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INTERACTIVE ELECTRONIC TEXTILE DEVELOPMENT:
A Review of Technologies

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ABSTRACT

Electronics may soon be integrated into textiles in our near environment. These "Interactive Electronic Textiles" (IETs) will benefit many traditional textile applications. Firms that understand how to incorporate emerging IET technologies into their new product strategies will establish and sustain financial and competitive advantages. Currently, product development practitioners and academic researchers are investigating multiple technologies for their potential in IET development. This research explored the emerging area of IETs by examining the potential supporting technologies including their strengths and limitations.

KEYWORDS: Electronic textiles, smart fabrics, smart clothes, wearable computing, interactive textiles

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INTRODUCTION

The electronics that facilitate our daily pursuits and interactions may soon be integrated into the textiles in all areas of our near environment. These "Interactive Electronic Textiles" (IETs) may find niches in many traditional textile applications. Opportunities exist for IETs in fashion and industrial apparel, residential and commercial interior, military, medical and industrial textile markets. IETs are being developed for communication, entertainment, health and safety. IET technologies may one day integrate multiple electronic devices directly into textile and apparel products using shared resources increasing the mobility, comfort, and convenience of such devices (Heerden, Mama, & Eves, 1999). For example, communication devices may be integrated into products such as the garments in Figures 1 and 2 (Softswitch, 2001; Philips, 2001). Integrated compact disk players, MP3 players, electronic game panels, digital cameras and video devices, and interactive club apparel that changes colors with the beat of the music are all being developed (Heerden et. al.., 1999). Textile keypads on

Figure 1: Integrated Textile Keypad (Softswitch, 2001)

Figure 2: Sleeve Integrated Communication Device, (Philips, 2001)

Figure 3: (Left) Remote Control (Right) Light Switch (Softswitch, 2001)

Figure 4: Electronic Sportswear Garment, (Philips, 2001)

a sleeve might be used to dial phone numbers, type pager messages, and play music. Interior textiles for the home or office might control lighting, temperature, or other electronic devices. For example, a television remote control might be integrated into the arm of a sofa, or a light switch integrated into a curtain (Figure 3). IETs can also be developed to detect pressure and/or movement in sensitive medical textiles, engineering fabrics, active sportswear, and automotive seats (Softswitch, 2001).

IETs have the potential to improve current healthcare practices for monitoring breathing, heart rate, stress levels, and body temperature. These IETs may increase patients' mobility, provide added convenience, and improve the quality of life for those with health problems or disabilities (Havich, 1999). High-performance electronic sportswear can track, and enhance performance for a workout at the gym or for extreme sporting activities. The garment in Figure 4 features integrated fabric sensors to monitor and display pulse, blood pressure, time, distance, speed, and calories. Such sensors can also record arm action for improving golf or tennis swings, body temperature, or can be used to develop workout regimes (Roberts, 2000).

Textiles integrated with sensory devices driven by a Global Positioning System (GPS) can detect a users exact location anytime and in any weather (The Aerospace, 2001). IETs with integrated GPS, such as the ski suit in Figure 5, enhance safety by quickly locating the wearer and allowing the suit to be heated. Parents can easily keep track of a child’s

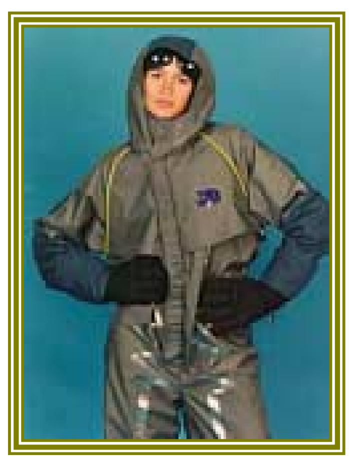

Figure 5: Electronic Ski-Suit, (Philips,2001)

location with garments containing integrated GPS (Figure 6) (Foster, 1999). GPS can also provide added safety for emergency personnel by facilitating offsite monitoring of vitals (Havich, 1999).

Textile firms that understand how to incorporate emerging IET technologies into their new product strategies will establish and sustain financial and competitive advantages. Wearable electronics are already finding many opportunities in non-textile products such as implanted microchips and digital jewelry (Rajkhowa, 2000). Progressive apparel firms are developing strategic partnerships and exploring ways to market interactive apparel ("Smart Clothes", 2002). This research investigated the emerging area of IETs by examining the technologies currently being scrutinized for IET development.

CONDUCTIVE TECHNOLOGIES

The area of IETs has emerged from the wearable computing arena. Many of the wearable computing devices developed to date are cumbersome and awkward (Figure 7), typically strapped or carried on the body. But, textile-based wearable electronics that allow interactive touch, voice, and body heat activation are being developed. The current versions use integrated wiring and carrying devices that add bulk and weight to the garments making them uncomfortable and impractical for daily use. These items are also expensive and present issues relating to maintaince, flexibility, and user safety

Figure 7: "Wearable" computing devices

(Mann, 1998). The first wired electronic apparel line to be marketed to consumers included four jackets, such as the Mooring (Figure 8). In these jackets, concealed inner wiring connects a mobile phone and MP3 player, built-in speakers, a microphone and a

Figure 8: (Left) Jacket by Levi Strauss & Philips Research Laboratories, (Right) Integrated Communications System (Izarek, 2000)

display. The devices and the control pad can be disconnected for garment laundering, however the inner wiring and connectors cannot be removed limiting maintenance options. These jackets also have very limited compatibility and upgrading options (Izarek, 2000).

To develop more appealing wearable electronics, conductive materials are being used to transform traditional textile and apparel products into 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.

One way IETs can be created is by using minute electrically conductive fibers. These fibers have historically been used in industrial applications to control static and provide electromagnetic interference shielding. They can be produced in filament or staple lengths and can be spun with traditional non-conductive fibers to create yarns that possess varying degrees of conductivity (Figure 9). The yarns can be used to develop wash and wear conductive fabrics that look and feel like a normal fabric (Electro Textiles, 1999). 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), or .001 to .080 millimeters. They are typically produced by a bundle-drawing process or by a shaving process during which the fibers are shaved off the edge of thin metal sheeting. Though highly conductive, metallic fibers are 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, 2001).

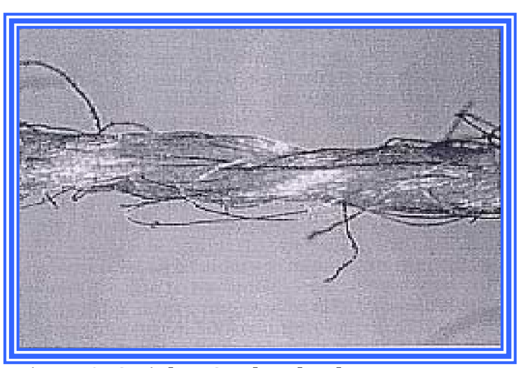

Figure 9: Stainless Steel and Polyester Yarn

Electrically conductive fibers can also be produced by coating fibers with metals, galvanic substances or metallic salts like copper sulfide and copper iodide. Metallic fiber coatings produce highly conductive fibers, however adhesion and corrosion resistance can present problems. Galvanic coatings provide relatively high conductivity, but can only be applied to conductive substrates such as graphite and carbon fibers. Due to manufacturing complexity and expense, galvanic coatings are usually not used for textiles. A variety of fibers can be coated with metallic salts using traditional textile machinery. These coatings can only achieve low conductivities that are further reduced during laundering. Altering coating procedures can improve these limitations (Lennox-Kerr, 1990).

Optical or glass fibers, about 120 microns in diameter, can also be used to produce IETs. Optical fibers are used in composites, telecommunications, local area networks (LAN's), cable TV, closed circuit TV, optical fiber sensors, and conductive textiles to carry signals in the form of pulses of light (Bell College, 1997). They are developed by drawing molten glass through bushings, creating a filament. Though optical fibers offer excellent strength and sunlight resistance, they are relatively stiff possessing poor flexibility, drapability and abrasion resistance (Owens Corning, 2001).

Optical and electrically conductive fibers were used to develop a "Smart Shirt" that monitors the wearer's heart rate, EKG, respiration, temperature, and other vital signs. The textile platform (Figure 10) collects data from various parts of the wearer's body and routes it to a small transceiver device attached to the shirt (Georgia Institute, 2000). Collected data is processed and transmitted via the Internet for biomedical monitoring and wearable computing applications (Sensatex Incorporated, 2001).

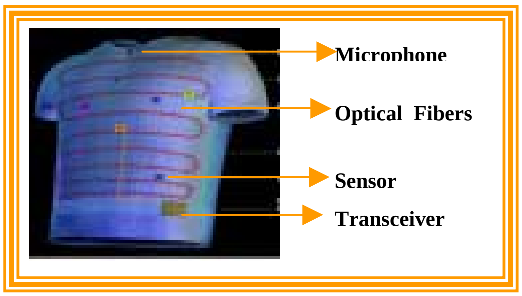

Figure 10: "Smart Shirt" Textile Platform (Georgia Institute, 2000)

Metallic yarns, created by wrapping a non-conductive yarn with a metallic copper, silver, or gold foil, can also be used to produce electrically conductive textiles (Post, Orth, Russo, & Gershenfeld, 2000). One example of this technology uses a metallic organza woven with a plain silk warp yarn and a silk yarn wrapped with copper in the weft direction (Figure 11). The silk provides tensile strength and tolerance for high temperatures. This allows the metallic organza fabric to be sewn or embroidered on industrial machinery (Orth & Post, 1997).

Figure 11: Micrograph of Metallic Silk Organza (Orth, 1997)

Conductive threads, typically finer and stronger that conductive yarns, can be machine sewn to develop IETs. Their conductivity can be

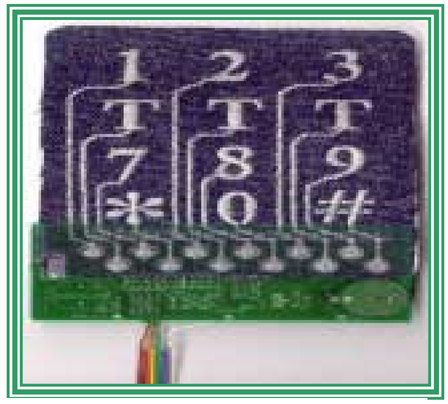

Figure 12: Embroidered Fabric Keypad ("Musical Jacket Project," 2001)

controlled through stitch placement. Embroidering with conductive threads offers advantages for IET development including the abilities to stitch multiple layers of fabric in one step and to precisely specify circuit layout with CAD (Post et al., 2000). The keyboard in Figure 12 was embroidered with a stainless steel and polyester composite thread. It is highly responsive to touch allowing the user to play notes, chords, and rhythms ("Musical Jacket Project," 2001).

Conductive coatings can transform substrates into electrically conductive materials without significantly altering the existing substrate properties. They can be applied to the surface of fibers, yarns or fabrics through processes including electroless plating, evaporative deposition, sputtering, coating with a conductive polymer, filling or loading fibers, and carbonizing. Electroless plating involves immersing a textile in an electroless plating solution where chemical reactions form the typically nickel or cooper coating on the textile. Electroless plating produces a uniform electrically conductive coating, but is expensive (Vaskelis, 1991). In evaporative deposition, a textile substrate is exposed to vaporized metal, typically aluminum, that condenses on the surface and forms a coating. This process can produce a wide range of coating thickness for varying levels of conductivity, and is being investigated for development of relatively thin, highly conductive evaporative coatings for highly conductive yet lightweight fabrics

(Smith, 1988). In the sputtering process, the coating material is ejected atom by atom onto the surface of a textile substrate, creating a thin coating. Sputtering can achieve a uniform coating with good adhesion, but is only about 10% of the speed of evaporative deposition, and is consequently quite costly (Siefert, 1993). Textile substrates can be coated with a conductive polymer such as polyaniline and polypyrole to achieve conductivity (Kahn, Kimbrell, Fowler, & Barry 1993). Presently, such polymers are used for conductive and anti-static coatings on yarns, fabrics and films. These polymer coatings are more conductive than metal and have excellent adhesion and non-corrosive properties, but they are difficult to process using conventional methods ("Electroactive Polymers," 1999). Filling or loading textile fibers with carbon or metallic salts such as copper sulfide also creates a conductive coating. Carbon-loaded fibers possess good conductivity and are easily processed in conventional textile systems, while metallic-salt loaded fibers have comparatively lower conductivity (Heisey & Wightman, 1993). Finally, carbonizing involves processing the textile in a carbonization furnace at 1000^{o}C to create an electrically conductive textile. This process has been used to create a garment that reacts to changes in temperature, controlling body temperature within 0.5^{o}C. (Lennox-Kerr, 2000).

Conductive ink technology offers another alternative for IET development. Adding metals such as carbon, copper, silver, nickel, and gold to traditional printing inks creates conductive inks that can be printed onto various substrates to create electrically active patterns. Conductive ink technology, originally developed for smart cards or printed circuit boards, has been used in various market applications including computers, communications, automotive, industrial electronics, instrumentation, government/military, consumer (e.g. home thermostats) (US Market, 1998). Use of conductive inks for flexible printed circuits has increased due to cost saving over traditional production techniques, improvement in durability, reliability and circuit speeds and reduction in circuit sizes (Cahill, 1998). A technology for using conductive inks to make interactive talking products such as T-shirts, sound books, packaging, and wallpaper has been patented. The inks withstand bending and laundering without losing conductivity (Colortronics, 2000). Conductive inks are currently applied with technologies such as gravure, flexographic, and rotary screen-printing that use rollers to print the inks onto substrates. These methods are both labor and capital intensive, and may create long production delays when designs are changed over (Miles, 1994). The benefits offered by digital printing technologies have prompted many conductive ink developers to experiment with digitally printing them onto textile substrates. Digital printing eliminates many of the intermediary steps associated with traditional printing methods offering greater design versatility and production flexibility. Additionally, digital files can be sent electronically to other locations for printing (Rehg, 1994). Digital printing of conductive inks presents several challenges including pre- and post- treatments, developing the appropriate ink viscosity, achieving the conductivity through constant agitation of the ink reservoir, delivery of appropriate ink quantities, and proper drying (Armbruster, Borgenstein & Emil, 2001).

ENABLING TECHNOLOGIES

The technologies previously discussed are used to create textiles that have the ability to conduct electricity. Additional components including input and output devices, sensors, and power supplies are necessary to create an IET. Input devices including keyboards and speech and handwriting recognition systems are some options being explored for IET data entry. The output technologies under investigation include Cathode Ray Tubes (CRT's), Liquid Crystal Displays (LCD's), mirror displays and flexible light emitting displays (Ducatel, 2000). Sensors are small electronic devices that can receive and respond to stimuli enabling electronic textile functions to be related to the user. They can either be attached to or integrated into a textile substrate (Farringdon, 2001). Power supply technologies, typically batteries, provide the electrical power for activating the components in an electronic textile. In recent years batteries have not only become smaller and more powerful, some varieties are mechanically flexible, water-resistant (washable), and lower cost (Hahn & Reichl, 1999). One type is fabricated by screen printing silver-oxide based paste on a substrate to yield battery only 120-microns (µm) thick. Solar energy and energy created by the human body are also being studied as sources of electrical power for IETs (Hahn & Reichl, 1999).

Molecule-sized computers, sensors, and electronic devices can be directly integrated into textiles using nanotechnology (McGuinness, 1997). Microelectromechanical Systems (MEMS), also known as micromachines, nanomachines, or transducers, are less than one square millimeter in size and usually consist of mechanical microstructures, microsensors, microactuators, and electronics integrated into a single chip. MEMS could potentially provide smart-sensors for IETs (Holme, 2000).

COMPONENT INTEGRATION

Regardless of the conductive materials used to develop an electronic textile, the electronic components and power supply must be integrated into the textile to create an IET. 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 surface of a textile. Soldering achieves good electrical contact, but the toxicity of soldered components makes them unsuitable for applications where they could come in contact with a user's body. Furthermore, fabric flexibility is often compromised, making soldering unfavorable for many apparel applications. Bonding involves using conductive adhesives to embed components into textile substrates. Non-toxic, highly conductive, highly durable, and moderately flexible conductive adhesives can potentially be used to bond rigid components with flexible textile substrates. Components can also be stapled into conductive stitched circuits to create electronic textile circuitry. When the substrate flexes or bends the conductive trace is free to move. However, such flexing 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 constraining the components to specific locations and allowing the conductive threads to be evenly balanced (Post et al., 2000).

WIRELESS TECHNOLOGIES

In order to simplify the connections between electronic devices, new wireless technologies may be used. Commonly used wireless devices, such as cellular phones and pagers, use radio frequency local area networks [RF LAN's], but the limited radio frequency spectrum is quickly being filled. Personal Area Networks (PAN's) provide an alternative. PAN's enable electronic devices to exchange digital information, power, and control signals within the users' personal space (Zimmerman, 1996). PANs work by using the natural electrical conductivity of the human body to pass incredibly small amounts of current through the body. These currents can transmit data at speeds equivalent to a 2400-baud modem, or approximately 400,000 bits per second. The current used is less then the body's natural currents, measuring one-billionth of an amp or one nanoamp. By comparison, the electrical field created when a comb is passed through hair is 1,000 times greater than the current used by PAN technology ("Personal Area Networks," 1996). Modular devices supporting shared functions can be connected with a PAN.

A new radio frequency standard enables electronic equipment to form a network and communicate automatically without wires, cables, or any direct action from a user ("How Bluetooth," 2001). This wireless technology has created some public concern because radio frequency (RF) fields broadcast in all directions and therefore are emitted into the body. To overcome this health concern, researchers are exploring options such as the Fabric Area Network (FAN) to restrict the range of the RF fields to the surface of the textile. FAN's use wireless RF communication links, but the communication fields are restricted to the surface of a textile eliminating emission into the body (Hum, 2001).

RELATED CHALLENGES

In order for IETs to succeed in the consumer market, they will need to possess easy care characteristics, and maintain their conductivity through repeated care cycles. Wearable IETs must not be damaged by constant motions and stress from body movements, static from fabrics, perspiration, and body heat. Rapidly changing technologies make upgradability another key issue. Today, radiation and electrocution are small threats to our health and safety, but use of IETs may increase these threats. IETs worn by children demand strong structures lacking small detachable parts. Environmental characteristics such as rain, humidity, extreme temperature fluctuations, and other inclement weather may create safety hazards.

IET products support a society where home, office, transportation, clothing and even our bodies will be seamlessly connected by wireless networks, raising personal privacy and security concerns (Thieme, 1999). The right to personal privacy and security are universal expectations. In a recent study, seventy-five percent of those interviewed felt personal privacy and security were very important social issues in today's society (Coleman, 1997). Advancing technology and the unrestricted exchange of electronic information justifies increasing concerns. As new technologies that involve large amounts of personal information become more predominant, users will no doubt be interested in protecting their personal privacy and security (Garfinkel, 2000). We may soon have a greater capacity to monitor individuals without their knowledge, develop more heinous weapon systems, or eliminate the need for human contact in many activities (Johnson, 1991).

CONCLUSION

The volume of available literature on each technology could suggest that product development efforts are advancing more rapidly for conductive thread, metallic fiber, and optical fiber technologies. Challenges noted in developing flexible electronic circuits from conductive coatings and inks could explain slower development in those technologies. Though not among the technologies dominating the literature, there were some indications that conductive polymer fibers and conductive polymer materials are also being studied for IET development. These materials offer advantages in that they can be developed according to specific requirements, and may overcome many of the limitations of metal-based solutions.

Health monitoring and feedback seem to be important foci of development efforts, perhaps due to the abundance of military funding supporting work in this area. However, entertainment applications may be an equally important application area because these IETs need not be as robust or powerful as those for health, safety, and military applications.

Because IETs will incorporate many kinds of electronic devices into their structures, some level of skill will be required to operate and use them. The ease of use is an important criteria for product development and some IET products may require a level of product knowledge for operation that could affect market success. The industry will need to educate consumers on product usage and possibly offer post-purchase product assistance to make these products appealing.

Upgrading and compatibility options, retail price points, and care and maintenance requirements are all important to the market appeal of IET products. Consumer appeal will rely heavily on the ability of IET products to be easily cared for and maintained, and these issues need to be addressed in product development. As IETs enter the market they are likely to be expensive at first and, as technology progresses and production processes are perfected, prices will decline. Updated and advanced product versions appear on the market so quickly that many consumers consider compatibility and upgradability in the purchase decision. IETs will need to be compatible with various types and brands of electronics, and will need to be upgradeable to achieve market success.

Though product development is still faced with many challenges, the future for IETs looks promising. Research and development efforts will enable product developers to overcome current challenges to advancing IET development. Research to support IET development is being conducted in universities (DARPA, 2001; Holme, 2000; Brunel University, 2001; Fiber Materials, 2001), businesses ("Smart Clothes," 2002; Orth, Post, Russo & Gershenfeld, 2001), and government supported agencies (El-Sherif, 2000). Growing consumer interest in mobile, convenient electronic devices will fuel the demand for IET products.

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