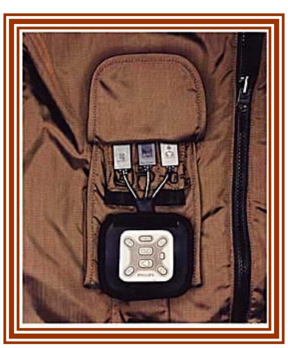

Figure 4: Communications System

Figure 5: Speakers and Microphone

The devices and the control pad can be disconnected for garment laundering, however the inner wiring and connectors cannot be removed.

Currently, these jackets only work with Philips' devices, and will require upgrading as new technology makes its way into clothing. Limited editions of these jackets are now available in Europe for $600 to $900, and may be launched soon in American markets (Izarek, 2000).

As the demand for practical lightweight mobile devices for storing, accessing, and transferring information increases, so does the demand for wireless wearable devices. Many believe the future is wireless. Electronic devices such as cellular phones, personal stereos, and computers can be integrated directly into textiles and apparel by using conductive materials to provide these highly mobile and convenient wireless capabilities.

2.3 INTERACTIVE ELECTRONIC TEXTILE TECHNOLOGIES

The tactile and aesthetic properties of textile and apparel products are important to consumers. Many are reluctant to wear bulky gadgetry or have wires and hard plastic cases containing electronics against their bodies. In the effort to develop lighter more appealing wearable devices, conductive materials are being used to transform traditional textile and apparel products into fashionable, desirable, lightweight, wireless wearable computing devices. Materials, such as metallic and optical fibers, conductive threads, yarns, fabrics, coatings and inks are being used to supply conductivity and create wireless textile circuitry.

2.3.1 METALLIC AND OPTICAL FIBERS

Electronic textiles can be created by using minute electrically conductive fibers. These metallic fibers have been used for years in various industrial applications for the purpose of controlling static and electromagnetic interference shielding. Today, metallic fibers are finding new applications in the development of electronic textiles. Electrically conductive fibers can be classified into two general categories, those that are naturally conductive and those that are specially treated to create conductivity (Lennox-Kerr, 1990).

Naturally conductive fibers or metallic fibers are developed from electrically conductive metals such as ferrous alloys, nickel, stainless steel, titanium, aluminum, copper, and carbon. Metal fibers are very thin metal filaments, with diameters ranging from 1 to 80 microns (µm). Officially called a micrometer, a micron (µm) is one thousandth of a millimeter. To illustrate the fineness of a metallic fiber of 1 µm, a comparison can be made between these fibers and the diameter of a strand of human hair which ranges between 70 and 100 µm (Figure 6) (Bekaert Fiber Technologies, 2001).

Metallic fibers are typically produced by either using a bundle-drawing process or by a shaving process. The bundle-drawing process consists of bundling several fine metal wires then drawing them continuously and simultaneously from source metals.

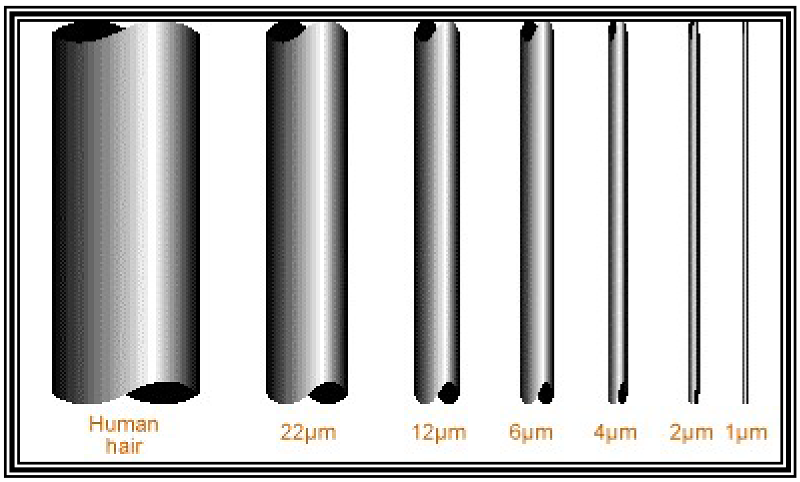

Figure 6: Metallic Fiber Diameters Compared to Human Hair

Figure 7 illustrates the steps involved in the metal fiber bundle-drawing process. While the shaving process in Figure 8, develops metallic fibers by shaving off the edge of a coil of a thin sheet of metal.

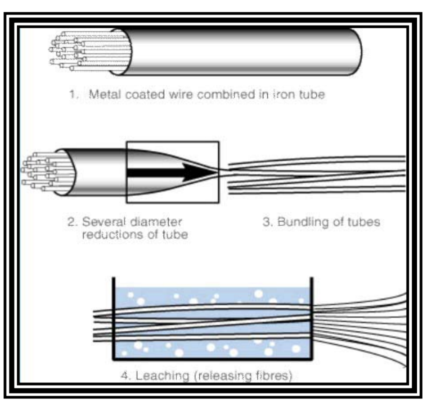

Figure 7: Bundle Drawing Process

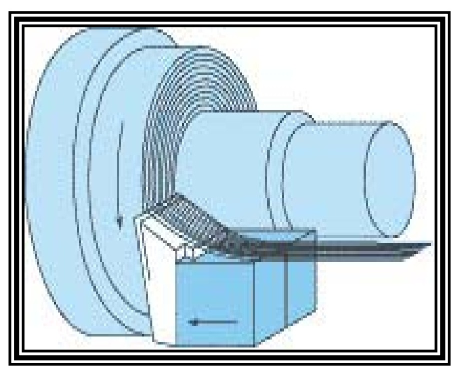

Figure 8: Shaving Process

A thread developed from steel and polyester fibers is shown in Figure 9, while a 100% stainless steel thread is illustrated in Figure 10. Metallic fibers are highly conductive, however they expensive and their brittle characteristics can damage spinning machinery over time. In addition, they are heavier than most textile fibers making homogeneous blends difficult to produce (Bekaert Fiber Technologies, 2001).

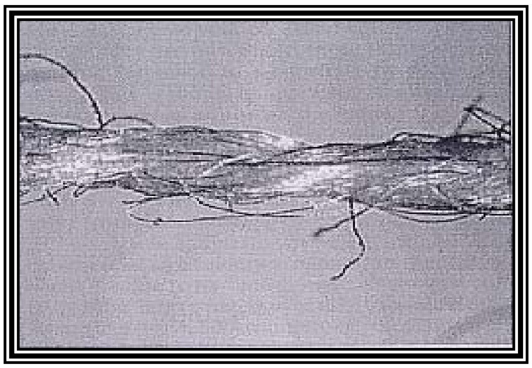

Figure 9: Stainless Steel and Polyester Thread

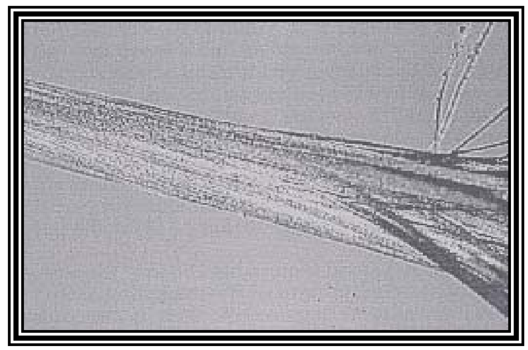

Figure 10: 100% Stainless Steel Thread

Electrically conductive fibers can also be produced by coating the fibers with metals, galvanic substances or metallic salts like copper sulfide and copper iodide. Metallic fiber coatings produce highly conductive fibers, however adhesion between the metal and fiber and corrosion resistance can present problems. Galvanic coatings produce fibers with relatively high conductivity. However, galvanic coatings can only be applied to conductive substrates, limiting these galvanic coatings to graphite and carbon fibers. Furthermore, the galvanic coating process is complex and expensive. Due to these limitations, galvanic coatings are usually not used for textiles. A variety of fibers can be coated with metallic salts and the coating process can be accomplished on traditional textile machinery. Metallic salt coatings can only achieve low conductivities and the fibers lose conductivity during laundering. Altering coating procedures can improve these limitations and the appeal of metallic salt coatings (Lennox-Kerr, 1990).

Electrically conductive fibers can be produced in filament or staple lengths and can be spun with varying ratios of traditional non-conductive fibers to create yarns that possess different degrees of conductivity. Conductive fibers are functionally compatible with the base material so they can be used to develop a wash and wear conductive fabric that will look and feel like a normal fabric. The electronic textile is completed when microelectronics are linked to the fabric. Micro electronics provide digital and analog functions in response to mouse input to activate sound and voice synthesis, and to incorporate remote controls for signals, guiding, and controlling the electronic textile (Electro Textiles, 1999).

Optical fibers can also be used to produce interactive electronic textiles. Optical or glass fibers, are about 120 micrometers in diameter. They are used to carry communications or computer data signals in the form of pulses of light over long distances without the need for repeaters. Optical fibers are used for many different applications including: composites, telecommunications, local area networks (LAN's), cable TV, closed circuit TV, optical fiber sensors, and conductive textiles (Bell College, 1997).

Optical fibers are developed from a mixture of silica sand, borates and trace amounts of specialty chemicals. The mixture is then blended and fed into a furnace to dissolve the sand mixture into molten glass. The molten glass flows to heat resistant platinum trays with small tubular openings called "bushings." The molten glass is drawn out through the bushings to a precise diameter and cooled by air and water to set the diameter and create a filament. The filaments are then coated with an aqueous chemical mixture called a "sizing" to protect the filaments during processing and handling. The production process is completed when the sized filaments are wound and packaged. Optical fibers offer excellent strength and they are not affected by sunlight exposure. However, they are relatively stiff fibers that possess poor flexibility, drapability and abrasion resistance (Owens Corning, 2001).

In 1996, optical and electrically conductive fibers were used by researchers at Georgia Institute of Technology to develop a smart shirt for a project funded by the United States Navy. The "Smart Shirt" is a T-shirt that functions like a computer to monitor the wearer's heart rate, EKG, respiration, temperature, and other vital signs. The third and forth generation "Smart Shirt" prototypes are illustrated in Figure 11 (Georgia Institute of Technology, 2000).

This smart T-shirt utilizes a groundbreaking electro-optical textile, the Wearable Motherboard™ Smart Shirt, that integrates broad based sensors with the human body to eliminate the need for loose wires and discomfort associated with many currently used patient monitoring devices.

Figure 11: "Smart Shirt" 3rd (Left) and 4th (Right) Generation Prototypes

The technology behind this shirt allows sensors to be mounted at various locations on the garment and allows information to be transferred to and from the sensors. The two technology platforms used to develop the Smart Shirt are a proprietary textile platform and a wireless communications/data management software platform (Sensatex Incorporated, 2001).

The “Smart Shirt” textile platform (Figure 12) consists of the

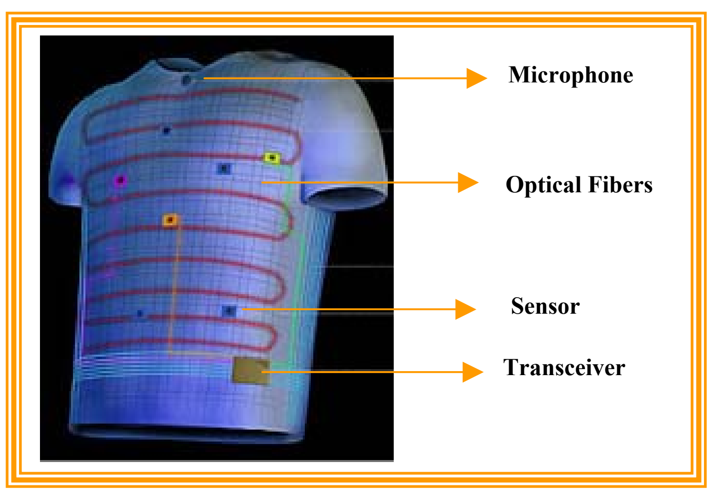

Figure 12: "Smart Shirt" Textile Platform

Wearable Motherboard™, that permits information to be transferred and exchanged within the garment. This textile platform collects data from various parts of the wearer's body and routes the data to a small transceiver device attached to the waist portion of the shirt. The transceiver handles the processing, transmission, and display of the wearer's vital signs. After the data is collected by the transceiver the data management software platform consisting of a computing system and a programming interface, transfers the information from the garment to a wireless gateway. The gateway then transmits the complex time-critical health data through the Internet where the actual monitoring occurs. The data is processed with monitoring software then it is sent to the wearer and/or the wearer's caregivers via the Internet. Together these platforms form a versatile framework for incorporating sensing, monitoring, and information processing devices for biomedical monitoring and wearable computing applications (Sensatex Incorporated, 2001).

Georgia Tech Research Corporation and Sensatex Incorporated, a start up company funded by New York-based Seed One Ventures, formed a licensing agreement to manufacture and market the "Smart Shirt." Sensatex expects the Smart Shirt to be less costly than current monitoring systems and predicts the Smart Shirt will be available to consumers in 2001. Presently, the Smart Shirt is being tested in over 12,000 clinical trials in the United States and is in the process of receiving FDA approval (Georgia Institute of Technology, 2000).

2.3.2 CONDUCTIVE YARNS AND THREADS

Conductive and optical fibers are just two materials that can be used to develop conductive yarns, and therefore interactive electronic textiles. Metallic yarns can also be used to produce electrically conductive textiles. Metallic yarns are created by wrapping a non-conductive yarn with a metallic copper, silver, or gold foil to provide conductivity. Believed to have originated in India, decorative fabrics developed from metallic yarns have been produced since the mid-18th century (Post, E.R., Orth, M., Russo, P.R., and Gershenfeld, N., 2000).

One example of this technology uses metallic silk organza. Metallic silk organza is a finely woven silk fabric developed from two types of yarns, the warp is a plain silk yarn and the weft is a silk yarn wrapped in a thin copper foil or thread (Figure 13). The metallic foil or thread is prepared just like a cloth-core telephone wire, and is highly conductive (~0.1 Ω/cm).

The copper thread transforms the silk yarn into a highly conductive yarn with a silk core. The physical properties of the silk core give the total yarn high tensile strength and a tolerance for high temperatures, allowing it to be sewn or embroidered on industrial machinery without being damaged. Furthermore, these properties make metallic yarns very promising for mass-producing interactive electronic textiles (Orth, 1997).

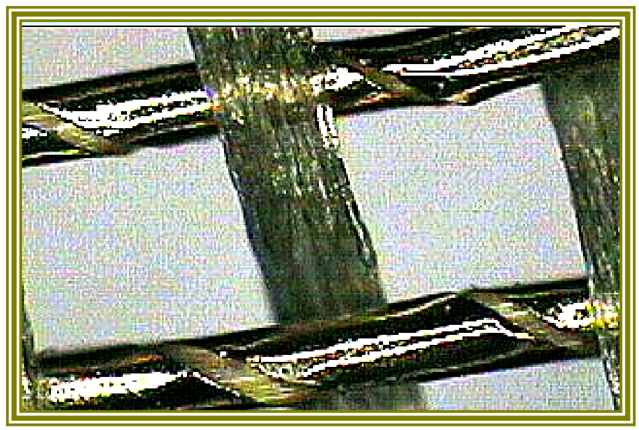

Figure 13: Micrograph of Metallic Silk Organza

A micro controller circuit attached to the organza provides the electronic interactive component for the fabricated circuit. The micro controller circuit shown in Figure 14 enables the textile to control light emitting displays (LED'S), sense touch along the length of the fabric, and use audible feedback through a piezoelectric speaker for interaction.

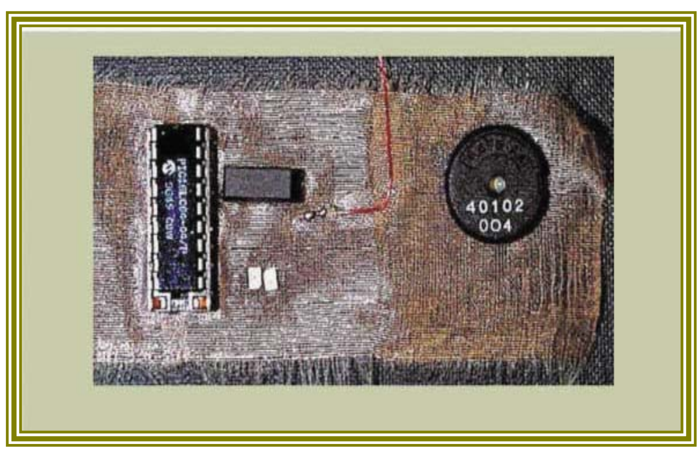

Figure 14: Micro Controller Circuit on Silk Organza

The micro controller and all of its supporting components are soldered on the surface of the metallic organza weave (Post et al., 2000).

Protecting the fabricated circuit is the final phase in completing the interactive electronic textile. Fabricated circuit protection assures the conductive yarns will not come into contact with each other when the material is folded or twisted. Coating, supporting, or backing the fabric with an insulating cloth layer can accomplish circuit protection. Coating the fabric has proved to disturb the conductivity. Backing is the preferred method because it provides a high degree of fabric flexibility (Post et al., 2000).

Conductive threads can also be used to develop interactive electronic textiles. Conductive threads are similar to conductive yarns, due to their composition of conductive fibers. However, there are some important differences between the two. Conductive threads have smaller diameters and therefore they perform better when machine sewn. The threads can easily pass through ordinary sewing machine needles and the thread's conductivity can be controlled through stitch placement. Furthermore, the conductivity of some conductive threads will increase from needle and bobbin contact. There are various types and diameters of conductive thread available today (Post et al., 2000).

Conductive fibers, yarns, and threads can be processed on ordinary textile machinery or by using embroidery techniques. Embroidery offers advantages over knitting or weaving. Conductive thread and yarn embroidery can be accomplished on single or multiple layers of fabric or can be applied on various types of textile and apparel products in one step. In addition, the circuit layout and stitch patterns can be precisely specified in a computer-aided design (CAD) environment (Post et al., 2000).

The embroidered fabric keyboard shown in Figure 15 was produced with a mildly conductive stainless steel and polyester composite thread using ordinary embroidery techniques. The keyboard is integrated into the Levi's Musical Jean Jacket developed by Massachusetts Institute of Technology (MIT) Media Lab (Figure 16). This flexible and durable embroidered fabric keyboard is highly responsive to touch, turning an ordinary denim jacket into a wearable musical instrument that allows the wearer to play notes, chords, and rhythms. The Levi's Musical Jean Jacket is not available in stores yet, but is currently being test marketed in Europe ("Musical Jacket Project").

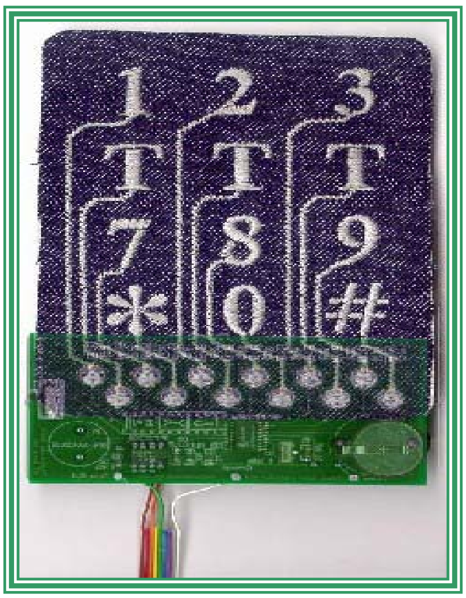

Figure 15: Embroidered Fabric Keypad

Figure 16: Levi's Musical Jean Jacket

2.3.3 CONDUCTIVE COATINGS

Traditional textiles can also be transformed into electrically conductive materials by using conductive coatings. These coatings are suitable for use on many fiber types. They also produce good conductivity without significantly altering existing substrate properties such as density, flexibility, and handle. Coatings can be applied to the surface of fibers, yarns, or fabrics to create electrically conductive textiles. Common textile coating processes include electroless plating, evaporative deposition, sputtering, and coating the textile with a conductive polymer.

Electroless plating involves immersing the substrate in an electroless plating solution. Chemical reactions between the reducing agent in the solution and the metal ions form the metal coating on the textile. Nickel and cooper are the most popular metals used for electroless plating, however various types of metals can also be used. Electroless plating has many advantages: it produces a uniform electrically conductive coating; any substrate that remains stable in the electroless plating solution can be coated in this manner; and it is possible to obtain coatings that possess unique mechanical, magnetic, and chemical properties. The main disadvantage of electroless plating is the expense, this is due to the high cost of the reducing agent used in the plating solution (Vaskelis, 1991).

Evaporative deposition takes place in a vacuum chamber. As the fabric enters the vacuum chamber the pressure inside the chamber is adjusted to accommodate the substrate. The coating metal is then heated to a temperature just below the boiling point to allow the metal to substantially evaporate. The fabric is exposed to the vaporized metal where it condenses on the surface and changes to a solid forming the coating. Aluminum is commonly used for this coating process, however various types of metals can be used. This process can produce extremely thin coatings for lower levels of conductivity or relatively thick coatings when higher conductivity is required. The major markets for evaporative deposition coatings include wall coverings, shades and drapery liners, automotive trim, solar energy control films, paper stock for microwave browning and crisping bags, and protective clothing. Research is being conducted to develop relatively thin highly conductive coatings to create highly conductive lighter weight fabrics (Smith, 1988).

The sputtering process also takes place in a vacuum chamber, however the coating process is different from evaporative deposition. The coating material is ejected atom by atom and is collected on the surface of the fabric, creating a thin coating. A wide range of textile substrates can be coated in this manner. In addition, different metals, alloys, or oxides can be mixed or layered in a single application to create specialized coatings for specific applications. This process can achieve a uniform coating with good adhesion to the substrate. The sputtering coating process is slow, about 1/10 of the speed of evaporative deposition. This is due to the low deposition rate of the coating material. This coating method is costly due to the speed limitation. Presently, the main applications for this coating process are textiles for military and aerospace applications (Siefert, 1993).

Conductive coatings can also be achieved by coating a textile with a conductive polymer. A process called doping develops conductive polymers. Doping is an oxidation or reduction process that mobilizes the electrons in the polymer creating an intra- or intermolecular structure within the polymer. This new polymer structure allows the polymer to conduct electricity, hence creating an electrically conductive polymer. Polymer properties such as conductivity, hydrophilic/hydrophobic state of the polymers surface, color, volume, and permeability for gases can also be adjusted during doping for specific end use applications (Aldissi, 1989).

The commercialization of electrically conductive polymers is still in its infancy. Presently, conductive polymer materials are used for various conductive and anti-static coatings, and films. Modern research has revealed that conductive polymers can be used to coat yarns or fabrics in an aqueous solution or by spraying the liquid conductive polymer on the substrate. Conductive polymer coatings are superior to metal coatings because they are highly conductivity, and have excellent adhesion and non-corrosive properties. Numerous conductive polymers have been developed to date and new patents in this area are emerging daily. Polyaniline and polypyrole are common conductive polymers being explored to coat textile substrates (Kahn, Kimbrell, Fowler, & Barry 1993).

Challenges still remain in the area of conductive polymers. Existing conductive polymers possess only moderate environmental stability and intractability, making them difficult to process into end products using conventional processing methods. Presently, conductive polymers are under intense research and development in the academic sector and also in the chemicals and electronics industry to solve these production problems and advance conductive polymer technology. As technology develops, researchers predict conductive polymers will be used for a wide variety of applications within many industries such as aerospace, automobile, chemical processing, electronic equipment, military hardware, and textiles ("Electroactive Polymers," 1999).

Conductive coating can also be achieved by filling or loading textile fibers with carbon or metallic salts such as copper sulfide. Carbon-loaded fibers possess good conductivity and they are easily processed in conventional textile systems. Metallic-salt loaded fibers have comparatively lower conductivity and are usually used when lower conductivity is desired. Today conductive coatings are primarily used for industrial and home furnishing textile applications, however they are finding new applications and opportunities in the area of interactive electronic textile development (Heisey & Wightman, 1993).

In addition to using conductive coatings, a carbonizing process can be used to develop electrically conductive textiles. Gortix Limited of Southport, UK is using this process to develop electrically conductive textiles that provide constant heat at low voltages. The carbonizing process involves processing the textile in a carbonization furnace at $1000^{O}C$ to create an electrically conductive textile. The resulting carbon textile is then encapsulated by a reflector and moisture wicking layer, for durability and user comfort. The textile is then connected to a power source (power pack or battery). As low voltage current is passed through, the fabric is warmed according to changes in resistivity with temperature allowing the simple circuitry to be used to control the temperature within $0.5^{O}C$. Gorix is a non-flammable textile that will not melt or react with water. Presently, the company is developing outlets for its Gorix fabrics in Europe and the United States (Lennox-Kerr, 2000).

2.3.4 CONDUCTIVE INKS

Conductive ink technology is another method used to create interactive electronic textiles. Adding metals such as carbon, copper, silver, nickel, and gold to traditional printing inks creates conductive inks. These specialized inks can be printed onto various substrates such as paper, plastic, and textiles to create electrically active patterns and therefore electronic textiles. Companies such as Creative Materials Incorporated, DuPont, Methode Electronics Incorporated, Motson, and Think and Tinker Limited currently produce and sell conductive inks for creating electrically active patterns on substrates.

Conductive ink technology, originally developed for the production of smart cards or printed circuit boards, has been used for years in various market applications. Computer applications are by far the largest markets for smart cards or printed circuit boards. Other markets that use printed circuit boards developed from conductive ink technology include: communications, automotive, industrial electronics, instrumentation, government/military, consumer (e.g. home thermostats) , and business retail (US Market, 1998).

Printed circuit boards are classified into two categories, rigid or flexible. Many of the applications previously mentioned utilize rigid circuit technology, where the material is incapable of bending or twisting. The demand for flexible circuit technology is increasing as electronic and telecommunication devices are becoming more compact and lightweight. In addition to reduced circuit sizes, flexible circuitry offers 360 degree bending capabilities, 3-D design capability, weight reductions, the ability to easily adapt to various applications, greater conceptual design freedom, and increased circuit reliability (US Market, 1998).

As of 1998, rigid printed circuit boards represent 89% of the market, while flexible printed circuit boards capture the remaining 11%. However, the flexible market is growing at a faster rate than the rigid printed circuit board market. The total U.S. circuit board market is estimated to reach $13 billion in 2003. The rigid circuit market is forecasted to increase 6% annually, reaching $11 billion, while the flexible market will increase 15.5% annually reaching $2 billion (Cahill, 1998).

The use of conductive inks for flexible printed circuits has increased in popularity because they offer substantial cost saving over traditional plating techniques. Recent technology has improved the durability and reliability of conductive inks, increasing their popularity and use within many industries. Technological advances currently are improving integrated circuit processing by increasing circuit speeds and reducing circuit sizes, further increasing popularity of conductive inks (Cahill, 1998).

Colortronics is an example of one United States company successfully marketing a conductive ink package for the development of flexible printed circuit boards on textiles. Colortronics, located in Pennsylvania, is a research and development company specializing in the development, manufacturing, and marketing of flexible conductive inks, paints and coatings. Recently, they have patented a new technology called, The Brillion™ System. This system combines colorful conductive inks, electronic components, and technology know-how to create interactive talking products such as educational toys, T-shirts, sound books, greeting cards, packaging, posters, and wallpaper.

Once printed, the conductive inks become the sensors creating a wireless current carrying circuit. Electronic components, provided by small modules, are then attached to the printed sensors for touch and voice activation. These small modules can fit unobtrusively anywhere on the printed material, and are necessary to complete the wireless textile circuitry. The Brillion™ System uses non-toxic conductive inks that maintain flexibility to withstand bending and laundering without losing conductivity. This patented technology can be licensed from Colortronics or products can be printed in their in-house facilities according to specific requirements (Colortronics, 2000).

Conductive inks are currently being applied to substrates by using gravure, flexographic, and rotary screen-printing technologies. Gravure printing technologies utilize solid metal rollers engraved with the print design or wooden rollers carrying an engraved metal wrapper. Ink is supplied to the engraved roller from a color tray via two intermediate rollers. The excess ink is removed from the roller surface by a doctor blade, leaving ink only in the engraved areas. As the substrate comes in contact with the engraved roller, the ink that is deposited in the engraved areas transfers to the substrate creating the print. The depth of the engraved design determines the amount of ink delivered, which controls the depth of color applied to the substrate. This printing method is very capital intensive, for both printing machinery and rollers. Since a separate engraved roller is required to print each color in the design, it is necessary to keep a large inventory of print rollers on hand. Purchasing and maintaining this large inventory of print rollers is expensive (Miles, 1994).

Flexographic printing is also a roller printing method. The print roller, also called the stereo, is covered in rubber or a composite molding, and carries the design in relief. Laser techniques are used to cut out the design in the material covering the rollers. The ink is delivered to the stereo rollers by an engraved metering roller. The number of stereo rollers used for printing depends on the number of colors in the print, normally there are between six and eight stereo rollers. Flexographic printing is less capital intensive than gravure printing in regards to both machinery and roller costs. However, ink costs are considerably higher, due to the heavier ink loading necessary to achieve the required shade depth on textile substrates. In addition, Flexographic printing is frequently slower and offers less design complexity than gravure printing (Miles, 1994).

Rotary screen is a continuous printing method that uses engraved seamless metal or plastic screen cylinders for applying print designs on substrates. A separate engraved screen is required for each color in the print design and each color requires a separate print application. The circumference of the screen cylinder determines the size and repeat of the pattern. The design cannot exceed the circumference of the screen cylinder. Sixteen inches is the maximum repeat size obtainable for roller printing while screen-printing can obtain forty-inch design repeats. The engraving process is expensive and long production delays are common during design changeovers (Cohen & Price, 1994).

Digital Printing is another area drawing much attention in the application of conductive inks. This is due to the unique production process of digital printing, creating designs via computer then electronically transferring them directly to a printer. Digital printing eliminates many of the intermediary steps associated with traditional printing methods, offering greater design and production capabilities.

The unique digital printing process begins with the graphic image. Graphic image data can be represented by either analog or digital signals. Many graphic images today begin as an analog image, consisting of data in a continuous form. Digital printing technologies require the print image to be in a digital format. If the graphic image is in a continuous analog format than conversion to a discontinuous form using binary numbers is necessary to create a graphic digital image (Cahill, 1998).

The conversion to a digital image from analog representation may be accomplished by using one of three methods: scanning the design (artwork), creating the design using computer aided design (CAD) software, or by screen separations. Using an electronic scanner to scan the artwork into a computer software program automatically formats the design into a digital format. Designs created in a CAD software programs produce a similar effect, the image is naturally in a digital format upon creation. Screen separations, from traditional rotary screen-printing production, can also be used to create a digital file. The digital file created from the screen separations can be used to quickly create new colorways with a digital printer.   For many purposes, digital images are superior to analog images because they can be easily manipulated by using computer software programs (Easterling, 2000). Digital printing technologies offer many areas of design flexibility (Table 1).

Table 1: Areas of Design Flexibility for Direct Digital Printing

Unlimited Effects	Unlimited design repeats Reproduce original artwork Fine line precision and detail Photo realism Tonal textural effects
Digital Media	Computer design rendering Scanning Digital photography Simulations
Engineered Designs	Continuous designs and pattern matching (darts, seams, armholes, and collars)
Mass Customization Opportunities	On demand printing using digitally integrated automation to produce custom orders quickly
Product Variation	Custom designs and colorways Multiple product printing Multiple versions of a single design Limited edition/special event items New product development

(King, 2000)

Once the design is in a digital format it is highly versatile. It can be printed to a variety of substrates such as paper, vinyl, plastic, and textiles. Digital images are printed from a digital printer directly onto the substrate. Many CAD software packages will interface with digital printers, providing flexibility and reduced production times. Digital files can also be used to drive a variety of digital printers, so images can be sent electronically to other locations for viewing or printing. This allows the Internet to be used as a data source and to generate a global network for the printing industry. Designs can be transferred via the Internet to one location for production approval, and in seconds be sent to another location for printing (Rehg, 1994).

Digital printing increases production efficiency from design conception to production offering significant benefits over traditional printing methods. The benefits offered by digital printing technologies have prompted many conductive ink developers to experiment with digitally printing conductive inks onto textile substrates. According to leading conductive ink developers, there are several challenges for successfully using digital technologies for printing conductive inks. These challenges include:

- Selecting the appropriate pre- and post- textile treatments
- Developing the appropriate ink viscosity
- Achieving the appropriate conductivity by:
  - Constant agitation of the ink reservoir to prevent settling of the metallic additive
  - Delivering appropriate ink quantities to the textile substrate
  - Proper drying of the printed material (Armbruster, Borgenstein & Emil, 2001).

Even though there are many challenges for conductive inks, there is great potential for creating flexible circuits on textiles using digital printing technologies. Research and development to perfect mechanical circuit integrity and develop appropriate ink concentrations for proper substrate adhesion is currently ongoing in this area. Overcoming these production hurdles will enable conductive ink technologies to successfully use digital printing for producing electronic textiles.

2.4 ENABLING TECHNOLOGIES

The electronic textile technologies previous discussed are used to create textiles that have the ability to conduct electricity. Additional components including input and output devices, sensors, and power supplies provide the necessary technologies for interaction, hence creating an interactive electronic textile.

2.4.1 INTERACTIVE TECHNOLOGIES

Input devices including keyboards, speech and handwriting recognition systems are some options being explored for interactive electronic textile data entry. Keyboards will be around for a long time, but speech activated computing systems are expected to grow in importance. By 2010, speech activated systems will be widely used in a variety of devices. The output devices being explored for displaying data include Cathode Ray Tubes (CRT's) and Liquid Crystal Displays (LCD's). CRT's are a major technology used for desktop displays and televisions, while LCD's are growing fast for mobile and portable applications. Other output technologies being explored include mirror displays and flexible light emitting displays (Ducatel, 2000).

Sensors add features and functionality to interactive electronic textiles. They are small electronic devices that have the ability to receive and respond to signals or stimuli. Sensors enable electronic textile functions to be related to the users current activity or situation. There are many types of sensors available that can be used in various combinations to add selected functions to interactive electronic textiles. Camera and keyboard sensors are being used to provide a variety of functions. Sensors can also be used to monitor vital signs and signal the user when vitals go out of a certain range. Sensors can either be attached or integrated into a textile substrate to add a variety of features to the interactive electronic textile that can benefit the user (Farringdon, 2001).

Power supply technologies provide the electrical power for activating the components integrated in the electronic textile. Batteries are currently being used to provide electrical power for component activation. Battery technology has advanced over recent years due to high demand for smaller, high energy, rechargeable batteries. Batteries have not only become smaller and more powerful, some varieties are mechanically flexible, water-resistant (washable), and can be fabricated at lower costs (Hahn & Reichl, 1999).

An example of a battery capable of providing electrical power for interactive electronic textiles was recently developed by a German research team led by The Fraunhofer Institute for Reliability and Microintegration (FhG-IZM). This research team developed a small battery that can be printed on a substrate and fabricated at high production speeds in button-sized or coin-type format at cost below one United States Dollar. The battery is fabricated by screen printing a thick layer of a silver-oxide based paste then applying a thin sealing layer. The final result is a textile substrate with a printed 120-micron (µm) thick

AgO-ZN battery. These batteries can be printed on a variety of substrates. In addition to textile substrates, they can also be directly integrated into plastic cards, smart labels, and hybrid circuits. As an alternative to battery power and to further expand power supply technology, research is underway to utilize solar energy and energy created by the human body as a source of electrical power for interactive electronic textiles (Hahn & Reichl, 1999).

2.4.2 NANOTECHNOLOGY

Nanotechnology is a new key technology that can further develop the previously mentioned interactive technologies. Nanotechnology is defined as the fabrication of devices with molecular scale precision. This involves controlling the structure of matter molecule-by-molecule throughout the manufacturing process to create products and byproducts with specific engineered characteristics. The idea of fabricating devices and materials according to atomic specifications was first suggested by scientist Richard Feynman in 1959. The first journal article published on molecular nanotechnology: "Molecular Engineering: An approach to the development of general capabilities for molecular manipulation," appeared 12 years later in 1981 in the *Proceedings of the National Academy of Sciences*. Currently, nanotechnology is still in an infantile stage. However, the future looks promising, many companies are fabricating nonomachines, nanoelectronics, and other nonodevices to improve existing products and to create many new ones. In addition, nanotechnology is also being applied to areas of textile production ("The Coming Revolution in Molecular Manufacturing," 2001).

Devices fabricated with features less than 100 nanometers (nm), are considered products of nanotechnology. A nanometer is a unit of length measuring one billionth of a meter (10^{-9} m) and is usually used to describe the size of a single molecule. This revolutionary technology has the potential to create stronger and smarter textiles by enabling textiles to be created at the molecular level ("Introduction To Nanotechnology," 2001).

Molecules, the building blocks of textiles, are tangled together in various ways to form fibers. Spinning fibers into yarns and then weaving or knitting them into various designs creates a fabric. By using nanotechnology to create textiles from the molecular level we can reinforce the original molecules with additional molecules to develop stronger textiles. For example, carbon molecules can be used as reinforcement to increase tensile strength without affecting the textiles flexibility. Furthermore, nanotechnology can potentially make textiles smarter or electrically interactive. Molecule-sized computers, sensors, and electronic devices, that can be programmed for specific purposes, can be directly integrated into textiles using nanotechnology (McGuinness, 1997).

Considering nanotechnology is still being perfected, it is having an enormous impact on many fields of science. Presently, nanotechnology is expanding into the areas of physics, biology, engineering, chemistry, and computer science. As this rapid progress continues, we will increase our ability to implement beneficial breakthroughs in many areas including interactive electronic textile development ("Introduction To Nanotechnology," 2001).

Microelectromechanical Systems (MEMS), is another area closely related to nanotechnology that is impacting interactive electronic textile development. MEMS are also known as micromachines, nanomachines, or transducers that are less than one square millimeter in size. MEMS usually consist of mechanical microstructures, microsensors, microactuators, and electronics integrated into a single chip. MEMS could potentially provide smart-sensors for electronic textiles, however further research is necessary to materialize this idea (Holme, 2000).

2.4.3 ELECTRONIC COMPONENT INTEGRATION

Regardless of the conductive materials used to develop the electronic textile, the electronic components and power supply must be either attached or embedded into the textile to create a truly interactive electronic textile. Soldering, bonding, stapling, and joining are some of the methods being used to accomplish electronic component and power supply integration (Post et al., 2000).

Soldering involves mounting the components directly onto the textiles surface. The solders are soft alloys of lead (Pb), tin (Sn), or sometimes silver (Ag), that are used to join the metallic electrical components within the textile. Soldering achieves good electrical contact within the textile. However, soldered components are not suitable for applications where they could potentially come in contact with a user's body, due to their toxicity. Furthermore, fabric flexibility is often compromised, making soldering unfavorable for many apparel applications (Post et al., 2000).

Bonding involves using conductive adhesives to embed components into textile substrates. Conductive adhesives can be developed according to the end use application. Therefore, this method is more favorable over soldering for apparel applications. Non-toxic, highly conductive, highly durable, and moderately flexible conductive adhesives can potentially be used to bond rigid components with flexible textile substrates. Conductive adhesives present a viable fabrication technique for embedding components into textile substrates. Further work in this area will advance the possibilities for fabricating textile circuitry in this manner (Post et al., 2000).

Components can also be stapled into conductive stitched circuits to create electronic textile circuitry. This involves pressure-forming a component to grip a sewn conductive trace within the textile substrate. When the substrate flexes or bends the conductive trace is free to move within the pressure-formed component, forming a self-wiping conductivity between the fabric and the components. However, mismatches often occur when pressure-forming rigid components to flexible substrates, potentially limiting the textiles flexibility. In addition, normal flexing of the textile stretches the pins that attach the component to the substrate, accelerating wear and tear on the textile (Post et al., 2000).

Joining involves attaching an electronic component's thread frame directly to a stitched fabric circuit. Threads leading out of the electronic component can be stitched, punched, or woven through the substrate and can also be connected to other components. Joining components to textile substrates in this manner constrains the components to specific locations allowing the conductive threads to be evenly balanced. Figure 17 shows square and round component packages that have been stitched onto a textile substrate and Figure 18 shows a stitch fastened component package that has been applied by laying thread flat on the textile surface and fastening it by stitches at regular intervals (Post et al., 2000).

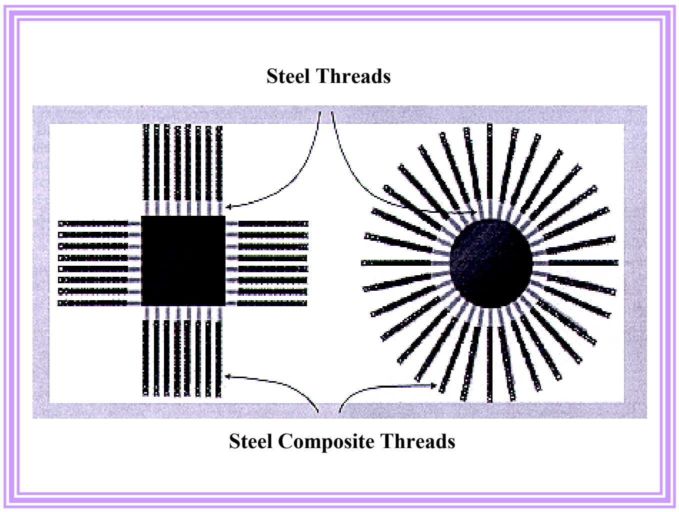

Figure 17: Stitched Square and Round Component Packages

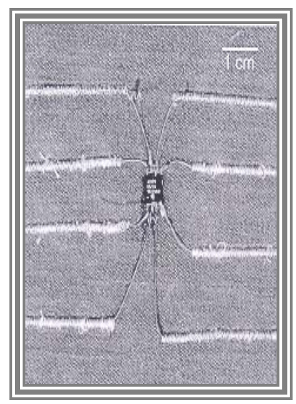

Figure 18: Stitch Fastened Component Package

Soldering, bonding, stapling, and joining are some of the methods being used to embed electronic components into textile substrates. Each of these textile circuit fabrication techniques has its advantages and disadvantages. Therefore, the textile substrate and its final application will help determine the appropriate circuit fabrication technique to complete the interactive electronic textile.

2.4.4 WIRELESS COMMUNICATION NETWORKS

Electronic components must be connected by some means in order to create versatile, interactive systems. Wires, cables, and connectors are common physical methods used to connect electronics together. There are many different ways these items can be used, making the art of connecting electronics highly complex. For example, desktop computers have a central processing unit (CPU) connected to a mouse, keyboard, and a printer; personal data assistants (PDA'S) are normally connected to computers by a cable and a docking cradle; in stereo systems, the compact disk player, tape player, and record player connect to the receiver, which connects to the speakers; televisions are normally connected to a video cassette recorder (VCR) and a cable box, with a remote control for operating all three components ("How Bluetooth Short Range Radio Systems Work," 2001).

Due to the complex nature of connecting electronics together, there are several points to consider before information can be exchanged between any two electronic devices. The first point to consider is will the devices talk over wires or through some form of wireless signals. If wires are chosen, the correct number must be determined. The second point relates to whether the information will be sent one bit at a time in a scheme called serial communications, or in a group of bits (usually 6 or 16 at a time) in a scheme called parallel communications. Third, all devices involved must be capable of processing the data and the message received should be the message that was sent. In most cases this means developing a language of commands and responses known as a protocol. Some types of electronic products used today, such as modems, have a standard protocol used by virtually all companies. Other types of products, such as printers, have multiple standards and speak their own language so that the commands intended for one product will seem like gibberish if received by another. In order to simplify the connections between electronic devices and develop user-friendly interactive electronic textiles, new wireless technologies offer countless opportunities ("How Bluetooth Short Range Radio Systems Work," 2001).

Wireless technologies such as wireless network ports eliminate the need to carry bulky processors and storage devices, simplifying the task of connecting electronics together. Commonly used wireless devices such as cellular phones and pagers use radio frequency local area networks [RF LAN's], or far-field wireless networks. However, as wireless services continue to grow the limited radio frequency spectrum is quickly being filled. Personal Area Networks (PAN's), or near-field wireless networks are emerging as an alternative to combat the congested airwaves (Zimmerman, 1996).

The development of PAN's grew out of a MIT Media Laboratory meeting between Professor Mike Hawley's Personal Information Architecture Group and Professor Neil Gershenfeld's Physics and Media Group. Hawley was looking for a way to interconnect body-borne information devices, while Gershenfeld was applying electric field sensing to position measurement. Through collaboration they realized that by modulating the electric field they were using for position measurement they could send data through the body (Zimmerman, 1996). Initial research based on this concept was funded by the IBM Corporation, Hewlett-Packard and the Festo Didactic Corporation ("Personal Area Networks," 1996).

PAN's are considered the backbone of interactive electronic textile development. They can provide the wireless technology necessary for creating interactive electronic textile products. PAN's enable electronic devices to exchange digital information, power, and control signals within the users' personal space. IBM researchers predict PAN technology will soon be used to:

- Pass simple data between electronic devices carried by two individuals, such as exchanging electronic business cards during a hand shake
- Exchange information between personal computing and communication devices including cellular phones, pagers, personal data assistants (PDA's), and smart cards
- Provide wireless information exchange for interactive electronic textile products ("Personal Area Networks," 1996).

A PAN works by using the natural electrical conductivity of the human body to transmit electronic data. Natural saline produced by the human body provides an excellent conductor of electrical current. PAN technology uses this natural conductivity along with a small transmitter embedded with a microchip to create an external electric field to pass incredibly small amounts of current through the body. These small currents are used to transmit data through the body at speeds equivalent to a 2400-baud modem, or approximately 400,000 bits per second. The current used by PAN technology is lower than the natural currents already in the body, measuring one-billionth of an amp or one nanoamp. As a comparison, the electrical field created when a comb is passed through hair is 1,000 times greater than the current used by PAN technology. PAN technology is emerging as an effective, secure, and cost-effective way to transmit data within a users' personal space ("Personal Area Networks," 1996).

Modular devices with functions shared by different applications can be hooked up to a PAN. For example, a single display can be used for phone call information and compact disk track selection. Intelligent software allows the devices to communicate naturally, for example when the phone rings the compact disk player will automatically mute. The modular network architecture and the user-centric design of a PAN enables the system to be configured to match the user's preferred interaction styles, rather than requiring the user to adapt to the system (Zimmerman, 1996).

Bluetooth is another wireless technology generating interest in the interactive electronic textiles arena. Bluetooth, named after Harold Bluetooth the king of Denmark around the turn of the last millennium, has emerged as a new wireless and automatic technology being used to form electronic connections. Bluetooth is a new radio frequency standard that enables any sort of electronic equipment to make its own connections without wires, cables, or any direct action from a user. The three main features of Bluetooth technology include:

- It's wireless

- It's inexpensive, manufacturers predict this technology will add about $15 to the price of a product, and within a year it will add only $5
- It works without any user input ("How Bluetooth Short Range Radio Systems Work," 2001)

Bluetooth wireless technology works by using small radio modules. Building these small modules into computer, telephone, and entertainment equipment enables devices to communicate by using radio frequencies rather than wires. Hardware vendors such as Suemens, Intel, Toshiba, Motorola, and Ericsson have recently developed a specification for producing these small radio modules. When two Bluetooth capable devices come in range of one another they form a network and the electronic conversation happens automatically. Bluetooth systems also establish a Personal-Area-Network (PAN) so devices can switch frequencies in unison so they can stay in touch with each other and avoid interface from other PAN's operating in the same room. Bluetooth was developed by a group of electronics manufacturers. Currently there are over 1,000 companies involved in the Bluetooth Special Interest Group that's working toward advancing radio communications as a replacement for wires for connecting peripherals, telephones, and computers ("How Bluetooth Short Range Radio Systems Work," 2001).

Bluetooth is a promising wireless technology for connecting personal devices like mobile phones, laptops, headsets, and personal computer cards within a short communication range. However, there is public concern on the health hazards of using this wireless technology for interactive electronic textile applications. The radio frequency (RF) fields used by Bluetooth wireless technology broadcast in all directions and therefore are emitted into the body. As individuals use more and more Bluetooth devices, the amount of emission into the body will increase. Users of Bluetooth devices are exposed to two constant sources of emission or radiation. One source of emission is generated from the wireless link between the electronic devices, while the other source is between the electronic device and the base-station. To overcome this health concern researchers are exploring options to restrict the range of the RF fields to the surface of the textile to avoid emission into the body (Hum, 2001).

The Fabric Area Network (FAN) is another new wireless communications infrastructure to enable networking and sensing on interactive electronic textiles. The FAN is an emission-safe, low-power, low-cost, wireless link that can be easily implemented on textile substrates. Similar to Bluetooth wireless technology, FAN uses wireless RF communication links to supply power to the electronic devices. However, the RF communication fields are restricted to the surface of the textile eliminating emission into the body. In addition, restricting the RF fields also enables easy control over interference and data security (Hum, 2001).

The infrastructure of the FAN on apparel is illustrated in Figure 19. Nodes with antennas at the ends, serving as communication ports, are routed from a central controlling base station to various positions on the clothing. The antennas are routed to the trouser pockets (front and back), shirt pockets, cuffs of the trousers, sleeves, the back of the shirt, and other locations. These antennas can then be used to communicate with chips that are embedded in the wallet, shoes, pens, watches, accessories, or other personal items. To enable wireless communications across gaps between different pieces of clothing, repeater RF links are used to create a hopping network of transformer chains. Square, triangle, and round shaped antennas are used as symbols to define the portals of hopping into or out of various pieces of clothing. This enables layers of clothing to be electronically connected without the need for wires (Hum, 2001).

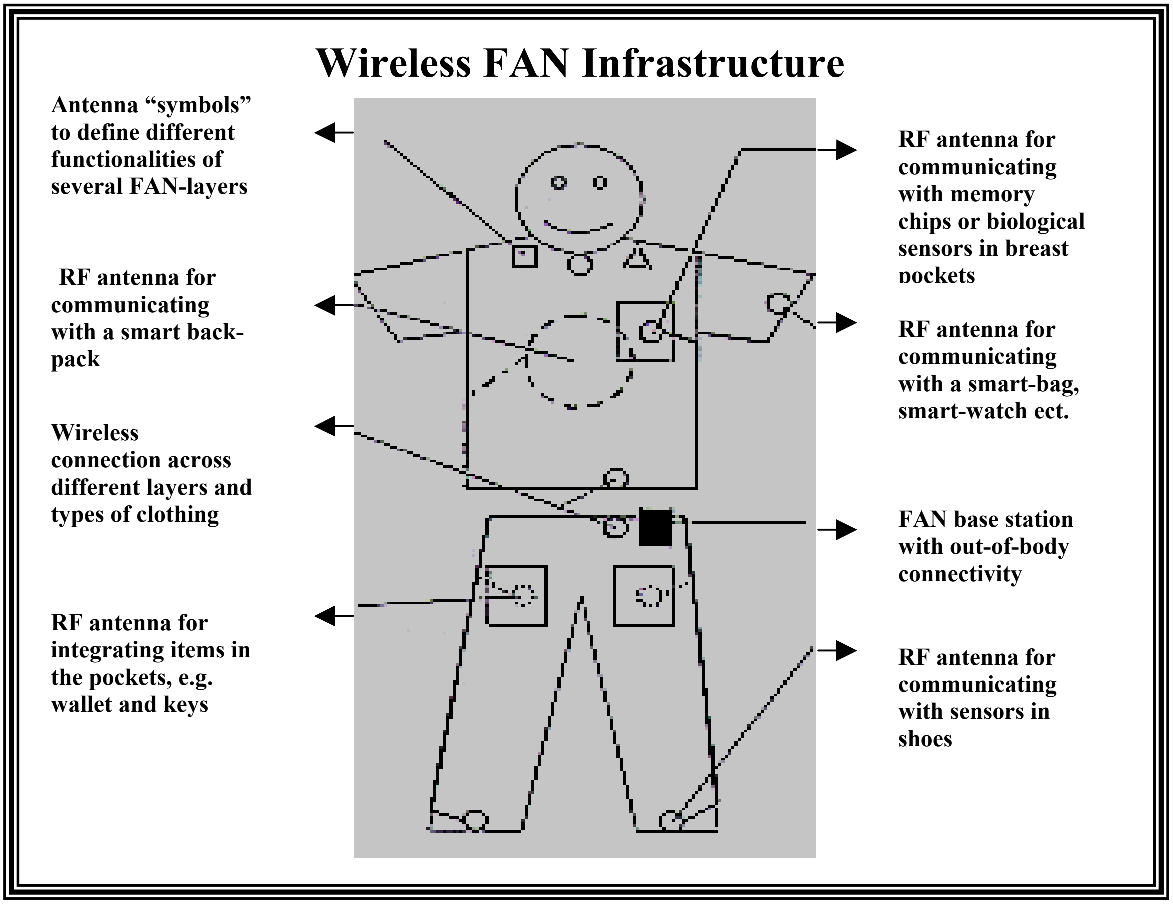

Figure 19: FAN Infrastructure

Various functionalities can be built into each separate clothing layer to serve different applications. Sensor, actuator, audio, video, interference, storage, motion, and memory layers can be used to function independently or can also work together to provide a higher level of function creating an individualized interactive electronic garment. A multi-layer FAN enabled garment is shown in Figure 20.

Figure 20: Multi-Layer FAN Garment

Antennas located in the shoulder and neck regions of the garment anchor the various layers and transmission between layers is done on the base-layer. Hopping portals are located on the shoulders and the tail of the shirt for transmission between additional pieces of clothing (Hum, 2001).

The FAN is a promising wireless networking and communications infrastructure for interactive electronic textiles. Presently, FAN research is still in progress and further details on this new wireless technology have not been released. A few United States FAN patents are pending and several others are in the filing process (Hum, 2001).

Interactive technologies, nanotechnology, circuit integration procedures, and wireless communication networks are all key technology areas for furthering interactive electronic textile development. Even though many technologies within these areas are still being developed and perfected, the available literature suggests these technologies have tremendous potential in the area of interactive electronic textile development.

2.5 RELATED APPLICATIONS AND OPPORTUNITIES

Interactive electronic textiles have numerous applications and opportunities. Similar to traditional textiles, interactive electronic textiles are finding opportunities in fashion and industrial apparel, residential and commercial interiors (upholstery, curtains, and carpets), military intelligence, and medical and industrial textiles. Basically, any traditional textile application can benefit from integrated interactive electronic features. These applications and opportunities can be further categorized according to their functional purpose. Integrating electronic devices into textile and apparel products provides wireless freedom for communication, entertainment, and health/safety purposes.

In the area of business and personal communication, there are many applications and opportunities for interactive electronic textiles. Computers, cellular phones, personal data assistants, beepers, and pagers are common devices used today for mobile communication. Users of these technologies are carrying around a separate display, battery, keypad, speaker, and ringer for each of these devices. Interactive electronic textile technologies can potentially integrate these items directly into textile and apparel products with shared resources. This would eliminate the need to carry such devices and increase mobility, comfort, and convenience. The technologies supporting interactive electronic textile communication include integrated input and output devices such as computer keypads and display screens and integrated antennas for mobile phones use, Internet connections, and downloads (Heerden, C.V., Mama, J., & Eves, D., 1999).

The applications and opportunities for electronic textile communications are endless. Some ideas presently being explored include airline cabin crew uniforms with built in personal digital assistants and earpiece microphones for communicating with colleagues aboard the plane and on the ground, and digital business suits to support e-mail, videoconferences, and interaction with coworkers. Similar to the carriage clock developed 300 years ago that became the pocket watch then the wearable wrist watch, communication devices may be easily worn in the future by being integrated into textile and apparel products. Figure 21 illustrates a garment developed by Philips Research Laboratories with a sleeve integrated communication device (Philips Research Laboratories, 2001).

Figure 21: Sleeve Integrated Communication Device

For entertainment purposes, integrated compact disk players, MP3 players, electronic game panels, digital cameras, and video devices can provide a wide variety of personalized mobile entertainment options. A jacket, developed by Philips Research Laboratories, featuring a personal audio device with built-in microphone and earpiece is illustrated in Figure 22 (Philips Research Laboratories, 2001). New applications and opportunities are emerging daily. For example, ideas for marketing electronic textiles to clubbers are underway to develop interactive club or disco apparel that changes colors with the beat of the music (Heerden et al., 1999).

Figure 22: Integrated Personal Audio Device

Future interactive electronic textile and apparel products will serve both communication and entertainment purposes. Softswitch technology creates touch sensitive, interactive textiles by using textile-based switches and keypads to control a wide variety of electronic devices. Softswitch technology was recently developed by WRONZ, a New Zealand based textile research and development organization and electronic materials company Peratech Limited of Darlington in the United Kingdom. Figure 23 illustrates a jacket incorporating Softswitch technology. The textile keypads on the sleeve can be used to dial phone numbers, type pager messages, and play music (Figure 24) (Softswitch Press Release, 2000).

Figure 23: Softswitch Jacket

Figure 24: Sleeve Integrated Textile Keypad

In addition to apparel, Softswitch technology is also being used to develop many other innovative products. Interior textiles for the home or office incorporating Softswitch technology can be used to control lighting, temperature, or other electronic appliances. For example, Softswitch technology can be used to integrate a television remote control into the arm of a sofa (Figure 25), or light switches can be embedded into curtains (Figure 26), and pillows (Figure 27).

Figure 25: Softswitch Remote Control

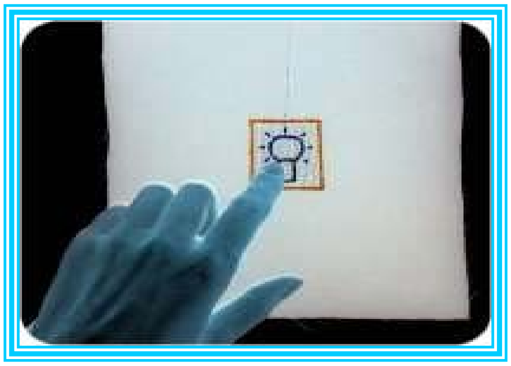

Figure 26: Softswitch Light Switch

Figure 27: Softswitch Pillow

Since Softswitch technology makes fabrics touch sensitive, this technology can also be used to detect pressure and/or movement. There are numerous textile applications for pressure and movement detection such as pressure sensitive medical textiles, engineering fabrics, active sportswear, and automotive seat sensors. Figure 28 illustrates the automotive pressure sensing application (Softswitch Electronic Fabrics-Applications, 2001).

Figure 28: Softswitch Seat Sensors

For purposes of health and safety, interactive electronic textiles are finding many useful applications and opportunities for providing a wide variety user benefits. In the healthcare field, interactive electronic textiles have the potential to improve current healthcare practices for monitoring breathing, heart rate, stress levels, and gauging body temperature. For example, these specialized textiles can be used to monitor post-operative patients as they recuperate at home, or they can assist individuals with disabilities by improving the use of impaired senses. Furthermore, they can be used to monitor infants susceptible to SIDS (Sudden Infant Death Syndrome) or those with cardiovascular problems, asthma, or lung disease. Interactive electronic textile and apparel products used for healthcare applications will increase patients mobility, provide added convenience, and improve the quality of life for those with health problems or disabilities (Havich, 1999).

Interactive electronic textile technologies are also making a big impact in fitness and athletic applications. High-performance electronic sportswear can monitor, track, and enhance performance for a workout at the gym or for extreme sporting activities such as rock climbing, cycling, snow boarding, and running. Figure 29 illustrates a sportswear garment developed by Philips Research Laboratories with integrated fabric sensors to monitor and display pulse, blood pressure, time, distance, speed, and calories. Opportunities are also developing for golfers and tennis players. Integrated sensors can register and record arm action for improving swing movements.

Figure 29: Philips Electronic Sportswear Garment

In addition, these specialized garments can also monitor body temperature and then flow coolant to air condition the user. Furthermore, personal trainers can use this information for developing appropriate workout regimes and coaches can optimize strategic placement of team players (Roberts, 2000).

For safety purposes, there are many applications and opportunities for interactive electronic textiles. Textiles integrated with sensory devices driven by Global Positioning System (GPS) can detect a users exact location anytime and in any weather. The GPS consists of 24 satellites that orbit 11,000 nautical miles above the Earth. Ground stations located worldwide continuously monitor these satellites. Each satellite transmits radio signals that can be detected by GPS receivers. When a GPS receiver detects a satellite radio signal the distance between the receiver and the satellite is measured. The receiver uses this measurement to calculate where on or above Earth the user is located. GPS was originally developed for military use by the Department of Defense, but new opportunities are continuously emerging. Presently, GPS receivers are used for moving-map displays that give drivers directions on dashboard mounted display screens and they are used to locate and track aircraft, ships, and public and commercial vehicles. Furthermore, GPS receivers are also finding numerous opportunities in the interactive electronic textiles arena (The Aerospace Corporation, 2001).

Interactive electronic textiles with integrated GPS can ensure user safety and can potentially save lives. Users involved in emergency situations can quickly be located with GPS. For example, skiers buried in an avalanche or lost/injured climbers can easily be located and rescued. Figure 30 illustrates a ski-suit developed by Philips Research Laboratories with a built-in electronic GPS for personal safety. The suit is also equipped with a personal stereo system and temperature sensors to allow the user to control heating of the suit. The GPS can also be used to locate and track children. Parents can easily keep track of a child's location with garments containing integrated GPS receivers and miniature cameras, while a computer game console worn on the sleeve makes the garments appealing to children (Figure 31) (Foster, 1999).

GPS can also provide added safety for fire fighters, policemen, astronauts, and military personnel in the line of duty. In the event of an emergency, signals sent to a monitored receiver will alert medical personnel and provide them with the extent and location of the injury, the individuals' vital signs, and their physical

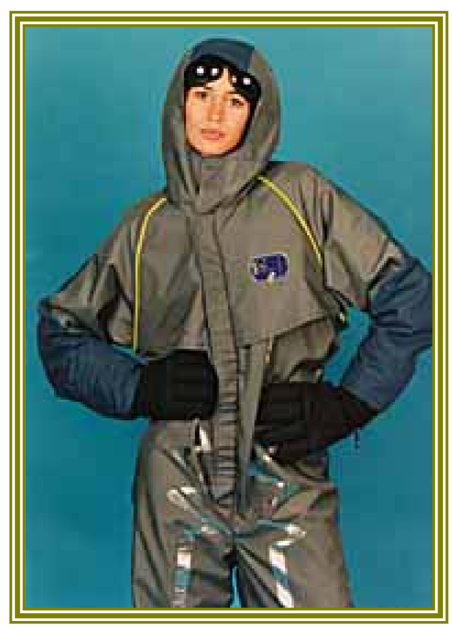

Figure 30: Philips Electronic Ski-Suit

location so the appropriate emergency medical action can be taken. As the area of interactive electronic textiles continues to develop, so will application possibilities for integrated GPS (Havich, 1999).

Figure 31: Electronic Children's Garments

Presently, most applications and opportunities for interactive electronic textiles are still being researched and developed. Therefore, the previously described interactive electronic textile and apparel products are not on the market as of yet. According to spokes people at Philip Research Laboratories, many of their interactive electronic textile developments are still in an exploratory stage and they are not yet marketing these products or technologies (Philips Research Laboratories, 2001). Similarly, a representative at Softswitch technology informed me that a number of companies are currently engaged in Softswitch research and development therefore they are unable to release product or market launch details at this time (Peratech Inquiries, 2001).

In addition to the numerous textile and apparel applications, wearable electronics are finding many opportunities in non-textile products. Several products currently being developed include: thinking name tags or "tags that think," that have the ability to display selected personal information of those wearing the tag, microchips implanted in the body to identify, monitor, and control individuals locations, touch and know devices transforming the human body into a communications cable, able to pass digital information between people and machines, and digital jewelry incorporating speakers, pagers, microphones, and telephones (Rajkhowa, 2000).

IBM is on the forefront of digital jewelry development and recently they have launched a Digital Jewelry Project. According to company officials, scientists at design laboratories are working toward developing sterling silver rings that can receive pages and earrings and tie clips that can place and receive telephone calls. This jewelry is not a product prototype, but rather a research prototype. IBM is researching how individuals will interact with these new wearable electronic devices rather then the technology behind developing them (Rajkhowa, 2000). Interactive electronic textile and non-textile products have the ability to improve our quality of life, however as these items develop and gain widespread acceptance and use there will be many issues that will need to be addressed.

2.6 RELATED CONCERNS

In the next decade, many new interactive electronic textile products will enter the market. These products have the potential to benefit society. However, as any new technology develops, so will many concerns and issues that have yet to be discovered. Addressing potential concerns and issues while this area is still developing will assist future market acceptance and growth for interactive electronic textile products. The concerns and issues for interactive electronic textile products can be categorized into two areas; those relating to the products and those relating to society in general.

Interactive electronic textile product issues of foremost importance relate to care & maintenance requirements, product durability & longevity, and potential health & safety hazards. Care and maintenance are two extremely important issues facing electronic textile products. In a society where convenience is of utmost importance, consumers prefer to purchase easy care products. In order for electronic textile products to succeed in the consumer market, they will need to possess easy care characteristics, such as being able to be laundered and tumble dried. Furthermore, as these items are repeatably laundered, their conductivity will be expected to remain intact. Upgrading presents another issue, as technology rapidly changes, many electronics become out dated and obsolete. Will interactive electronic textiles be able to be upgraded as technology progresses or will they have to be discarded and replaced?

Durability and longevity also present issues for electronic textiles. Similar to traditional apparel products, those developed from electronic textiles will be in constant motion and subject to stress from body movements, static from fabrics, perspiration, and body heat. Normal everyday stresses imposed on our apparel must be kept in mind to develop durable electronic textiles products that can withstand repeated use.

Potential health and safety hazards raise questions about electronic textiles. How long and under what conditions will it be safe to use and wear these items? Today, radiation and electrocution are small threats to our health and safety, will electronic textiles increase these threats? Safety for children presents another concern. Items worn by children demand strong structures that lack small edible detachable parts to ensure safety. Customers will want to feel assured these items are safe, before purchasing them for children. Environmental characteristics such as rain, humidity, extreme temperature fluctuations, and other inclement whether may also create safety hazards. The need to determine how electronic textiles will affect user health and safety is imperative to widespread acceptance.

New information and communication technologies often raise concerns among society. In the coming years, interactive electronic textile products will create new possibilities for human interaction on individual and collective levels. Therefore, we may soon be living and working in a society where our home, office, transportation, clothing and even our bodies will be seamlessly connected by wireless networks. Undoubtedly, these new technologies will raise personal privacy and security concerns (Thieme, 1999).

The right to personal privacy and security are basic universal expectations that are usually not clearly articulated, however they are keenly felt when threatened. Society recognizes the importance of preserving the right to personal privacy and security. According to a recent opinion poll on public concerns about personal privacy and security, 75% of those interviewed felt personal privacy and security were very important social issues in today's society. Advancing technology and the unrestricted exchange of electronic information justifies increasing concerns (Coleman, 1997).

In the context of new technologies, privacy and security relate to how we define ourselves as we interact with others via electronic systems and connections. In an effort to ensure that new technologies do not diminish our personal privacy and security rights, the implications of using these new technologies must be assessed. Assessing potential personal privacy and security implications of any new technology requires understanding what the new technology will mean for the individual. This requires identifying whether the technology will reduce or support individual freedom, choice, and sense of security or trust. Furthermore, identifying what information will be generated, how it will be used, and what controls exist to protect the integrity of the communication are also important to assessing potential privacy and security implications. Ideally, assessment should begin during technology development and be a continuing appraisal of the impact on society. As society becomes significant users of new technologies that involve large amounts of personal information, we will no doubt be interested in protecting our personal privacy and security (Garfinkel, 2000).

New technologies also raise social and ethical concerns among society. These concerns often result from the new possibilities for individual and institutional behavior that were not present before. Interactive electronic textiles, like other technological innovations, potentially will create both desirable and undesirable possibilities. We may soon have a greater capacity to track and monitor individuals without their knowledge, develop more heinous weapon systems, or eliminate the need for human contact in many activities (Johnson, 1991).

Although social and ethical concerns are interrelated, a distinction between the two can be made. Sociological concerns deal with the impact interactive electronic textiles will have on society and how they will change the world in the future. Ethical concerns are raised because these changes affect human relationships and social groups in ways that challenge our moral beliefs, conceptions of individual rights and responsibilities, and our ideas and strategies. The interactive electronic textiles arena must identify potential social and ethical concerns and inform the public of the potential risks as well as the benefits of these technologies (Johnson, 1991).

Interactive electronic textile products have the potential to benefit society but there are also several concerns and issues challenging future development and growth. Potential product and society related concerns such as care & maintenance requirements, durability & longevity, health & safety hazards, personal privacy & security, and social & ethical issues need to be identified and assessed. Addressing these challenges while this area is developing will minimize and overcome potential product and society related concerns and issues. Informing the public regarding the capabilities of these technologies will assist future development and growth for interactive textile products.

2.7 SUMMARY

The previous sections have described the emerging area of interactive electronic textiles. The technologies, applications, opportunities, and concerns have all been explored. Considering this area is still in its infancy, the key technologies, applications, and market potential for interactive electronic textiles have yet to be identified. The following chapters attempt to provide an expert perspective for future interactive electronic textile development and marketing strategies.

CHAPTER THREE: HYPOTHESES

3.1 HYPOTHESES GENERATION

The previous chapters have described the research objectives and introduced the reader to the emerging area of interactive electronic textiles. The research questions presented in chapter one were structured to ensure the purpose of the research is satisfied. These questions focus on the perceptions and opinions of industry experts presently involved in the area of interactive electronic textile development. The questions of interest were: 1) Which technologies have the greatest potential in the area of interactive electronic textiles? 2) Which application areas have the greatest potential for interactive electronic textiles? 3) According to an expert industry perspective, what will be the potential market appeal for interactive electronic textiles? In an effort to speculate on the results that will emerge from this research, the research questions have been extended to testable research hypotheses.

3.2 HYPOTHESIS 1

Various technologies are being used for developing interactive electronic textiles. Available literature identifies metallic fibers, optical fibers, conductive threads, coatings, and printing inks as the technologies presently being explored for interactive electronic textile development. However, the literature does not reveal the significance of each individual technology. Identifying the significant technologies will be beneficial for further developing interactive electronic textiles. This brings us to hypothesis one:

H1: Technologies being used to develop interactive electronic textiles will be perceived by experts in the field to have differing potentials for success in future product development.

3.3 HYPOTHESIS 2

Once the significant interactive electronic textile technologies have been identified they can be applied to the appropriate application areas for developing products most desired by consumers. Communications, entertainment, education, health, and safety have been identified as the main application areas for interactive electronic textiles. Determining the potential success for each application area will facilitate understanding development efforts currently underway, and the foci of these efforts. This brings us to hypothesis two:

H2: Not all interactive electronic textiles application areas will be perceived by experts in the field to have an equal potential for success.

3.4 HYPOTHESIS 3

Identifying the potential niche and mass-market opportunity is vital for any new emerging product area. Considering this area is still in the early stages of development, industry experts advancing this area can provide valuable insight on the perceived future market potential for interactive electronic textiles.

H3: Expert perceptions of potential niche and mass-market success for interactive electronic textiles within the next 5 and 10 years will vary.

3.5 CONCLUSION

Extending the research questions to testable research hypotheses enabled the research questions to specifically satisfy the objectives of this study (Aaker, D., Kumar, V., & Day, G., 1998). The following chapter describes the research methodology chosen for this study to test the hypotheses including a description of the sample, the data collection methods, the variables, and the procedures used for data analysis.

CHAPTER FOUR: RESEARCH METHODOLOGY

The previous chapters have provided the foundation for this study. This chapter describes the research methodology used including a description of the survey sample, the data collection methods, the variables investigated, and the statistical data analysis procedures.

4.1 SAMPLE

Sampling involves determining the appropriate population for a particular study. Identifying the sample properly and accurately is a critical part of any research study. If the sample is defined improperly, it is possible that a correlation between the research results and the research objectives will not be achieved. By thoroughly examining the research objectives and becoming familiar with the research area or market, the researcher is able to clearly define and select an appropriate sample to satisfy the research objectives (Aaker et al., 1998).

A purposive sample of experts in the field of interactive electronic textiles was used in this research. This sample was identified as appropriate and developed based on the literature review. The study of journal articles, trade articles, newspaper articles, technical papers, academic papers, conference proceedings, and corporate and organizational literature revealed the recognized interactive electronic textile experts. This enabled a list of qualified survey participants to be developed. The selected sample shares expertise in the area of interactive electronic textile technologies and product development. Those selected to receive questionnaires are industry experts presently involved in interactive electronic textile research, engineering, product development, manufacturing, marketing, and education. Selecting the sample in this manner restricted it to those currently contributing their expertise and knowledge to further interactive electronic textile research and development. The collective expertise of this sample qualifies them to provide the critical assessment of the emerging interactive electronic textiles area that is required to accomplish the research objectives.

4.2 DATA COLLECTION METHOD

An electronic, Internet-based, survey questionnaire was chosen as a data collection method for this study. This method proved to be the most appropriate for the technically savvy geographically dispersed sample chosen for this study. Electronic survey methods have become popular and effective methods for collecting data. Collecting data electronically offers numerous advantages over traditional paper survey methods (Table 2). Advancing technology, the Internet, and interactive multimedia computing can all be attributed to the success of electronic data collection methods (Aaker et al., 1998).

Table 2: Electronic Data Collection Advantages

Relatively lower cost involved
Requires minimal staff and facilities
Access to widely dispersed samples
Respondents are not limited to time restraints
Faster - data can be sent and received via computer
Increased reliability over traditional mail survey methods

(Aaker et al., 1998)

According to a recent survey experiment conducted at Washington State University (WSU), electronic survey methods can also achieve improved data quality and response speeds with no reduction in response rates. The permanent faculty of WSU was used as the sample for an experiment, in which half of the sample received a traditional paper version of a survey, while the other half received an e-mail version. The results revealed the electronic survey obtained improved data quality results due to more complete returned questionnaires and lengthier responses for open-end questions. Response speeds also improved as the average time required to receive a completed electronic questionnaire was approximately 9 days (as compared to 14 days for the paper version). Response rates were similar, however a slightly higher response rate was obtained by the electronic mail version at 58% verse 57.5% for the paper version. This experiment was conducted to assist the development of a standard e-mail survey methodology and to prove effective techniques used in traditional mail surveys are also appropriate for e-mail surveys (Dillman & Schaefer, 1998).

The electronic survey questionnaire developed to test the hypotheses outlined in chapter three was designed to capture expert opinions on the technologies, applications, and market appeal for interactive electronic textiles. (See Appendix A for a complete copy of the survey.) The survey began with demographic questions. A few introductory questions followed to determine the participants' level of knowledge and expertise in this emerging area. These questions also confirmed that the sample consisted of industry experts. The survey consisted of three main sections; (1) interactive electronic textile technologies, (2) interactive electronic textile applications and opportunities, and (3) interactive electronic textile potential market success. Each of these sections included several questions, and a 10-point scale for responses followed each question. At the end of each section the participants were provided with the opportunity to make additional comments.

A personalized e-mail containing a brief cover letter and a link to the on-line electronic survey was sent to each participant. Upon clicking on the link, participants were connected directly to the web page containing the electronic survey. Participants completed the survey on-line then submitted completed surveys by clicking the submit button located at the end of the survey. The submit button electronically mailed the survey data directly to a spreadsheet previously organized and coded for the survey responses. This automatic data entry was designed to reduce errors and facilitate data analysis. An additional copy of each completed survey was sent to my personal e-mail account for purposes of backing up the data.

In an attempt to achieve the highest response rate possible for this study, three additional follow-up e-mails were administered containing a brief cover letter and the web link to the survey. The first follow-up e-mail was sent to all participants one week after the original contact. This first follow up served as a thank you for those who had responded and as a friendly reminder for those who had not. The second follow-up e-mail was sent three weeks after the original to those who had not yet responded. The second follow up was used to inform nonrespondents that their questionnaire has not been received and to appeal for its return. The third follow-up e-mail was sent six weeks after the original. The third follow-up sent to nonrespondents served as a final effort to elicit a response. This methodology of using follow-up contacts to increase response rates is referred to as the Dillman Method (Dillman, 1978). Research conducted by Don Dillman has revealed that the number of attempts to contact a survey participant influences response rates. Several e-mail survey studies conducted by Dillman have revealed the average response rate for a single contact e-mail survey is 28.5 percent, two contacts increased this to 41 percent, and three or more contacts increased this even further to 57 percent (Dillman & Schaefer 1998).

4.3 VARIABLES

A number of variables must be captured by the survey instrument to properly test the hypotheses. These variables are classified as dependent and independent variables. Dependent or responding variables change as a result of the change in the independent variable. Independent variables are those manipulated or changed by the experimenter. Prior to data analysis it is imperative these variable are identified (Zitzewitz & Murphy, 1990). The dependent variables captured by this research include the expert perceptions concerning the potential technologies, applications, and market appeal for the emerging area of interactive electronic textiles. The survey captures perceptions through a series of questions developed for each section of this emerging area. A 10-point scale for responses follows each question. The independent variables captured by this research included the interactive electronic textile technologies, the applications, and market appeal timing success factors. Perhaps an individual perceives a specific interactive electronic textile application to be viable but not in the near future. To address timing issues, 5-year and 10-year time frames were used to further define market appeal perceptions. These dependent and independent variables were the basis for data analysis. Various combinations of these variables were used during statistical analysis to test the hypotheses. Statistical tests were performed to determine if the time frame effects perceptions on the market appeal for interactive electronic textiles.

4.4 DATA ANALYSIS

Data analysis included several data preparation techniques and various statistical procedures to test the hypotheses presented and discussed in chapter three. The preliminary data preparation techniques included cleaning and coding the data. These techniques were used prior to statistical testing to assure accurate results were obtained from the statistical analysis. Data cleaning identified omissions, ambiguities, and response errors via review of individual survey responses. When such problems were identified, the problem questions were omitted and the remainder of the data was retained. The coding process consisted of two procedures. The first coding procedure consisted of assigning an identification number to each completed survey received. The identification number served two purposes: (1) to keep all data anonymous throughout tabulation and analysis and (2) to keep track of the number of surveys received. The second coding procedure consisted of double-checking the coded spreadsheet to ensure submitted data was arranged properly. Upon completing the preliminary data preparation techniques, a spot check was performed to correct any errors that may have occurred. Frequencies were generated to summarize the data and perform a final check for errors. The data was then analyzed using appropriate statistical procedures (Aaker et al., 1998).

Several statistical tests were used to test the hypotheses generated in chapter three. These statistical techniques included analysis of variance or ANOVA, Tukey-Kramer HSD, and Chi-Square. ANOVA is a statistical testing procedure that compares differences in two or more group means (Gibson, 1994). A basic one-way ANOVA technique was used to test hypothesis one, two, and three to determine if there were significant differences in expert perceptions of potential interactive electronic textile technologies, applications, and niche and mass market success supporting the hypotheses. Tukey-Kramer HSD (honestly significant difference) statistical tests compare pairs of means to determine exactly which among a set of means are significantly different from each other. Tukey-Kramer HSD was used to further test hypotheses two and three to determine the specifics of the significant differences found in the ANOVA testing results. Chi-Square tests analyze data in the form of frequencies or counts in two or more categories to determine the extent one variable influences another (Gibson, 1994). A two category Chi-Square test was used to determine the significant factors influencing the use of each technology for product development. A probability value of $\leq .05$ was used to identify significant values for all the statistical tests performed on the data.

CHAPTER FIVE: RESEARCH RESULTS

The following section begins with a description of the survey sample. Following the sample description, the results for each individual hypothesis are presented with an analysis of the findings. The demographic and introductory questionnaire responses provided the data for the sample description. The technology, application, and market success responses were used for hypotheses testing. Additional analysis was performed on the remainder of the survey questionnaire responses to provide further understanding of this emerging area. The survey questionnaire used for this research can be found in Appendix A.

5.1 SAMPLE CHARACTERISTICS

Invitations to participate in this research were sent electronically to 116 individuals recognized for their interactive electronic textiles research and development efforts. Of those 116 individuals, 39 completed the questionnaire giving this study a response rate of 33.62%. Most participants classified their familiarity with the area of interactive electronic textiles in the range of somewhat to very familiar, while the remaining few classified themselves in the range of not at all to somewhat familiar (Figure 32). Similar results were obtained when participants were asked to indicate how knowledgeable they were in this area. Most participants classified their knowledge in the range of average to expert, while only a few classified their knowledge in the range of novice to average (Figure 33).

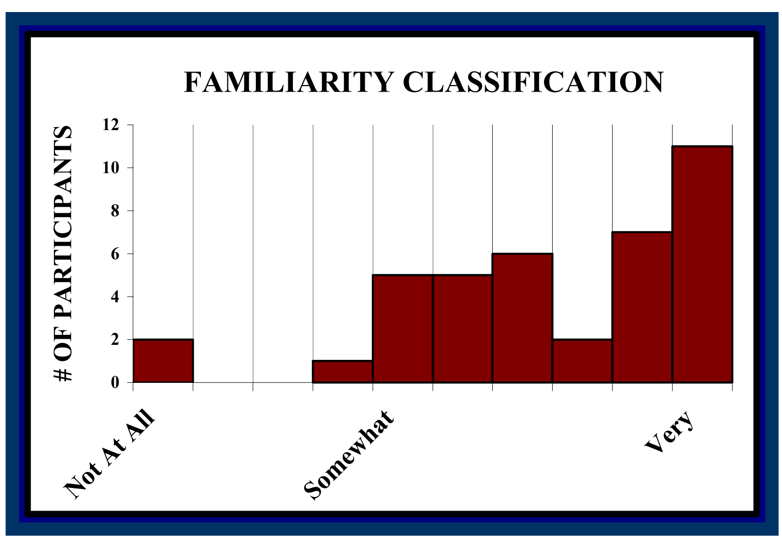

Figure 32: Familiarity Classification

The respondents who classified their familiarity with the entire area of interactive electronic textiles in the range of not at all to somewhat and their knowledge of the area in the range of novice to average were retained for this research because their expertise in select areas of interactive electronic textiles proved beneficial for the study.

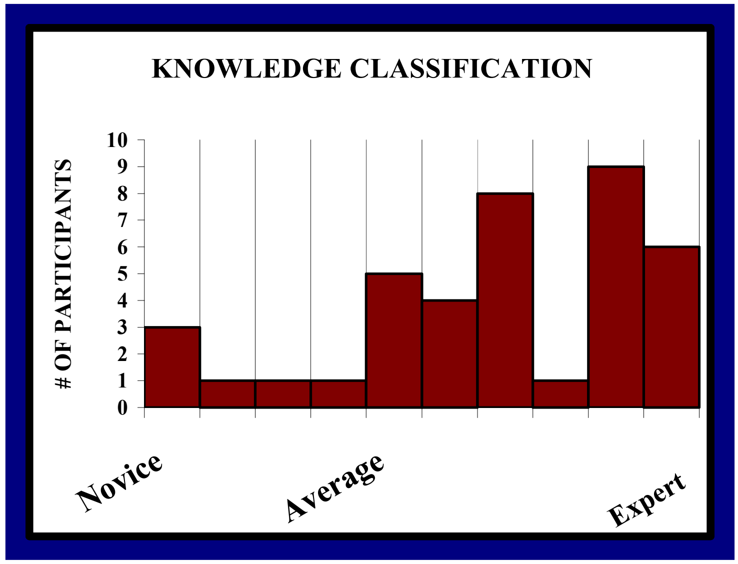

Figure 33: Knowledge Classification

Also, the questionnaire was constructed so that respondents were not asked to answer questions outside their range of expertise (See Appendix A). So, the 39 respondents who participated in this study were predominately those quite familiar with and knowledgeable about the broad field of interactive electronic textiles, while the remaining few participants were quite familiar with particular areas in the field.

A variety of different organizational sizes and functional backgrounds were represented in the sample. Sixty seven percent (n= 26) of the respondents represented companies or organizations employing over 300 individuals (Figure 34).

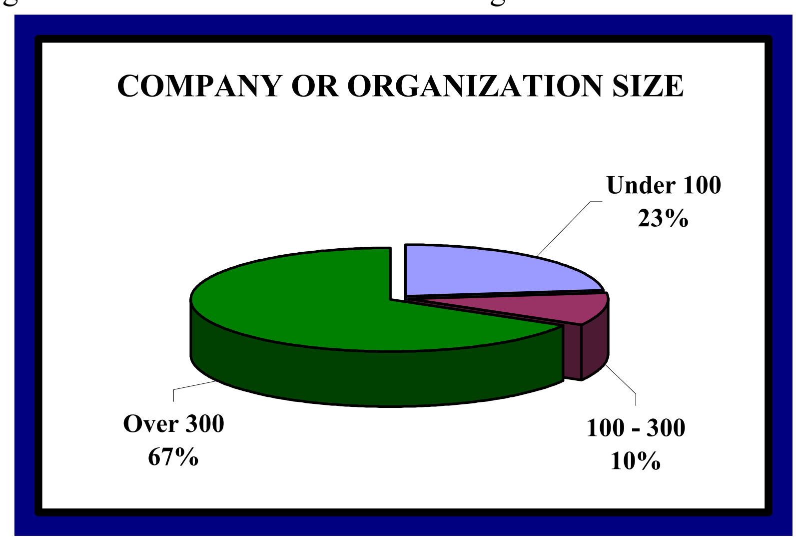

Figure 34: Company or Organization Size

Participants' characterization of their position or functional areas within the organization revealed that 67% (n=26) were involved in research and development and 15% (n=6) were in the functional area of education (Figure 35).

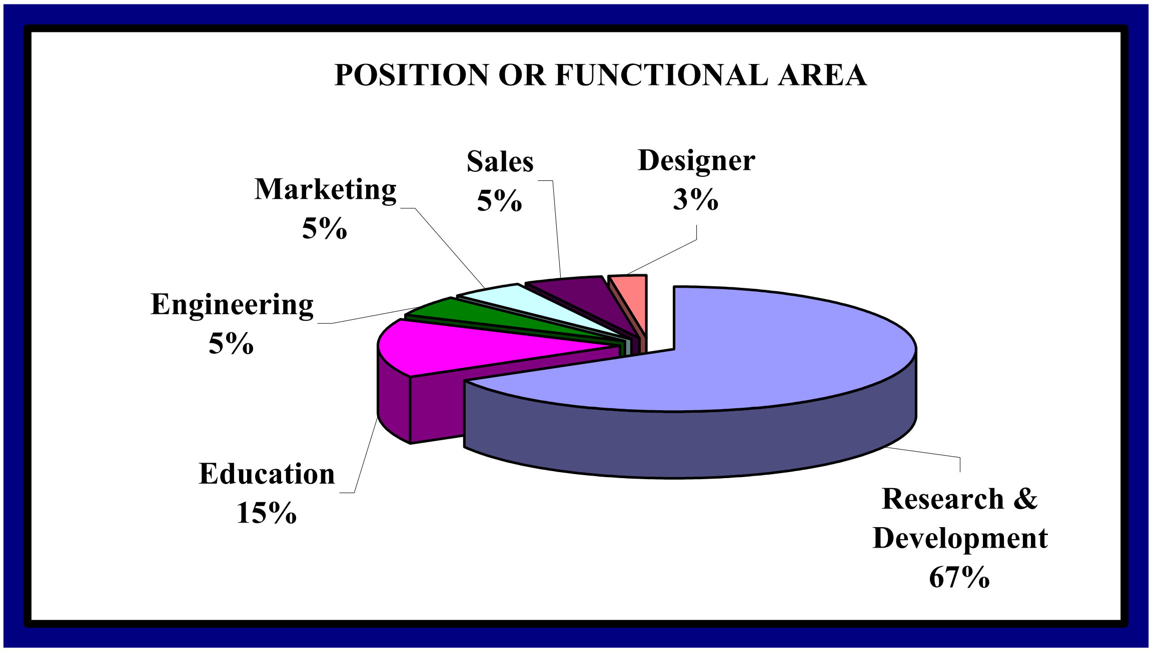

Figure 35: Position or Functional Area

Geographically, the sample consisted of both domestic and international participants, however responses from international locations dominated (Figure 36).

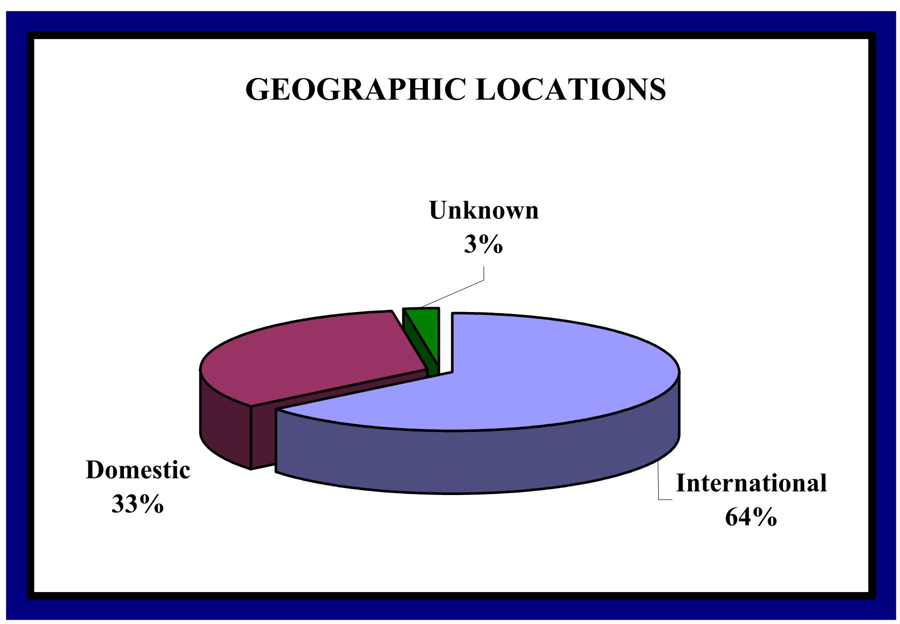

Figure 36: Geographic Locations

5.2 HYPOTHESES TESTING

The sample described in the previous section provided the data to test the research hypotheses. This section presents the individual hypothesis testing results and provides an analysis of the findings. These findings address the level of support for each hypothesis.

Hypothesis 1: Technologies being used to develop interactive electronic textiles will be perceived by experts in the field to have differing potentials for success in future product development.

As noted in the sample description, not all respondents were familiar with all technologies (see Table 3). Only those respondents familiar with a particular technology responded to questions regarding that technology. Thus, testing results are based exclusively on data provided by respondents familiar with the indicated technologies.

Table 3: Percent of Sample Familiar With Each Technology

Technology	***% of Sample Familiar***
Conductive Threads	84.21% (n=32)
Metallic Fibers	82.05% (n=32)
Optical Fibers	82.05% (n=32)
Conductive Coatings	73.68% (n=28)
Conductive Inks	71.05% (n=27)

A one-way ANOVA statistical procedure was then used to determine perceived differences in the potential for success among the interactive electronic textile technologies, and the level of support for Hypothesis 1. The results failed to reveal, at a significance level of $p \leq .05$, any difference in the potential for success for future product development among the interactive electronic textile technologies studied. However the result does approach significance at p = .0651. As seen in Table 4, trends in the sample means suggest conductive threads were perceived to have the greatest potential, followed by metallic fibers, while conductive inks were perceived to have the least potential. Note that the sample means fell between the ranges of somewhat to very likely for all variables. This hypothesis testing result could have been due to the limited sample size resulting from the relatively small number of experts in this emerging area that restricted the eligible sample for this study.

Table 4: **Technology One-Way ANOVA Testing Results**

Technology	*Number*	*Mean*	*Standard Deviation*	*DF*	*F Ratio*	*Significance Level*
Conductive Threads	32	7.53	2.18	4	2.26	.0651
Metallic Fibers	32	7.13	2.27	146		
Conductive Coatings	28	6.82	2.00			
Optical Fibers	32	6.19	2.18			
Conductive Inks	27	6.19	2.20			

The primary factors affecting the use of these technologies for developing interactive electronic textiles were then analyzed. Respondents had indicated whether each factor: application flexibility, durability, material flexibility, safety, cost, degree of conductivity, manufacturing flexibility, and manufacturability would affect use of each technology. Chi-Square statistical tests were performed for each technology to determine if there were differences in the proportion of experts who perceived that each factor would affect the use of the technology. The Chi-Square testing results revealed significant differences among the factors affecting the use of optical fibers and conductive inks (Table 5) for product development. Response frequencies for factors affecting use of optical fibers and conductive inks are found in table 6 and 7 respectively. These frequencies reveal that degree of conductivity and safety were perceived as the least significant factors to affect the use of optical fiber technology. While, manufacturing flexibility and safety were perceived as the optical fiber technology, while manufacturing flexibility and safety were perceived as the least significant factors to affect the use of conductive ink technology. There were no significant differences among the factors affecting the use of the remaining technologies.

Table 5: Chi-Square Results for Factors Affecting Technology Use

Technology	***Chi-Square***	***Prob>ChiSq***	***Top 3 Factors Affecting Use***
Optical Fibers	21.926	.0026	1. Material Flexibility 2. Application Flexibility 3. Manufacturability
Conductive Inks	24.778	.0008	1. Durability 2. Degree of Conductivity 3. Manufacturability

Table 6: Factors Affecting Use of Optical Fibers

Factors Affecting Use	***Responses***			
	No		***Yes***	
	n	***%***	***n***	***%***
Application Flexibility	18	56.25	14	43.75
Durability	21	65.63	11	34.37
Material Flexibility	15	46.88	17	53.12
Safety	24	75.00	8	25.00
Cost	22	68.75	10	31.25
Degree of Conductivity	30	93.75	2	6.27
Manufacturing Flexibility	21	65.63	11	34.37
Manufacturability	20	62.50	12	37.50

Table 7: Factors Affecting Use of Conductive Inks

Factors Affecting Use	***Responses***			
	No		***Yes***	
	n	***%***	***n***	***%***
Application Flexibility	16	59.26	11	40.74
Durability	7	25.93	20	74.07
Material Flexibility	21	77.78	6	22.22
Safety	21	77.78	6	22.22
Cost	17	62.96	10	37.04
Degree of Conductivity	12	44.44	15	55.56
Manufacturing Flexibility	19	70.37	8	29.63
Manufacturability	15	55.56	12	44.44

Hypothesis 2: Not all interactive electronic textile applications will be perceived by experts in the field to have an equal potential for success.

A one-way ANOVA statistical procedure was performed to test for differences in the perceived potential for success among various interactive electronic textile applications. As can be seen in Table 8, the results revealed differences in perceived potential for success at the p = .0001 level of significance, providing support for Hypothesis 2. Therefore, the application areas for interactive electronic textiles are perceived by experts to have differing potentials for success.

Table 8: Application Area One-Way ANOVA Testing Results

Application Area	***Number***	***Mean***	***Standard Deviation***	***DF***	***F Ratio***	***Significance Level***
Health & Safety	39	7.64	2.33	4	10.56	.0001
Entertainment	39	6.74	1.77	190		
Personal Communication	39	6.23	2.05			
Business Communication	39	5.69	2.15			
Education	39	4.69	2.28			

Hypothesis two was tested further using a Tukey-Kramer HSD statistical test. This test compared the application area mean pairs to determine specifically which areas were significantly different from each other. The Tukey's testing results revealed five pairs of means were significantly different (Table 9). Health and safety applications were perceived to have a greater potential for success than education, business, and personal communication applications. In addition, entertainment and personal communication applications were perceived to have greater potential than education applications as well.

Table 9: Tukey's Application Area Testing Results

Application Area Pairs	***m***	***T-K HSD***	α
Health/Safety & Education	7.64 4.69	1.622	0.05
Entertainment & Education	6.74 4.69	.724	
Health/Safety & Business Communication	7.64 5.69	.622	
Personal Communication & Education	6.23 4.69	.212	
Health/Safety & Personal Communication	7.64 6.23	.083	

Hypothesis 3: Expert perceptions of potential niche and mass market success for interactive electronic textiles within the next 5 to 10-years will vary.

Results of one-way ANOVA testing of expert perceptions of market potential for interactive electronic textiles supported Hypothesis 3 revealing differences in the 5-year and 10-year time frames for both niche and mass markets. Differences were found in expert perception of niche market success at the p = .0008 level of significance for the 5-year time frame and at the p = .0004 level of significance for the 10-year time frame. Differences were also found in expert perception of mass market success at the p = .0025 level of significance for the 5-year time frame and at the p = .0029 level of significance for the 10-year time frame. Tables 10 and 11 summarize the ANOVA testing results for the niche market 5 and 10-year timeframes. Tables 12 and 13 summarize the ANOVA testing results for the mass market 5 and 10-year timeframes.

Table 10: Niche Market ANOVA Testing Results: 5-Year Time Frame

Application Area	*Number*	*Mean*	*Standard Deviation*	*DF*	*F Ratio*	*Significance Level*
Health & Safety	39	7.28	2.34	2	7.57	.0008
Apparel	39	6.54	2.21	114		
Residential & Commercial Furnishings	39	5.33	2.14			

Table 11: Niche Market ANOVA Testing Results: 10-Year Time Frame

Application Area	*Number*	*Mean*	*Standard Deviation*	*DF*	*F Ratio*	*Significance Level*
Health & Safety	39	8.56	1.76	2	8.45	.0004
Apparel	39	8.00	2.04	114		
Residential & Commercial Furnishings	39	6.80	2.02			

Table 12: Mass Market ANOVA Testing Results: 5-Year Time Frame

Application Area	*Number*	*Mean*	*Standard Deviation*	*DF*	*F Ratio*	*Significance Level*
Health & Safety	38	5.74	2.40	2	6.34	.0025
Residential & Commercial Furnishings	40	4.23	2.24	114		
Apparel	39	4.03	2.22			

Table 13: Mass Market ANOVA Testing Results: 10-Year Time Frame

Application Area	***Number***	***Mean***	***Standard Deviation***	***DF***	***F Ratio***	***Significance Level***
Health & Safety	39	7.13	1.99	2	6.16	.0029
Apparel	39	5.90	2.12	112		
Residential & Commercial Furnishings	37	5.55	2.29			

Hypothesis three was tested further using a Tukey-Kramer HSD statistical test. This test compares pairs of means to determine which are significantly different. Tukey-Kramer HSD was used to compare application area mean pairs to determine areas that are significantly different from each other. The Tukey's testing results for the niche market success for both the 5-year and 10-year timeframes revealed two pairs of means were significantly different in both the 5 and 10-year time frame in the same order (Table 14). In both timeframes, health and safety applications and apparel applications were perceived to have greater potential for niche market success than furnishings applications.

Table 14: Niche Market Tukey'sTesting Results for 5 and 10-Year Timeframes

Niche Market Pairs	***5-Year Timeframe***		***10-Year Timeframe***		α
	m	***T-K HSD***	***m***	***T-K HSD***	
Health/Safety & Residential/Commercial Furnishings	7.28 5.33	.748	8.56 6.80	.725	0.05
Apparel & Residential/Commercial Furnishings	6.54 5.33	.004	8.00 6.80	.161	

The Tukey's testing results for 5 and 10-year mass market success were similar revealing two pairs of means that were significantly different (Table 15). In both timeframes, health and safety applications were perceived to have greater potential for mass-market success than either apparel or furnishings applications.

Table 15: Mass Market Tukey's Testing Results for 5 and 10-Year Timeframes

Mass Market Pairs	***5-Year Timeframe***		***10-Year Timeframe***		α
	m	***T-K HSD***	***m***	***T-K HSD***	
Health/Safety & Apparel	5.74 4.03	.464	7.13 5.90	.084	0.05
Health/Safety & Residential/Commercial Furnishings	5.74 4.23	.272	7.13 5.55	.479	

5.3 ADDITIONAL TESTING RESULTS

In addition to the hypotheses testing, several other analyses were performed on the data. This additional analysis provides further understanding of how the emerging area of interactive electronic textiles is perceived by industry experts. Along with studying the technologies, applications, and market potential for interactive electronic textiles it was equally interesting to examine expert perceptions of the potential for new opportunities, product operation difficulty levels, product attributes, and the potential concerns for interactive electronic textiles.

The numerous applications for interactive electronic textiles that were discussed in chapter two illustrated the variety of recognized opportunities for this emerging area. In addition, 97.44% (n=38) of the sample perceived that it was at least somewhat likely that new interactive electronic textile applications and opportunities will develop within the next 5-years (Figure 37).

Considering the challenges of incorporating electronics into the structures of interactive electronic textiles, the anticipated level of difficulty with operation or use was important to examine. Experts perceive that interactive electronic textile products will be not at all to only somewhat difficult to use or operate (m=3.72). However, experts indicated that operation difficulty levels were somewhat to very likely to affect market success (m=7.37). These seemingly inconsistent results could be due to the sample consisting of industry experts. Since they are quite familiar with these technologies operation difficulty many not seem significant, however at the consumer level this may affect market success.

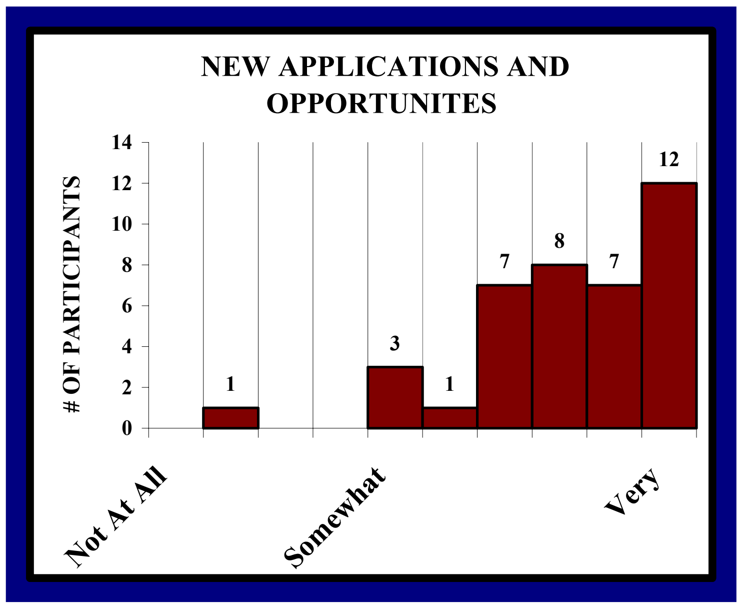

Figure 37: New Applications and Opportunities

The survey also captured perceptions on product attributes and potential concerns that could affect the market success or appeal for interactive electronic textiles. One-way ANOVA statistical tests were used to determine if there were significant differences in the impact of interactive electronic textile product attributes and concerns with respect to market appeal. The ANOVA results revealed differences at the p = .001 level of significance. The ANOVA testing results on product attribute perceptions are presented in Table 16.

Table 16: Product Attribute One-Way ANOVA Testing Results

Product Attributes	*Number*	*Mean*	*Standard Deviation*	*DF*	*F Ratio*	*Significance Level*
Care & Maintenance Requirements	40	7.63	1.96	3	12.56	.0001
Retail Price Points	39	7.21	1.84	152		
Compatibility Options	38	6.24	1.92			
Upgrading Options	39	5.15	2.06			

The product attributes were tested further using a Tukey-Kramer HSD statistical test. This test compared the product attribute mean pairs to determine the attributes that are significantly different from each other. Though all of the product attributes were perceived by experts to be somewhat likely to limit market success, the Tukey's testing results revealed three pairs of means were significantly different (Table 17). The Tukey's testing results revealed that care and maintenance requirements are more likely to limit market success than upgrading and compatibility options. In addition, retail price points were perceived as more likely to limit market success than upgrading options.

Table 17: Tukey's Product Attribute Testing Results

Product Attribute Pairs	*m*	*T-K HSD*	α
Care/Maintenance & Upgrading Options	7.63 5.15	1.367	0.05
Retail Price Points & Upgrading Options	7.21 5.15	.854	
Care/Maintenance & Compatibility Options	7.63 6.24	.239	

ANOVA testing revealed differences in interactive electronic textile product concerns at the p = .03 level of significance. The ANOVA testing results for perceptions on potential interactive electronic textile concerns are presented in Table 18.

Table 18: One-Way ANOVA Testing Results for Concerns

Product Concerns	*Number*	*Mean*	*Standard Deviation*	*DF*	*F Ratio*	*Significance Level*
Safety	38	5.61	2.57	3	3.06	.0301
Security	39	5.15	2.28	150		
Personal Privacy	39	4.46	2.47			
Ethical Issues	38	4.08	2.34			

The potential concerns were also tested further using a Tukey-Kramer HSD statistical test. However, the Tukey's testing results revealed that one pair of concern means were significantly different (Table 19). All of these concerns were somewhat likely to affect market success. However, product safety was perceived as more likely to affect market success than ethical issues.

Table 19: Tukey's Testing Results for Potential Concerns

Potential Concern Pairs	*m*	*T-K HSD*	α
Safety &	5.61	.085	0.05
Ethical	4.08		

The survey also included several open-ended questions. These questions were placed after each section within the survey to allow participants the opportunity to make additional comments concerning the previous group of structured questions they had answered. The open-ended questions and responses are presented in Appendix B and are discussed further in the next chapter.

CHAPTER SIX: DISCUSSION OF RESULTS

The previous chapters described the emerging area of interactive electronic textiles and the purpose and relevance of this research. Three research questions were developed for the purpose of obtaining relevant data on this emerging area. These questions were: 1) Which technologies have the greatest potential in the area of interactive electronic textiles? 2) Which application areas have the greatest potential for interactive electronic textiles? 3) According to an expert industry perspective, what will be the potential market appeal for interactive electronic textiles?

These research questions were addressed by first transforming them into testable hypotheses. An electronic Internet-based survey was used to collect data from experts in the field. The collected data was analyzed statistically and the results were presented in chapter five. This chapter discusses those results and the open-end survey responses. (The survey questionnaire can be found in Appendix A and the open-ended survey responses can be found in Appendix B.)

According to the available literature, there are many technologies being explored for developing interactive electronic textiles. The survey used in this research captured expert opinions on the most recognized technologies within this emerging area. These technologies included: metallic fibers, optical fibers, conductive threads, conductive coatings, and conductive inks. Participants were asked if they were familiar with each technology before answering the questions concerning the technology. Participants not familiar with a particular technology were instructed to proceed to the next technology. This provided increased response accuracy, by capturing opinions only from those familiar with each technology. In addition, this enabled the researcher to classify the technologies according to their familiarity among industry experts. According to the survey results, the sample was most familiar with conductive thread, conductive fiber, and optical fiber technologies and least familiar with conductive ink and conductive coating technologies (Table 20).

Table 20: Percent of Sample Familiar With Each Technology

Technology	*Sample Familiarity (%)*
Conductive Threads	84.21% (n=32)
Metallic Fibers	82.05% (n=32)
Optical Fibers	82.05% (n=32)
Conductive Coatings	73.68% (n=28)
Conductive Inks	71.05% (n=27)

These results are consistent with the available electronic textiles literature presented in chapter two. Literature on conductive thread, metallic fiber, and optical fiber technologies was more abundant than that of conductive inks and conductive coatings. Potentially this means that development efforts are advancing more rapidly for conductive thread, metallic fiber, and optical fiber technologies, while conductive ink and conductive coating technologies are developing at a slower pace. Slower development in these areas could be explained by the challenges previously discussed in chapter two. Recall that the major challenges for developing flexible electronic circuits from conductive coatings and inks included achieving the required conductivity and durable substrate adhesion. The testing results for hypothesis one provide expert perceptions for the potential success of each of these technologies for developing interactive electronic textiles.

Hypothesis one stated that the technologies being used to develop interactive electronic textiles will be perceived by experts in the field to have differing potential for success in future product development. As previously mentioned in chapter five this hypothesis was not supported at the $p \leq .05$ level of significance, revealing all the technologies are perceived to have an equal potential for success in future product development. This result could have been due to the limited number of experts in this emerging area, which restricted the eligible sample for this study. Even though the hypothesis was not supported, the results approach significance at $p = .0651$. Considering these results approach significance, the technologies with the higher means, specifically conductive threads, metallic fibers, and conductive coatings could be more significant for future product development (Table 21).

Table 21: Interactive Electronic Textile Technology Testing Means

Technology	***Mean***
Conductive Threads	7.531
Metallic Fibers	7.125
Conductive Coatings	6.821
Optical Fibers	6.188
Conductive Inks	6.185

In addition to the most common technologies included in the survey, other technologies are also viable for developing interactive electronic textiles. Though not among the technologies predominantly mentioned in the literature, open-ended responses revealed that other technologies are being investigated for developing interactive electronic textiles. (The open-ended survey responses can be found in Appendix B.) Some comments referred to "electrically conductive" materials without mention of specific types. However, experts suggested electrically conductive materials could be chosen according to their properties for integrating special kinds of sensors into fabrics. Several respondents mentioned specifically that they perceived conductive polymer fibers and conductive polymer materials as being dominant technologies for future product development. Conductive polymer materials offer significant advantages over other technologies. They can be developed according to specific requirements, and many overcome many of the limitations of metal-based solutions. These comments coincide with the information provided in chapter two concerning conductive polymer materials. Presently, conductive polymer materials are being explored for future interactive electronic textile development because of the numerous advantages they offer over existing conductive materials.

In an attempt to further understand these technologies the survey captured expert perceptions on the factors affecting the use of each technology for developing interactive electronic textiles. These factors included: cost, safety, durability, manufacturability, material flexibility, application flexibility, manufacturing flexibility, and degree of conductivity. The testing results demonstrated that these factors were perceived as equally important when using metallic fiber, conductive thread, and conductive coating technologies for product development. However, expert opinions did differ with respect to these factors for the optical fiber and conductive ink technologies. The three primary factors identified for the use of these technologies are presented in Table 22.

Table 22: Primary Factors Affecting Optical Fiber and Conductive Ink Use

Technology	*Top 3 Factors Affecting Use*
Optical Fibers	1. Material Flexibility 2. Application Flexibility 3. Manufacturability
Conductive Inks	1. Durability 2. Degree of Conductivity 3. Manufacturability

The primary factors perceived by experts that will affect the use of optical fibers for developing interactive electronic textiles can be related back to the optical fiber characteristics presented in chapter two. Recall that optical fibers are actually glass fibers that possess poor flexibility, drapability, and abrasion resistance and therefore they must be coated for protection. These fiber characteristics correlate with the primary factors (material and application flexibility, and manufacturability) indicated by experts. As for conductive inks, the primary factors affecting technology use can be related to the challenges that remain for practical application of this technology. These issues discussed in chapter two include developing appropriate ink concentrations, achieving appropriate conductivity, and durability of the inks.

In addition to the factors affecting technology use addressed in the survey, open-ended survey comments revealed many other interesting factors that could potentially affect interactive electronic textile technology use. Table 23 summarizes these open-end comments.

Table 23: Summary of Open-Ended Comments: Technology Use

Technology	*Comments on Factors Affecting Technology Use*
Metallic Fibers	• Integrating flexible connection methods with current garment manufacturing technologies • Application suitability • Conductivity, making connections, and withstanding wash cycles
Optical Fibers	• Ability to integrate with optical sensors • Cost of launching light into the fibers and receiving optical signals • Conductivity and making connections
Conductive Threads	• Limited applications and interactivity • Making connections, insulation, and withstanding wash cycles
Conductive Coatings	• Compatibility between polymers - adhesion • Making connections and withstanding wash cycles
Conductive Inks	• Making connections and withstanding wash cycles

The table above reveals the dominant comments concerning technology use focus on electrical connections and maintenance. These perceptions stress the importance of connectivity and easy care requirements and the necessity of further development in these areas. Presently, the industry is working toward overcoming these product development hurdles to successfully use these technologies for developing interactive electronic textile products. As these issues are resolved many applications and opportunities for these specialized textiles will develop.

As mentioned in chapter two, there are numerous potential applications for interactive electronic textiles. The literature suggests the main applications areas for interactive electronic textiles will be communication, entertainment, and health and safety. Hypothesis two stated expert perceptions on the success of each of these application areas will differ. As shown in chapter five this hypothesis was supported, expert perceptions on interactive electronic textile application area success does vary. The response means revealed that experts perceive health and safety applications to be one of the most important areas for interactive electronic textiles. Open comments revealed that experts believe health monitoring and feedback will be a big area for early applications. Some experts believe this is due to the abundance of military funding being used to further interactive electronic textile development. Potentially, military research may solve some of the problem areas associated with the development of interactive electronic textiles. As product development issues are resolved and production costs decline, more emphasis will be placed on product development for the consumer market.

Entertainment applications were perceived as an equally important area for interactive electronic textile success according to the mean responses. Comments revealed that technical applications, such as the popular area of virtual games, will be important early applications for interactive electronic textiles. Contrary to the open responses for health and safety applications, some experts perceive fashion items for entertainment purposes will be the most important because they need not be as robust and powerful as health, safety, and military applications. These experts believe that further groundwork is necessary to advance robust health, safety, and military applications.

Personal communication and business communication were also perceived as important. Educational applications were viewed as somewhat less important. Open comments also suggested some creative applications not mentioned in the literature. Experts perceive automatic inventory for clothing stores and warehouses, smart washing machines that recognize clothes, closets that identify availability of garments, and anti-counterfeit applications will also develop for interactive electronic textiles.

The application areas for interactive electronic textiles are closely related to the viable markets for distributing these products. Niche and mass markets are two viable market areas for potential sales of interactive electronic textile products. Niche markets focus on serving a limited number of special segments within a market to satisfy specific needs (e.g. products sold at specialty boutiques). Mass markets on the other hand, focus on serving an entire market to satisfy a broad range of needs (e.g. products sold at popular chain retail outlets such as Target). The survey captured expert opinions on the success of interactive electronic textile products in each of these market areas. Hypothesis three testing identified that perceptions of the potential niche and mass-market success for interactive electronic textiles within the next 5 to 10-years varies. This hypothesis was supported for both niche and mass markets at the 5 and 10-year time frames. Experts indicated that niche and mass-market success for interactive electronic textile products will differ.

Testing revealed experts perceive interactive electronic textile products will have a greater opportunity for success in niche markets in both the 5 and 10-year time frames. Experts indicated that niche market success for both the 5 and 10-year time frames will be most likely to occur within health and safety and apparel applications, with residential and commercial furnishing applications perceived to have somewhat less potential. Expert perceptions for mass-market success were similar. Results revealed health and safety applications are perceived to have the greatest opportunity for success in mass markets for both the 5 and 10-year time frames. In both time frames experts perceived residential and commercial furnishing applications and apparel applications to have somewhat less potential for mass-market success.

These results directly relate to with those obtained for hypothesis two. Recall that health and safety applications were perceived to have the greatest potential. When compared to the hypothesis three results, perceptions were the same. The greatest potential for niche and mass market success with in the next 5 to 10-years is perceived to be in the area of health and safety.

To further examine the emerging area of interactive electronic textiles, the survey captured expert opinions on the potential for new opportunities, product operation difficulty levels, product attributes, and potential concerns for interactive electronic textiles. These areas provide a further understanding of how experts perceive this emerging area. These expert perceptions can assist in identifying the areas and issues that require further development to advance interactive electronic textiles.

A majority of the sample 97.44% (n=38) perceive that it is somewhat to very likely new applications and opportunities for interactive electronic textiles will develop within the next 5-years. This could indicate that experts perceive that this emerging area will be quite significant for the textile industry in the near future. Furthermore, they perceive opportunities for growth as well.

Interactive electronic textiles will incorporate many kinds of electronic devices into their structures. This leads us to believe there will be some level of skill required to operate and use these specialized textile products. Therefore, perceptions on product operation difficulty and how this will affect the market success of these products was important to examine. Testing revealed a sample mean of 3.72, indicating that experts perceive interactive electronic textile products will be in the range of not at all to somewhat difficult to operate or use. Considering experts feel operation difficulty will be limited, their perceptions on product operation difficulty affecting market success were in the range of somewhat to very (m=7.37). These results reveal some interactive electronic textile products will require product knowledge and understanding for operation that could affect market success. To overcome these issues the industry will need to educate consumers on product usage and possibly offer post-purchase product assistance to make these products appealing to consumers.

Market appeal and success also depends on product attributes or characteristics. Upgrading and compatibility options, retail price points, and care and maintenance requirements are considered the most significant interactive electronic textile product attributes. The survey addressed these attributes to determine how experts perceive they will affect interactive electronic textiles market appeal. The sample means for all of these attributes were in the range of somewhat to very important revealing on some level each will potentially affect the market appeal for interactive electronic textile products.

Care and maintenance requirements were perceived to be the most significant attributes that will affect the market appeal for interactive electronic textile products. This relates back to the previously mentioned open comments concerning technology use. Participants mentioned the importance of the conductive materials withstanding wash cycles. Product developers are aware consumer appeal for interactive electronic textile products will rely heavily on their ability to be easily cared for and maintained. Therefore these issues need to be addressed as development progresses.

Retail price points were perceived as the second most important product attribute. New technologically advanced products that enter the market are usually expensive. As development progresses, and more efficient processes and economical materials are identified, prices usually decline. As interactive electronic textiles enter the market they are likely to be expensive at first and, as technology progresses and production processes are perfected, prices will decline.

Compatibility and upgrading options were perceived as the third and fourth most important product attributes influencing market success. Consumers are aware many electronic and high technology products they purchase today will be late models in the near future. New updated and advanced versions appear on the market so quickly that many consumers are considering compatibility and upgrading product options. Interactive electronic textiles will need to be compatible with various types and brands of electronics to achieve market success. In addition, upgrading these products will also be important as technology progresses. Presently these issues challenge interactive electronic textile product developers and will influence future development.

The introduction of interactive electronic textiles will also raise concerns among product end users. Survey responses revealed that safety is perceived to be the primary concern followed by security, personal privacy and ethical issues. The sample mean for these concerns was 4.83 revealing experts perceive these concerns to be somewhat important to the success of interactive electronic textiles. Related comments indicated that many of the interactive electronic textile systems presently being developed do not pose any health hazards or privacy and security concerns. Therefore, these concerns may be less significant with further development. Respondent comments also suggest that interactive electronic textiles will require social and cultural changes before they are widely adopted. These comments can be attributed to the fact that these textiles will increase mobility and change the way we accomplish many of our daily tasks. As with any new technological area, potential concerns are usually resolved with further development.

In summary, many technologies are viable for developing interactive electronic textiles. This research revealed no significant difference in expert perceptions of the potential for success among the most recognized technologies; metallic and optical fibers, conductive threads, and conductive coatings and inks. However, trends in the data suggested that conductive threads and metallic fibers may hold greater potential than the other technologies. Open-end survey responses suggested that as development progresses in the area of conductive polymer materials, this technology may become increasingly important for future development of interactive electronic textiles. In the area of potential applications and market success, health and safety was perceived to have the greatest potential for niche and mass market success throughout the next 10-years. Care and maintenance and safety were perceived as the most important attributes that will affect the success of interactive electronic textiles.

Though product development is still faced with many challenges, the future for interactive electronic textiles looks promising. Thirty-eight out of the thirty-nine experts who participated in this research perceive that new applications and opportunities will develop for interactive electronic textiles within the next 5-years. This reveals that experts are convinced interactive electronic textiles will succeed and the field will expand in the near future. Present and future research and development efforts will enable product developers to overcome the hurdles and challenges necessary to advance this field. The next chapter explores the noteworthy research efforts presently underway, the opportunities for further research, and provides some final thoughts on the emerging area of interactive electronic textiles.

CHAPTER SEVEN: RELATED RESEARCH

At present, there is an abundance of research being conducted to advance interactive electronic textile development. A majority of this research is occurring within universities, corporations, military facilities, and textile trade organizations both domestically and internationally. This section explores the significant research efforts occurring in these areas. Following the discussion of the current research, potential areas for future research are presented. The chapter closes with some final thoughts on the emerging area of interactive electronic textiles.

7.1 PRESENT RESEARCH EFFORTS

University research is a significant contributor to interactive electronic textile development. Numerous research projects to advance this area are presently occurring within various departments at many universities around the world. Many fiber and polymer science, textile and apparel technology, electrical, computer, and mechanical engineering departments at various universities are involved in interactive electronic textile research. As previously mentioned in chapter two, Massachusetts Institute of Technology (MIT) and Georgia Institute of Technology are presently conducting research in this area. North Carolina State University (NCSU), Brunel University in the UK, Tampere University of Technology (TUT) in Finland are just a few others are also conducting interactive electronic textile research.

Presently at NCSU, research in the areas of Microelectromechanical Systems (MEMS) and "computable fabrics" are underway to advance interactive electronic textile development. Recently a MEMS research project was conducted by Severine Gahide under the direction of G.L. Hodge, W. Oxenham, A.M. Seyam, and P.D. Franzon. As previously discussed in chapter two, MEMS are single chip systems that incorporate microstructures, microsensors, microactuators, and electronics. The NCSU team, funded by the National Textile Center (NTC), has investigated potential applications for interactive electronic textiles (Holme, 2000). The "computable fabrics" research project is being conducted to demonstrate how the principles of electrical and computer engineering can be integrated with current textile manufacturing processes to produce "smart textiles." This project was recently awarded funding by the Defense Advanced Research Projects Agency (DARPA). DARPA is the central research and development organization for the Department of Defense (DoD) that pursues various research and technology efforts for advancing traditional military roles and missions (DARPA, 2001).

Additional noteworthy interactive electronic textile research projects are being conducted at The Design for Life (DFL) Center at Brunel University in the United Kingdom and the Tampere University of Technology (TUT) in Finland. The DFL team has been researching technical specifications for utilizing conductive fibers in textile structures. The DFL team has developed several conductive textile samples and testing has demonstrated the feasibility of the technology. Currently, the DFL team has been applying this technology to the development of a user friendly switching and sensing textile capable of interfacing with speech systems. This research titled the "Sensory Fabrics Project" is being conducted to develop products for children with learning disabilities. This project is presently generating an abundance of funding from the European Union and local business partners (Brunel University, 2001).

In Finland, the fiber materials science department at TUT is conducting a survey of intelligent textiles funded by the Nokia Research Center. The research team is investigating the various kinds of intelligent textiles being developed around the world and how they can be applied to the development of smart garments. These researchers are testing the materials used to create intelligent textiles to verify their functions and suitability for intelligent garments. Then garments developed from these materials will be designed, constructed, and tested (Fiber Materials Science Research: Survey of Intelligent Textiles, 2001).

Numerous corporations are also involved with electronic textile research. Dominating the literature is Philips Research Laboratories in the United Kingdom. For the last few years they have been mixing electronics, fashion, and technology to create new apparel concepts. Their research and development efforts range from developing conductive fiber pathways for carrying electronic information, to constructing innovative garments utilizing smart seams. Some of the research being conducted at Philips is in collaboration with other companies also exploring the area of electronic textiles. Joint development agreements with Levi Stauss, Colbond Nonwovens, and Web Dynamics have recently been mentioned in the media (Holme, 2000). As electronic textile research and joint development progresses at Philips Electronics, they are emerging as one of the interactive electronic textile pioneers.

A new company called International Fashion Machines (IFM) is becoming another pioneer within the emerging interactive electronic textiles arena. CEO Maggie Orth, a recent MIT Media Laboratory Ph.D. graduate, recently founded IFM. The company performs smart textile research and consulting to bridge the gap between smart textile design and technology. IFM works with technology, fashion, and design companies to develop new products, applications, and markets for smart textiles. The company also conducts research and provides consulting services for advancing smart textiles. Maggie Orth, Ph.D. was an expert panelist at the Tech-U-Wear 2001 Conference held at Madison Square Garden on October 30th-31st 2001. The focus of Tech-U-Wear 2001 is wearable computing and the technologies behind the latest business applications that are driving the market forward (Orth, Maggie, PhD personal communication, August 28, 2001).

Many other corporations are also engaging in electronic textile research, those recognized in the literature for their interactive electronic textile research efforts are presented in Table 24.

Table 24: Corporations Conducting Interactive Electronic Textile Research

Adidas	North Face
Cambridge Display Technology	Nike
Charmed Technology	Nokia Research Center
DuPont	Panasonic
ElectroTextiles Company	Prada
Hitachi	Sony
IBM	Tactez Controls

Various electronic textile research is also being conducted at military research centers. Within the United States, the NASA Lewis Research Center, the United States Army Research Office, and the Department of Defense are all engaged in various research efforts to further the development of intelligent materials and structures for military applications. Research projects range from the development of smart materials and structures capable of detecting a variety of toxic agents to the development of optical fiber micro sensors that can be woven into fabrics to create smart combat gear and intelligent uniforms. In addition, the government is also funding many additional electronic textile research projects that are being conducted outside military facilities, similar to the NCSU DARPA research project previously mentioned (El-Sherif, 2000).

The National Textile Center (NTC), Nano-Tex LLC, and the New Zealand based textile research and development organization (WRONZ), represent a few of textile trade organizations presently advancing interactive electronic textile development with their research efforts. NTC is a research consortium of seven top research universities: Auburn University, Clemson University, Cornell University, Georgia Institute of Technology, North Carolina State University, Philadelphia University, and the University of Massachusetts Dartmouth. NTC serves the fiber, textile, fabricated products, and retail complex through innovative research and collaborative partnerships to improve the competitiveness of the textile industry. Various electronic textile research projects have been undertaken by the NTC. Design, development, and manufacture of specialized protein-based "smart" fibers are a recent example of the work being conducted by the NTC in the area of electronic textiles (National Textile Center, 2001). Nano-Tex LLC, established in 1998, is a knowledge-based research company founded on the principles of creating new or improved textile properties at the molecular level using nanotechnology. This research company is centered on a partnership between Nano-Tex and Burlington Industries (Nan-Tex, 2001). As previously mentioned in chapter two, research efforts at WRONZ have recently developed a new technology called Softswitch that offers numerous opportunities for interactive electronic textile development.

7.2 TECHNOLOGY RESEARCH OPPORTUNITIES

Despite the amount of interactive electronic textile research presently being conducted, there are still numerous opportunities for future research. Before addressing the specific areas that require further investigation, it will be helpful to discuss where the research presented in this paper fits into this emerging area. First, this research paper has provided an in-depth review of the available interactive electronic textiles literature. Second, expert industry perceptions concerning this field including the technologies, applications, opportunities, and potential market appeal were gathered and discussed. Thus a solid foundation has been laid for further research.

There are several specific technological areas that require further research to advance the development of interactive electronic textiles. In the area of conductive technologies, further research to perfect the use of these materials in textile applications is imperative. Recall from chapter two the conductive technologies being explored include metallic and optical fibers and conductive threads, yarns, coatings, and inks. According to the survey results many factors are equally important for developing electronic textiles from conductive materials. Factors such as cost, safety, durability, conductivity, manufacturability, and material, application, and manufacturing flexibility all require further exploration. Issues of connectivity between the electronic devices and the conductive and traditional textile materials also require further investigation. Furthermore, identifying and developing more advanced viable technologies such as conducting polymer materials will also benefit product development. Researching these conductive technology areas will solve many issues currently facing product developers.

Research in the area of enabling technologies is also necessary. The design and fabrication of electronic textile sensors, circuits, antennas, and electrodes requires further development for perfection. In addition, enabling technologies such as input and output devices necessary for sending and receiving information are also challenging electronic textile developers. These devices require size, flexibility, and power capacity modifications to be appropriate for interactive electronic textile applications. Research is necessary to develop acceptable keyboard devices for inputting information. Furthermore, devices such as miniature displays for providing output also require further development. The miniature displays that are currently available are only acceptable for some output applications and can only display limited amounts of information (Tenenbaum, 2000).

7.3 MARKET RESEARCH OPPORTUNITIES

Beyond the conductive materials and enabling technologies, there are also numerous consumer market research opportunities. The survey results revealed that product operation difficulty, product attributes, and potential concerns will be important for interactive electronic textile products. Therefore, an abundance of consumer research can be pursued in these areas to advance the developing area of interactive electronic textiles.

The survey results revealed that interactive electronic textile products will require product knowledge and understanding for operation and this may affect the market success for these products. Considering these results, it will be beneficial to conduct consumer research to determine how consumers feel about these issues. Exploring research in this area will also help to identify levels of consumer education and post-purchase product assistance that will be necessary for successfully marketing interactive electronic textile products.

Consumer research concerning product attributes such as care and maintenance requirements, retail price points, and upgrading and compatibility options will also benefit this emerging area. The survey results reveled care and maintenance requirements will be the most significant attributes that will affect interactive electronic textiles market appeal. Further research to determine care requirements necessary to maintain these products and how consumers respond to these care requirements is essential. Research to determine acceptable price points for interactive electronic textile products is also necessary. It is likely these products will be expensive as they enter the market. Therefore, it is important to determine consumer perceptions on acceptable price points. Research concerning compatibility and upgrading options will also advance this area. Today increasing numbers of consumers are interested in product compatibility and upgrading options to keep up with rapidly advancing technology. Product compatibility and upgrading options present excellent opportunities future research to determine the types of options most desired by consumers. Further investigation into how consumers will use these products and determining the most desirable product attributes will assist product development efforts.

Research addressing potential interactive electronic textile concerns such as safety, personal privacy, and ethical issues could also assist development within this area. Even though experts perceived that these concerns will only be somewhat important to the success of interactive electronic textile products, consumer perceptions may differ. In our technologically advanced society these concerns are becoming important to consumers. Therefore, it would be beneficial to undertake consumer research in these areas. Even though challenges and hurdles still remain for developing interactive electronic textile products, in the near future they may be the next most desired consumer products. Therefore, researching consumer demands and desires will be important to the market success for interactive electronic textiles.

7.4 CONCLUSION

Future trends toward mobile convenient electronic devices will fuel the demand for "interactive electronic textiles". According to recent studies for the potential wearable electronic market, several interesting predictions have been made.

- The US market for wearable computing will reach $600 million by 2003.
- Flexible polymer screens will be printed on T-shirts by 2005.
- Electronic apparel will be able to alter their thermal properties by 2007.
- Micro-actuators built into apparel for sensory feedback from computers by 2012 ("Suits You Sir," 2000).

According to the statistics above and the available literature, textiles in the near future will incorporate many forms of electronic devices into their structures. Recent interest generated among the textile and electronic industries determined there was a need to further explore this area. The goal of this research has been to provide a better understanding of interactive electronic textiles. This goal was achieved through an in-depth analysis of the available literature and by surveying industry experts in the field. The literature review identified the technologies, applications, opportunities, and potential market appeal for interactive electronic textiles, while the survey captured expert perceptions and future insight to support the literature review. Anyone who reads this paper will gain a better understanding of this emerging area.

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APPENDICES

APPENDIX A: SURVEY QUESTIONAIRRE

INTERACTIVE ELECTRONIC TEXTILES SURVEY QUESTIONNAIRE

CONFIDENTIALITY

All information provided below will be kept confidential except for the purpose of forming cumulative data from all participants. Any information or comments provided will not be attributed to an individual, company, or organization. No one from any other company or organization will see individual questionnaire responses.

This survey was developed to support a thesis research project and all your responses and comments are greatly appreciated.

I would like to thank you in advance for your participation in this research project.

INTERACTIVE ELECTRONIC TEXTILES

can be defined as textiles with integrated electronic-based intelligence. These specialized textiles have the potential to integrate touch and voice-activated communication, entertainment, and safety devices into traditional textile products. The purpose of this survey is to examine the technologies, applications, opportunities, and the potential market appeal for interactive electronic textiles.

DEMOGRAPHIC INFORMATION

Name (optional):

Company or Organization:

Address:

Position:

Engineering
Manufacturing
Marketing
Sales
Finance

Company or Organization Size (# of employees):

In the following sections please indicate your answers by selecting the button above the number that corresponds to your answer.
Thank You.

INTRODUCTORY QUESTIONS

1. How familiar are you with the emerging area of Interactive Electronic Textiles?

1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

2. How would you classify your knowledge of this area?

1	2	3	4	5	6	7	8	9	10
Novice				**Average**					**Expert**

INTERACTIVE ELECTRONIC TEXTILE TECHNOLOGIES

3. In your opinion, how likely is it that the following ***CONDUCTIVE MATERIALS*** will be on the forefront of electronic textile product development within the next 5 years?

CONDUCTIVE METALLIC FIBERS

I am not at all familiar with conductive metallic fibers. ☐ ***Please proceed to optical fibers.***

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

What are the primary factors affecting the use of conductive metallic fiber technology for developing interactive electronic textiles?

- ☐ **Cost**
- ☐ **Safety**
- ☐ **Durability**
- ☐ **Manufacturability**
- ☐ **Material Flexibility**
- ☐ **Application Flexibility**
- ☐ **Manufacturing Flexibility**
- ☐ **Degree of Conductivity**
- ☐ **Other (Please Specify)** ____________________

OPTICAL FIBERS

I am not at all familiar with optical fibers. ☐ ***Please proceed to conductive threads.***

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

What are the primary factors affecting the use of optical fiber technology for developing interactive electronic textiles?

- ☐ **Cost**
- ☐ **Safety**
- ☐ **Durability**
- ☐ **Manufacturability**
- ☐ **Material Flexibility**
- ☐ **Application Flexibility**
- ☐ **Manufacturing Flexibility**
- ☐ **Degree of Conductivity**
- ☐ **Other (Please Specify)** ______________________

CONDUCTIVE THREADS *(Used for stitched or sewn textile circuit development)*

I am not at all familiar with conductive threads. ☐ ***Please proceed to conductive coatings.***

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

What are the primary factors affecting the use of conductive thread technology for developing interactive electronic textiles?

- ☐ Cost
- ☐ Safety
- ☐ Durability
- ☐ Manufacturability
- ☐ Material Flexibility
- ☐ Application Flexibility
- ☐ Manufacturing Flexibility
- ☐ Degree of Conductivity
- ☐ Other (Please Specify) ____________

CONDUCTIVE COATINGS ***(Applied to knitted, woven, or nonwoven textiles)***

I am not at all familiar with conductive coatings. ○ ***Please proceed to conductive printing inks.***

○	○	○	○	○	○	○	○	○	○
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

What are the primary factors affecting the use of conductive coating technology for developing interactive electronic textiles?

- ☐ Cost
- ☐ Safety
- ☐ Durability
- ☐ Manufacturability
- ☐ Material Flexibility
- ☐ Application Flexibility
- ☐ Manufacturing Flexibility
- ☐ Degree of Conductivity
- ☐ Other (Please Specify) ____________

CONDUCTIVE PRINTING INKS ***(Specially formulated inks that contain metals to supply conductivity)***

I am not at all familiar with conductive printing inks. ☐ ***Please proceed to question 4.***

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

What are the primary factors affecting the use of conductive ink technology for developing interactive electronic textiles?

- ☐ **Cost**
- ☐ **Safety**
- ☐ **Durability**
- ☐ **Manufacturability**
- ☐ **Material Flexibility**
- ☐ **Application Flexibility**
- ☐ **Manufacturing Flexibility**
- ☐ **Degree of Conductivity**
- ☐ **Other (Please Specify)** ____________________

4. If you would like to make any comments concerning any of the previously mentioned or other interactive electronic textile technologies please use the scrolling text box provided below. ***Thank You.***

INTERACTIVE ELECTRONIC TEXTILE APPLICATIONS AND OPPORTUNITIES

5. Interactive electronic textiles can benefit any traditional textile application. In your opinion, ***how important will the each of the following applications be*** for this emerging area ***within the next 5 years***?

HEALTH & SAFETY APPLICATIONS

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

BUSINESS COMMUNICATION APPLICATIONS

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

PERSONAL COMMUNICATION APPLICATIONS

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

ENTERTAINMENT APPLICATIONS

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

EDUCATIONAL APPLICATIONS

1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

6. In your opinion, how likely is it that ***NEW APPLICATIONS & OPPORTUNITIES*** will develop for these specialized textiles ***within the next 5 years***?

1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

7. If you would like to make any comments concerning any of the previously mentioned or any other interactive electronic textile applications and/or opportunities please use the scrolling text box provided below. ***Thank You.***

INTERACTIVE ELECTRONIC TEXTILE POTENTIAL MARKET SUCCESS

8. In your opinion, how likely is it that interactive electronic textiles will gain ***NICHE MARKET SUCCESS*** within the next 5 to 10 years in the following markets?
(Niche marketing focuses on serving a limited number of special segments within the market to satisfy specific needs.)

APPAREL WITHIN THE NEXT 5 YEARS?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

APPAREL WITHIN THE NEXT 10 YEARS?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

RESIDENTIAL & COMMERCIAL FURNISHINGS WITHIN THE NEXT 5 YEARS?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

RESIDENTIAL & COMMERCIAL FURNISHINGS WITHIN THE NEXT 10 YEARS?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

HEALTH & SAFETY WITHIN THE NEXT 5 YEARS?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

HEALTH & SAFETY WITHIN THE NEXT 10 YEARS?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

9. In your opinion, how likely is it that interactive electronic textiles will gain ***MASS MARKET SUCCESS*** within the next 5 to 10 years in the following markets?

APPAREL WITHIN THE NEXT 5 YEARS?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

APPAREL WITHIN THE NEXT 10 YEARS?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

RESIDENTIAL & COMMERCIAL FURNISHINGS WITHIN THE NEXT 5 YEARS?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

RESIDENTIAL & COMMERCIAL FURNISHINGS WITHIN THE NEXT 10 YEARS?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

HEALTH & SAFETY WITHIN THE NEXT 5 YEARS?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

HEALTH & SAFETY WITHIN THE NEXT 10 YEARS?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

10. In your opinion, ***HOW DIFFICULT*** will interactive textile products be to use or operate?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

11. In your opinion, how much will ***OPERATION DIFFICULTY LEVELS*** affect the market appeal/success of interactive textile products?

1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

12. In your opinion, how likely is it that each of the following ***PRODUCT ATTRIBUTES*** will affect interactive textile products ***MARKET APPEAL/SUCCESS***?

CARE & MAINTENANCE REQUIREMENTS

1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

RETAIL PRICE POINTS

1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

UPGRADING LIMITATIONS

1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

COMPATIBILITY LIMITATIONS

1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

13. In your opinion, how likely is it that the following ***CONCERNS*** relating to interactive electronic textile products will limit their ***MARKET SUCCESS/APPEAL***?

PERSONAL PRIVACY

1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

SECURITY

1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

SAFETY

1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

ETHICAL

1	2	3	4	5	6	7	8	9	10
Not At All				**Somewhat**					**Very**

14. If you would like to make any comments concerning the potential market appeal/success for interactive textile products please use the scrolling text box provided below. ***Thank You.***

THANK YOU!

This survey was developed by Dina Meoli - Graduate Student - NCSU under the direction of Dr. Traci M. Plumlee - Assistant Professor - NCSU.

If you are interested in obtaining a copy of the cumulative survey data results please contact:

Dina Meoli
dmeoli@unity.ncsu.edu
North Carolina State University

Submit Reset

After submitting this survey, feel free to forward this link to anyone involved in electronic textile research and development that you feel may be interested in participating in this research. ***Thank You!***

APPENDIX B: OPEN-ENDED QUESTIONAIRRE RESPONSES

Open-Ended Survey Questionnaire Responses

Interactive Electronic Textile Technology Comments

- There are also several other types of electrically conductive materials. There may be other properties that you want to have for doing special kinds of sensors and also for encoding and adding electromagnetic identification into the fabric.
- Conducting polymer fibers rather than metallic will dominate.
- Polymer materials – in my experience metal-based solutions tend to have limitations that may be overcome by using new polymer technologies. In my opinion, these will be the single most important class of materials in this field within 5 years.
- I've answered all as "viability of application," because I'm not convinced there are compelling applications that make business and consumer sense. Once those are defined the technology will develop to fill the need. In engineering, it helps to know what the problem is in order to formulate the solution.
- Safety is important when designing optical fiber systems and this would have to be taken into account. Also while fibers are flexible, this is only to a limited extent and if they are bent too sharply they will break!
- I have listed factors that I see as limitations to each technology, although one could equally well interpret "factors affecting use" as advantages of each. While I can think of advantages of each, I wanted to be consistent.

Comments Concerning the Factors Affecting Technology Use for Developing Interactive Electronic Textiles

Conductive Metallic Fibers

- Robust and flexible connection methods that can be integrated with current garment manufacturing technologies
- Suitability
- Connectivity
- Making connections and withstanding wash cycles

- Insulating them, connecting to them and integrating them into yarns - as the fiber content increases, the yarns flexibility decreases

Optical Fibers

- Ability to integrate with optical sensors
- Useful for high bandwidth, not such an issue in textiles
- High band width, immune to external electromagnetic frequency disturbance
- Cost of launching light into fiber and cost of receiving optical signal
- Connectivity
- Making connections
- Conductivity is not applicable. Optical fibers are wave-guides. The primary problem with optical fibers is connecting to them! They require big bulky connectors. This is changing, but these future connectors will still be rigid.

Conductive Threads

- Limited applications and interactivity
- Making connections and withstanding wash cycles
- Connecting to them, insulating them, size of yarn, electrically connecting yarns with different electrical properties (necessary for different components on a surface)

Conductive Coatings

- Compatibility between polymers – adhesion
- Making connections and withstanding wash cycles

Conductive Printing Inks

- Connectivity
- Making connections and withstanding wash cycles

Interactive Electronic Textile Application & Opportunity Comments

- Automatic inventory of clothes in stores and warehouses
- Smart washing machines that recognize clothes and closets to tell you what is available to wear
- Anti counterfeiting purposes
- I think military applications will initially be the biggest use for these products
- I do not believe the most useful applications are in consumer electronics, except where there is a real technical need e.g.. sports or virtual reality games hardware.
- "Health & Safety" in the UK relates to protection from accidents or bad working practices. However, here I have taken it to mean health monitoring and feedback, which I think is a big area for early applications in this field. I would suggest separating out health from safety as I think the latter is much less relevant.
- Location, context, temperature sensors and power generation/storage sensors for heating/cooling. Interfaces and displays among others.
- The military application of electronics in textiles has attracted the attention of the top brass and they are willing to fund research in this area. For interactive electronic textiles to be successful in this area they will have to be robust, durable, cheap, and easy to use. If the research funded by the military can solve these problem areas I think that it is highly likely that the techniques used to solve the problems will be spun off into the civilian sector. The main reason for this is that the military sources its clothing from the civilian sector and the tendering system used to place orders favors the spread of techniques to a wide base of suppliers in cases of emergency. Any fears of about the technology falling into the hands of potential adversaries can be countered be controlling the electronic devices used in conjunction with the communications system built into clothing. Once the problems of using conductive fabrics to allow electronic devices to communicate with one another have been solved the civilian sector can use the same communication system to get civilian electronic devices (MP3, PDA's, Cellular Phones, ect.) to work as an integrated system.
- I think the first applications to really appear in quantity will be entertainment and fashion related. Time is needed to research various components of wearable systems (materials you listed above, plus interfaces, and how people wear devices). Some groundwork has

to be in place before other health/safety/military etc. applications (which are great...) will develop in robust ways. Fashion need not be robust.

- The next 5 years are likely to introduce the first mass-produced commercial applications and create the market for interactive electronic textiles. The first five years, or so, will probably be just trial and error until "real" market segments can be determined.

Interactive Electronic Textile Market Appeal/Success Comments

- I believe that markets with real technical need and therefore the willingness to pay will be served with new developments, first health & safety, medical, and military uses. These may then filter down to consumer products as costs reduce.
- What is mass market? It will be hard to predict EXACT market for new products.
- Having worked with many types of wearable systems and materials, I have not seen many systems that actually pose health hazards or ethical dilemmas.
- Ethical questions should be considered thoroughly when developing new fibers and products. For example, no animal testing should be used during the developing and testing processes.
- Interactive textiles will require social and cultural changes - these changes take time before they are widely adopted.
- The prototypes and applications of interactive textiles that I have seen seem to be quite easy to operate.