Smart textiles: Challenges and opportunities

Kunigunde Cherenack and Liesbeth van Pieterson
HTC 34, Philips Research, Eindhoven 5656AE, Netherlands

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Smart textiles research represents a new model for generating creative and novel solutions for integrating electronics into unusual environments and will result in new discoveries that push the boundaries of science forward. A key driver for smart textiles research is the fact that both textile and electronics fabrication processes are capable of functionalizing large-area surfaces at very high speeds. In this article we review the history of smart textiles development, introducing the main trends and technological challenges faced in this field. Then, we identify key challenges that are the focus of ongoing research. We then proceed to discuss fundamentals of smart textiles: textile fabrication methods and textile interconnect lines, textile sensor, and output device components and integration of commercial components into textile architectures. Next we discuss representative smart textile systems and finally provide our outlook over the field and a prediction for the future. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4742728]

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I. INTRODUCTION TO SMART TEXTILES

Imagine a world in which electronics are freed from their rigid, confining encapsulation, are intimately integrated into the fiber of our daily lives, and distributed throughout our ambient environment. This is impossible to do using conventional electronic circuits, which are limited by the maximum substrate size available for processing, substrate rigidity, and fragility. Textiles represent an attractive medium for electronic integration as they have been a fundamental and transformational component of our every-day lives for hundreds of years. Smart textiles represent the drive to integrate new sensing functionalities into hitherto inaccessible surfaces and are a new step in the continuing evolution of textiles.

A key driver for this research is the fact that textile fabrication processes are capable of automatically creating large-area surfaces at very high speeds. For example, typical industrial weaving machines as in Fig. 1(a) are capable of fabricating more than $10 \times 10^6$ square meters of textile per year. Roll to roll printing methods used to fabricate flexible electronics—as shown in Fig. 1(b)—are capable of printing 100–150 m/min. By combining complementary textile and electronic fabrication technologies, we can achieve completely new functionalities. Smart textile applications range from medical monitoring of physiological signals including heart-rate, guided training and rehabilitation of athletes, assistance to emergency first-responders, and commercial applications where electronics including ipod controls, displays, and keyboards are integrated into every-day clothing.

This paper is structured as follows:

(1) What are smart textiles and why do we need them?
(2) How did smart textiles develop?
(3) What are the challenges facing smart textiles development related to technology development but also including more general issues such as user acceptance and market creation.
(4) How are textiles fabricated—specifically focusing on the integration of “smart” components?
(5) Smart textiles from the bottom up (components → circuits → systems → applications).
(6) Outlook for smart textiles.

A. Definition

Smart textiles—also known as intelligent textiles, electro or e-textiles fall into the category of intelligent
materials that sense and respond to environmental stimuli. Smart textiles are sometimes defined to include simpler functional textiles (also referred to as “passive” smart textiles), but this is technically incorrect. In contrast to smart textiles, functional textiles are materials to which a specific function is added by means of material, composition, construction, and/or finishing (e.g., by applying additives or coatings). Functional textiles can include traditional textile products while smart textiles have intrinsic properties that are not normally associated with traditional textiles.

Sometimes smart textiles are also classified according to the design paradigm chosen to integrate electronic functions into the textile architecture. At the one extreme, one finds smart textiles in which the textile simply acts as a substrate for attachment of sensors, output devices, and printed circuit boards (garment and fabric level integration). Such textiles are similar to wearable computers (i.e., electronic systems including sensors and computational components that is built with standard off-the-shelf components that can be strapped to the body), and there is very little integration of devices into the textile. Subsequent development in this field has seen a drive to integrate the desired functionalities “disappearingly” inside the textile architecture. This implies creating smart textiles in which the electronic/optical sensors and output devices are introduced at the fiber level (fiber level integration). Separating these two extremes are various “hybrid” smart textile efforts that combine various functional fibers (with differing degrees of complexity) with attached integrated circuit components and off-the-shelf sensors. Here the textile may often form a part of the textile devices, e.g., forming electrodes in foam capacitors.

These categories will be discussed in more detail in the following section. It should be noted that there is no clear consensus in the field on various smart textile categories; those chosen in this paper represent the most common divisions used in literature.

B. History of smart textile development

People have been investigating medical applications of electricity in clothing such as corsets and belts as early as the 1850s, but the scientific community only became interested in wearable electronic applications (specifically wearable computing) fairly recently. The first wearable computer was developed in 1955 by Edward Thorpe and Claude Shannon. Wearable computers are distinguished by the fact that there is no integration between the electronic systems and the clothing of the wearer. Smart textiles, in which electronic functions are integrated more closely within the textile, evolved from wearable computing in the early 1990s. In this section we will discuss smart textiles categories based on the level of integration of “smart” components with the textile structure. It should be stated that the classification of smart textiles into these categories does not mean that these examples were developed in this order on a timeline.

The first category of smart textiles stayed close to the vision of wearable computing—to design a fabric computing platform. An important goal was to design easily reconfigurable interconnect technologies inside textiles using fibers and yarns with a single functionality (e.g., electrical or optical conductivity). These interconnects were combined with standard off-the-shelf components to achieve the designed system performance. For example, the Georgia Tech Wearable Motherboard (GTWM) in Fig. 2(a) was an early smart textile which was developed from 1996 onwards. This was followed by a second category of smart textiles that exploited various new textile fabrication methods such as embroidery to achieve hybrid smart textiles. In these smart textiles, the fabric generally formed an essential part of the textile device or circuit (i.e., it was more than simply a carrier for textile yarns and circuits). Smart textile design was still approached from a traditional electronic system design level, but more and more functions were achieved within the textile itself. A new emphasis was also placed on merging traditional textile fabrication methods (e.g., weaving or embroidery) with traditional electronic circuit fabrication methods such as printed circuit board design.

Early examples in this category include the quilted and embroidered keypads and the firefly dress (Fig. 2(b)) developed by the MIT Media Lab in 1997 and 1998. The first efforts to create more complicated fiber-level electronics (category 3) started appearing in the early 2000s. This field of research is also sometimes referred to as “fibertronics.” The philosophy behind these research efforts was to create devices and logic circuits “below the device level,” i.e., to achieve higher order electronic functions at the fiber level and implement more sophisticated smart textiles from individual fibers. These research efforts generally focus more on technology development, and systems are built from the fiber upwards (in contrast to the more traditional top-down methods used in previous categories). For example, fiber-level smart textiles...
were introduced into woven textile inverter circuits using flexible stripes with simple thin film transistor (TFT) circuits. Fig. 2 shows examples of different smart textile systems from categories 1-3. They are described in more detail in Sec. IV C.

C. Challenges facing smart textile development

In this section we will discuss some of these challenges facing smart textile designers. To understand the challenges facing researchers who want to develop smart textiles, consider some of the requirements textile circuits need to fulfill.

Circuits need to be extremely rugged as they will be exposed to mechanically demanding environments during fabrication and use of smart textile in daily life (for example, wearing the textiles in clothing). The comfort and washability of the smart textile should not be affected by the presence of the circuits, i.e., it should be rugged enough to survive being used in daily life. Circuits require power supplies that are light-weight and have a high capacity to ensure autonomous operation for several hours (or more depending on the targeted end-user application). Commercial smart textiles need to comply with requirements from both the textile and electronics field. These specifications can often be very stringent and may be contradictory. Here are some of the critical challenges facing smart textile development:

• Mechanical environment: In comparison to flexible display applications that are intended to be rolled around cylinders with diameters of a few cm, smart textile fibers may be exposed to bending radii much smaller than 1 mm (Refs. 22 and 23) and large tensile strains. The degree of tensile strain that e-fibers are exposed to depends on the textile architecture as well as the position on the body at which the textile circuit is located. Textile fibers within shirts and jackets experience the highest stress levels near the upper back. Simulations of textiles have shown that the strain in a shirt can be up to 20% at the shoulder blades.

• Washability: Early commercial smart textiles such as the ICD+ textile coat developed by Phillips and Levi required the wearer to remove all electronic components (including wiring) prior to washing. More recent smart textile demonstrators (such as the Eleksen textile keyboard shown in Fig. 2(f)) rely on waterproof packaging to protect sensitive electronics from damage during washing.

• Power supplies: Most smart textiles are powered by traditional rechargeable batteries, but these are large and bulky and impossible to integrate fully with the textile architecture. There is a strong drive to develop alternative conformal and lightweight power generation and storage devices. Examples include flexible or elastic batteries, supercapacitors, and solar cells and energy harvesting devices such as thermo and piezo generators. Unfortunately, none of these devices approach traditional batteries in terms of capacity and maximum current value. Urgent research is needed to improve the performance of such textile-compatible power supplies for future smart textiles applications.

• Product development and commercialization: The imbalanced contributions from electronic and clothing industries result in incompletely integrated applications. The
electronics field still dominates product development, and consequently most research attempts focus on solving technical problems such as integrating microchip and computer systems into clothing or overcoming washability issues. Application developments centered on the clothing industry are still uncommon and do not take into consideration or integrate the special product development and processing techniques of this sector.37 Due to this imbalanced contribution, it is difficult to achieve full integration of electronics and fashion and increases the difficulty that smart textiles face to differentiate themselves both from the conventional clothing and existing electronic devices. Successful design and development requires a multidisciplinary team of professionals including textile scientists, polymer chemists, physicists, bioengineers, software engineers, consumer specialists, and fashion designers. Finding a common meeting and sorting out the jargon associated with each field can be challenging. Furthermore, there is a lack of a coherent vision for smart textile development between different research laboratories and universities. Product development can also be a costly and often fruitless endeavor. For example, in 2004 alone Eleksen created 109 textile keyboard prototypes and landed only three deals.21 Smart textiles can therefore also become too expensive for the average consumer with limited elasticity and strength. This results in knots and breaks in the wires. In addition, the conventional way of cutting the fabric requires application of heat. This cutting method cannot be used for textiles with conducting metal wires due to the high thermal conductivity of the metal. In processes where the conductive wire is applied after the fabric has been finished (e.g., soutage, embroidery, and lamination), these challenges do not exist as the wires are not subjected to high fabrication forces but are merely “laid” down on the fabric and fixated. Mechanical demands of the yarns will in these cases fully depend on the intended use.

II. TEXTILE FABRICATION METHODS

Smart textiles can be fabricated using (1) textile fibers that have additional functions (e.g., electrical or optical conductivity), (2) attachment of commercial off-the-shelf components such as integrated circuits or light emitting diodes (LEDs) to the textile after fabrication, and (3) hybrid approaches combining both commercial and textile functionalities. In this section we discuss how “smart” functions are integrated into textiles. Since interconnect lines based on conductive yarns are critical for connecting various devices into circuits, we first discuss conductive textile yarns and how their structure impacts the textile fabrication process. Next, we discuss the two most common large-area textile fabrication methods: weaving and knitting. Finally, we discuss various methods to functionalize textiles following fabrication (i.e., textile finishing methods). These include printing, stitching/embroidery, and gluing.

A. Conductive textile yarns

Yarns can be integrated into textiles architectures in various ways. Possible methods include weaving, knitting, embroidery, lamination, and stitching. All these methods have been investigated for smart textile applications incorporating various functionalized yarns (e.g., electrically or optically conducting threads). Conductive wires are of particular interest for textile integration since they form textile interconnect lines for electrical circuits that are built subsequently using standard electrical building blocks (e.g., sensors or LEDs). Examples include the work published by Cotter,39 Locher,40 or Martin,41 who integrated an X-Y grid of copper wires into woven textiles to form interconnect lines. It is often necessary to make a trade-off between resistance and processability when choosing the conductive yarn for a smart textile process.

For smart fabrics, the targeted application plays a considerable role in the required conductivity of the conductive yarn. Some textile applications (e.g., lighting applications) may require considerable current and low ohmic (high conductivity) wires are preferred. Certain sensing or heating applications on the other hand work better when using a yarn with a lower conductivity. Conductive yarns are fabricated using either metallic wires or metalized textile yarns. Yarns can consist of a single fiber (monofilament) or can consist of various thinner fibers that are twisted together to form a composite fiber (multifilament). The conductivity of these yarns ranges from about 0.5 Ω/m to several kΩ/m, depending on the amount of metal used.42

The construction of a yarn or wire has large impact of processability and suitability of the yarn for use in a specific textile process. For instance, metal wires tend to break easily during weaving and knitting, whereas multifilament yarns can give rise to shorts when adjacent wires are too close. From a processability point of view, low resistance metal wires have limited elasticity and strength. This results in knots and breaks in the wires. In addition, the conventional way of cutting the fabric requires application of heat. This cutting method cannot be used for textiles with conducting metal wires due to the high thermal conductivity of the metal. In processes where the conductive wire is applied after the fabric has been finished (e.g., soutage, embroidery, and lamination), these challenges do not exist as the wires are not subjected to high fabrication forces but are merely “laid” down on the fabric and fixated. Mechanical demands of the yarns will in these cases fully depend on the intended use.

More complex conductive yarns with improved properties have also been constructed, e.g., by wrapping, strandng, and twisting metal fibers around a textile core or metallization of polymer yarns. Fig. 3 shows examples of conductive wires. The properties of the conductive wire can be further improved by adding an insulation layer. This makes the wire more robust and resistant when exposed to more challenging environments (e.g., washing). Insulation can consist of a polymer coating or by insulating yarns such as polyester that are wrapped around the conductive core. However, component attachment to insulated yarns and realization of electrical interconnections within a textile is more difficult when using insulated yarns compared to non-insulated yarns. This is because it is necessary to locally remove the insulation for the required electrical connection to be made.

B. Weaving and knitting

For smart textiles applications weaving and knitting have received widespread interest since they can generate large-area textile surfaces.
Weaving is a process that interlaces two perpendicular sets of yarns, called the weft and warp. During weaving, some of the warp yarns are moved up and the rest are moved down using a “harness,” and the opening created between the up- and down-warp yarns is called the shed. The raising/lowering sequence of warp yarns gives rise to many possible weave structures. In comparison, the weft yarns are rolled around several spools (known as bobbins) and inserted into the textile architecture perpendicular to the warp yarns by a device called a shuttle. Fig. 4(a) shows a close-up of the central weaving region in a weaving machine, including the warp and weft directions. Fig. 4(b) shows a standard band weaving machine. The dotted circle indicates the weaving region. Warp yarns are spanned parallel to each other on a loom and “pulled” through the weaving machine at a constant rate.

In addition to standard two-dimensional (2D) textiles, it is also possible to weave more complicated composite three-dimensional (3D) textiles. In 3D-fabric structures, the thickness (Z-axis) is considerable relative to planar (X-axis and Y-axis) dimensions. Fibers or yarns are intertwined, interlaced, or intermeshed in the X (longitudinal), Y (cross), and Z (vertical) directions. For 3D-structures, there may be an endless number of possibilities for yarn spacing in a 3-D space. These types of 3D fabrics are woven on special looms with multiple warp and/or weft layers. Fig. 4(c) shows an example of a woven 3D fabric. However, it is possible to fabricate more complex 3D fabrics using standard looms. For example, the Georgia Tech Wearable Motherboard14 used a novel 3D weaving process to produce a fully formed garment. Optical fibers were spirally woven into the garment for uncut garment manufacturing. This reduced the need to connect wires after fabric production, pattern cutting and sewing.

Knitting is a method in which yarns are arranged into consecutive loops (stitches) on a knitting needle. An assembly of loops is called a row or “wale.” To create the next row, a new section of the yarn is pulled through existing row loops (usually in order) using a second knitting needle. By adjusting the sequence of stitches or repeating individual steps per loop, it is possible to adjust the knitted pattern and thereby create more complex patterns in the fabric. It is possible to distinguish between warp and weft knitting methods depending on the general direction of the row yarn in the fabric as shown in Fig. 5(a). Knitting machines are also capable of weaving complex 2D and 3D structures (including seamless tubes43 as shown in Fig. 5(b).

General properties of both knitted and woven textiles are low weight, portability, and skin comfort (e.g., breathability) when compared to standard electrical and optical systems. Woven fabrics are durable and have a more stable shape than knitted fabrics. This allows for more accurate placement of individual yarns and more dense integration of electronic and optical functionalities. Furthermore, woven textiles are strong and deformation resistant. Knitted fabrics are characterized by high elasticity and elongation, good conformability in mechanically active environments (e.g., textiles used in clothing), as well as good air permeability, thermal retention, and humidity transport properties.

C. Smart textiles: Finishing touches

After the textile has been fabricated, the fabric’s appearance can be modified, and additional “smart” capabilities can be added (e.g., by using embroidery, printing, gluing, or lamination). The following are some examples.

A popular approach used to complete textile circuits is to attach electronic devices to interconnect lines inside the textile. Here, the key step is deciding how to establish electrical contacts between the fabric structure and the devices. Contacts can be made by micro-contacting devices with conductive adhesives and soldering or by mechanical methods (e.g., crimping). Fig. 6(a) shows a surface mount device light emitting diode (SMD LED) which was glued to a woven fabric by researchers from TU Braunschweig University, Germany.
SMD LED was picked up by a vacuum gripper and placed onto the fabric. A cannula and a precision dosing system were used to apply the conductive adhesive. Another method of integrating electronic devices into woven fabrics is shown in Fig. 6(b). Here, a narrow fabric weaving loom was modified so that electronic components could be placed into woven pockets inside a textile. Alternatively, the textile surface can be modified locally or globally. For example, galvanic electro-plating can be used to make partially conductive textile structures for sensing applications. Printing techniques can be used to coat textiles selectively with conductive polymer materials such as poly(3,4-ethylenedioxythiophene) (PEDOT) or chemically sensitive polymer materials (e.g., for use as temperature sensors or bio-sensors). Fig. 6(c) shows an example of a printed PEDOT line on a textile.

III. SMART TEXTILES SENSORS INPUT AND OUTPUT DEVICES

Smart textile systems can be considered at a number of levels. At the top system level we consider aspects such as overall performance, power management, manufacturability, cost, textile handle, and fault tolerance. One level down, smart textile sub-systems include memory storage and transmission, sensor processing, and control of input and output modalities by top-level circuit and software design. Finally, at the component level, we consider the various sensors and input and output devices available for integration into textiles. For example, a simple smart textile system could consist of sensors connected to a data processor and memory storage unit (powered using an on-board power supply) using textile-based conductive yarns. The changes in the sensor signals caused by environmental changes can be processed in the textile (i.e., by attached processors) or transmitted to an external computer for further analysis. Finally, the system could contain various output devices that respond to signals sent to them by the data processor or received via the wireless link (e.g., textile displays or status lights). Fig. 7 shows a schematic of a simple smart textile system using the ETH backmanager as an example to identify various hierarchical components.

In some special cases, smart textiles can contain components that combine sensing and user feedback. These simple systems do not have a computational element and instead respond to environmental changes instantly by changes in the textile appearance. For example, textiles can be coated with inks or resins that change color at certain temperatures and thereby provide colorimetric feedback on changes in the ambient temperature. In a “traditional” smart textile system this color change would be detected and used as input for a software program. This program could then use this information to provide feedback on the change in the environment experienced by the textile. However, the visible change in color can also provide quick feedback to an observer. The disadvantage of such systems is that the type of feedback that can be provided is limited, not very nuanced, transient, and does not result in a very intelligent textile system. This type of system can also not be used to provide other types of feedback since the sensor is not coupled to a computational element. The SWAY system is a commercial implementation that consists of a multi-color fabric with 4 basic colors. These colors are designed to reversibly change color between 40°C and 80°C. Shape memory materials (SMMs) are another category. These can be combined with textiles to create fabrics that react to a change in temperature by returning to a pre-programmed shape. Shape memory materials also can be used to fabricate simple smart textiles. These materials change their shape in response to an electrical signal and have recently been used by Corpo Nove to create a shirt which shortens its sleeves when the temperature rises and does not require ironing.

This section will present an overview of device-level functionalities (sensors and output devices) that have been
used to generate textile systems, with an emphasis on new functionalities that are unique to textile systems. In Sec. IV, we will discuss higher-level textile systems and applications.

### A. Sensors

A sensor is a device that measures a physical quantity (light intensity, pressure, temperature, etc.) and converts it into a signal which can be stored and analyzed. In the context of smart textiles, sensors integrated into smart clothing are often tailored to measure physiological parameters in humans (e.g., heart rate, body posture...) or to determine changes in the ambient environment such as pressure distribution changes when a person walks across a carpet or someone sits down on a sensorized chair. Many smart textiles operate using traditional, silicon-based sensors, but new sensing capabilities have been achieved within textiles using novel functionalized fibers, specialized fabrics, and coatings, and new textile integration methods such as sewing or knitting. Fig. 8 shows a variety of the sensors described below.

Pressure sensors: Pressure sensors have been incorporated into mattresses for medical monitoring and have also found various commercial applications, for example, to develop textile keyboards and touch-pads used in sportswear, interior fabrics, and street fashion. Various capacitive pressure sensors have been developed using a spacer material sandwiched between two conducting textile electrodes. The electrodes are fabricated by embroidering or coating textiles with conductive yarns or materials. Other pressure-sensitive spacer alternatives are electro-active polymers.

Heart rate sensors: Textile sensors exist for detecting electrocardiogram (ECG) and respiratory activity, for example, as reported in the MagIC system. In the NuMeTrex line of fitness gear from Textronics, conducting transmission lines and electrodes are knitted into the fabric that are able to stretch and move with the user. This helps the electrodes to maintain contact with the skin and sense the heart’s electrical pulse. A small transmitter is snapped into a pocket in the front of the garment where it instantaneously radios the heart rate to a watch worn by the user or an exercise machine for digital readout. By replacing the commonly used hard plastic chest straps that rub and chafe against the skin, NuMetrex offers a more comfortable alternative by combining heartbeat sensing with form-fitting shirts and sports bras.

Temperature sensors: Temperature changes can be extrapolated from resistance changes in conductive coatings printed onto textiles or metal fibers woven or knitted inside the textile. Alternatively, flexible thin-film temperature sensors on plastic stripes can be woven into textiles.

Strain sensors: Strains sensors in clothing can be used to detect body posture and joint movements. This information is useful to train athletes, for rehabilitation of patients, or to support emergency first responders (e.g., firefighters) during their work. Textile strain sensors have been integrated into the fabric of mattresses and used as contactless sensor to extract the heart rate, the respiration rate, and the movements (activity) of a subject during sleep. Strain sensors have been fabricated by incorporating piezoresistive or optical fibers into clothing to detect breathing rate or body positions by measuring fiber deformations. Piezoresistive films have also been printed directly onto textile surfaces to form sensors.

Biological sensors: Chemical and humidity sensors have been used in wearable applications to detect the presence and composition of biological fluids. These sensors are created using sensing materials such as carbon nanotubes embedded in polyelectrolytes that are either screen printed onto textiles or coated onto individual textile fibers. The EU project, BIOTEX, developed a range of textile sensors to detect pH, sweat rate, and electrolyte concentration in sweat. The pH sensors are used to monitor people suffering from obesity and diabetes. Various smart textiles incorporate knitted or woven metal fibers and electrodes that allow measurement of physiological parameters such as electromyography (EMG) and ECG measurements to support cardiac health.

Optical sensors: Plastic optical fibers (POFs) have been integrated into textiles and used in clothing for oximetry monitoring or to develop pressure sensors that operate by measuring changes in light intensity when the fiber is deformed. In the case of chemical sensors, optical fibers are generally coated with custom-designed cladding layer that reacts with the specified reagent and changes the light transmission within the fiber. Fiber optic sensors have been integrated into soldier uniform to detect chemical and biological warfare threats, above-normal field temperatures, and other hazards on the battlefield. In the GTWM (Ref. 14), optical fibers are used to detect damage to the fabric via broken light paths. This concept was commercialized by Sensatex to develop the “LifeShirt” that uses woven optical fibers in the fabric to measure the temperature and heart rate of the wearer.

Gas sensors: Recent methods of fabricating textiles with gas sensing capabilities involve coating the textile with a gas sensitive layer, weaving gas-sensitive nano-fibers into a fabric, and integrating commercial gas sensors into standard items of clothing. ETHZ is currently leading a Swiss federal funded project, TWIGS, to develop simple textile gas sensors for air-conditioning systems.

Input devices: Textile input devices are used by the user to provide data to other devices within the textile system. Input devices to interface to textile systems include keyboards.

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**Fig. 7. Schematic of a smart textile hierarchy modeled on the ETH “backmanager” reported in Ref. 4.**

**Fig. 8.** shows a variety of the sensors described below.
and may include a wide variety of sensors that stimulate a response within the system. All-textile “capacitive” keyboards such as the Eleksen keyboard in Fig. 2(f) have been fabricated using a variety of textile fabrication methods such as sewing and quilting and have been commercialized.

B. Output devices

Output devices are used to communicate changes in the textile system with the outside world. Displays are the most common type of textile output device. In many cases, smart textiles are interfaced with traditional display devices such as watches faces, colored LEDs, and optical fibers. Fig. 8(d) shows a textile display consisting of LEDs that are driven by a woven grid of conductive yarns forming a passive matrix. These types of textile lighting surfaces have been used in applications such as architectural and industrial art projects, automotive lighting, and even integrated into clothing. Color changing textiles can act as simple textile displays. One example is the Mosaic Textile display that has individual pixels which are controlled using conductive yarn resistors that act as localized heating modules. More exotic “vibro-active” displays provide a localized tactile stimulus to the skin by generating vibrations. This can be done by integrating smaller electro-motors into the textile. This concept has been investigated at the prototype-level for future commercial applications such as “emotion” generating jackets for gaming or therapy applications by Philips Research. Another approach carried out within the EU PlaceIt project is to bond organic light-emitting diodes (OLEDs) to textiles, as shown in Fig. 8(e).

In smart textiles, output devices can also be transistors. Various efforts to integrate transistors into textile at the fiber level are underway. Generally, however, smart textile circuits including transistor circuits consist of off-the-shelf or custom built integrated circuits that are attached to interconnect lines inside the textile and used to control the flow of information within the textile. “Artificial muscles” is another example of textile output devices. These are fabricated using materials such as electro-active polymers (EAPs) that can be interfaced with electrical circuits to control the shape of the actual textile surface.

IV. TEXTILE SYSTEMS

In the previous section we discussed how various sensing and actuation functions can be integrated into textiles. In this

![Image](image-url)
section we move up higher in the textile hierarchy (refer Fig. 7) and discuss examples of textile sub-systems and systems. Finally, we conclude the section by discussing various targeted application areas. While a full discussion of the various ways to build smart textile systems is beyond the scope of this paper we will use this section to provide a feeling of some of the new application possibilities enabled by smart textiles.

A. The role of conventional electronics

A special mention needs to be made of the role of conventional electronics in building smart textile systems. It is possible to implement a large variety of sensing and actuation functions at the device level using partial or fully textile-based methods. Interconnections between sensors and other system components can be created during textile fabrication by integrating conductive yarns into the textile, or following textile fabrication by printing or stitching. However, more complicated electronic circuits and subsystems such as microcontrollers, memory units for data storage, and wireless links need to be implemented using conventional electronics. Therefore, conventional electronics will always play an essential role in building complete textile-based applications and systems for portable and large-area 3D deformable electronics. In fact, specialized integrated circuits have been designed to be washable and easy to integrate into textiles by sewing. Fig. 8(f) shows an example of a LilyPad Arduino chip integrated into an embroidered textile surface.

For smart textiles systems, a promising area of research involves the development of portable power supplies. This is a growing research area, and recently many novel examples of more textile energy harvesting and storage devices have been presented. These include photovoltaic textile surfaces and fibers to harvest sun energy, mechanical energy harvesting devices built into shoes and a variety of light-weight flexible and elastic batteries that can be attached to textiles. Furthermore, various parts of wireless links are being replaced by textile components. Examples include textile antennas and transponders. Therefore, it is likely that more textile-compatible power supplies (i.e., power supplies that can be integrated into the structure easily during textile fabrication) will be developed in the near future.

B. Textile system categories

As discussed in the previous sections, textiles systems can also be distinguished by the method of integrating functions into the textile (categories 1–3). An early example of category 1 smart textiles, the GTWM shown in Fig. 2(a) is a smart textile which was developed from 1996 onwards. The GTWM contained several woven or knitted optical fiber sensors and interconnect lines (supplemented by commercial body-worn sensors) that were used to monitor soldier vital signs during combat situations. Other examples in this category include the beam-forming woven smart textiles from Virginia Tech and ETH Zürich’s SMASH shirt. An early commercial example of this type of smart textile is the Industrial Clothing Design Plus ICD coat developed in collaboration by Philips and Levi that incorporated a microphone, earphones, a remote control, a cell-phone, and an MP3 player. Recently more sophisticated smart textile computing platforms have emerged that create symbioses between large-area, conformable electronics, and textiles. The Klight dress is another prominent example. It was developed in 2009 within the European Union (EU) STELLA project and integrates an elastic circuit board into a dress using lamination methods. Fig. 2(e) shows a section of the elastic substrate embedded in a textile carrier.

For category 2, various purely textile capacitors consisting of insulating foam sheets placed between embroidered electrodes have been developed to measure muscle activity. An example of such a textile capacitor array is shown in Fig. 2(d). The EU project BIOTEX developed various biosensors to monitor parameters in human sweat such as pH level, electrolyte concentration, and sweat rate. To guide sweat along channels towards the main sensing region, textile “sweat pumps” were developed using combinations of hydrophobic and hydrophilic textile fibers. International Fashion Machines commercialized a “plush touch” sensing technology to develop textile dimmer light switches with woven, sewn and embroidered electronic yarns and materials within a fabric base. An example is shown in Fig. 2(c). Here, stroking the fabric will dynamically change the room lighting conditions. This technology has also been exploited by Maggie Orth in 2008 to create interactive art-works such as “Petal Pusher.” Other commercial examples include the 100% textile Eleksen keyboard shown in Fig. 2(f).

Efforts to develop fiber-level electronics have often focused on integration of transistors. For example, textiles with wire electro-chemical sensing transistors and “fiber-computing” efforts to embed transistors into weavable polymer fibers create TFTs from individual fibers, or shadow mask organic transistors onto fibers using a shadow masking process have received much interest in recent years. ETH Zürich has taken the “stripe” approach one step further by weaving textiles with stripes supporting simple thin film circuits including thin film transistors, sensors, and attached packaged miniaturized integrated circuits to create woven arrays and bus structures within textile architectures. Fig. 2(g) shows an example of woven textile incorporating a thin film temperature sensor stripe using this approach. Another interesting effort in this area involves fabricating “solar-powered” wires to incorporate photovoltaics into textiles. Commercially, Lumalive by Philips Research represents an effort to weave fibers with LEDs into textiles.

The examples listed in this section represent only a fraction of ongoing smart textiles efforts. Smart textiles research is ongoing across the globe—both at an academic and industrial level. In the US, governmental organization initiatives, particularly in the military field, are driven by NASA in the USA and the Ministry of Defense in the UK. In Europe, the European Union funds several international smart textile-focused projects including PASTA and Place-It. Many high-tech global companies conduct their own research or carry out collaborative work with academic institutes.
C. Textile applications

The development of ambient computing as represented by smart textiles has expanded the concept of computing from desktop based applications to a growing “landscape” of smart devices. Smart textile systems span the range of serious applications (e.g., smart uniforms for emergency workers exposed routinely to hazardous working conditions) to commercial applications such as lighting in fashion and even toys. Application areas include healthcare, fashion, sports and wellness, safety and security, automotive and transport construction, security, geo-textiles, lighting, industrial applications, defence, agro-textiles, home and interior textiles, packaging, architecture, energy, telecommunications, and displays. Here are some representative examples with a focus on mature (i.e., commercial) applications.

Protective clothing: The PROeTEX suit developed at the EU level includes an inner garment to monitor the wearer’s physiological status (temperature, earth, and respiration rate, blood O2 saturation, and dehydration) while the outer vest and boot contain embedded sensors to monitor the aggressive environmental conditions (e.g., temperature, position…) and flexible batteries.

Healthcare: Smart textiles have been used to develop textiles that monitor the health of infants, provide healing by light therapy, and detect physiological parameters such as heart rate and respiration for long-term patient health monitoring. Fig. 9(a) shows the Philips Baby blanket which was developed to provide infants with light therapy. Another example is the LifeShirt by Vivometrics. The LifeShirt System collects, analyses, and reports on the subject’s daily routine, providing pharmaceutical and academic researchers with a continuous “movie” of the subject’s health in real-life situations (work, school, exercise, sleep, etc). The field of sports related healthcare has also been very active and many global companies such as Adidas, O’Neill, Nike, and Polar have already introduced smart textile products into the market. The Numetrex sports bra represents a mature commercial application in which conducting fibers are knitted directly into the fabric of a sports bra to monitor heart rate. The textile sensor system is capable of capturing comprehensive physiologic data on the body and is designed to assist consumers in managing wellness concerns such as weight loss, physical health and energy level. The NuMetrex Heart Sensing Sports Bra was named 2006 Sports Product of the Year by the Sporting Goods Manufacturers Association.

Interactive clothing: Smart textiles in the fashion industry mainly use lighting effects to provide a new visual component to garments. Lighting effects can be interactive such as the firefly dress based on random events. The lighting effects in the Klight dress (Fig. 2(e)) can even be programmed. Luminescent effects can also be used in home-deco products such as curtains and furniture. Fig. 9(b) shows an example of textile cube with integrated lighting intended for interior decoration. Other functionalities such as textile keypads have also been commercialized. For example, the KENPO jacket and the Ipods jeans by Levis contain integrated MP3 players controlled by textile buttons. Another benefit realized by smart textiles such as the Smart Bra is increased wearer comfort. This bra, developed at the University of Wollongong, tightens and loosens its straps or stiffens and relaxes its cups to restrict breast motion, preventing breast pain and sag. Other companies that have released interactive clothing include Eleksen, Fibertronic, and O’Neill.

Automotive smart textiles: Automotive smart textiles are a promising application area for smart textiles since cars already contain a large variety of textile surfaces (e.g., in the seat cover, carpets, roof, and door liners, tires, hoses, safety belts, air bags, etc). So far, automotive smart textiles include textiles providing heating in car seats, textile dashboard lighting being developed by the EU project PASTA and external textile “skins” replacing standard car exteriors as used in BMW’s concept car “Gina.” Fig. 9(c) shows an example of textile switches integrated into a car steering wheel.

V. OUTLOOK

Smart textiles research has been ongoing for up to 20 years and yet few commercial products are on the market. This is despite the fact that the market for smart textiles was expected to grow by more than $300 billion dollars in 2012. Significant progress has been made in developing smart textiles recently and this research area has widespread support from both the research and commercial sectors. For example, in Europe the European Union is funding smart
textiles research with up to more than €100 million, spread over more than 30 R&D projects. Some of the information on market trends in this section is taken from the SYSTEX Vision paper. SYSTEX is a project funded by the EU that collects technological and non-technological information on smart textiles projects along the whole textile value chain. The goal is to identify the hurdles facing interdisciplinary knowledge transfer and to initiate actions to overcome them. At present, consumer goods account for a significant portion of commercially available products, but growth in military, biomedical, vehicle safety, and wellbeing applications is expected to have a major impact on the market. Various drivers support the further development of smart textile. These include societal factors (e.g., the need to improve quality of life of an aging population and increased consumer demands for more and varied applications), business factors (e.g., the trend towards increased diversification of businesses, higher competition, and the need to develop new markets), and sector driven factors (e.g., rejuvenation of established industries and the emergence of specialized markets).

In the near term, the focus of commercial smart textiles will be on sensing, heating, and lighting applications. Sensing textiles will increasingly be used in sports and health monitoring applications. As mentioned in previous sections, the physiological monitoring of parameters such as heart rate (ECG) is already available. Other sensing applications, such as bio-chemical monitoring, may be added in the near future for protective and military wear. Heating fabrics will find increasing use in cars, driven by the introduction of electric vehicles. Lighting fabrics will find more versatile use in fashion, promotion and event wear, and light treatment. In the future, combinations of these segments, e.g., sensing and lighting, may result in unique applications.

Various issues need to be addressed to ensure that smart textiles will successfully transition from research laboratories to industrial applications. Barriers that have been identified include lack of standardization, lack of regulations for new products, lack of coordination and collaboration among the value chain partners, and financial constraints among businesses to shoulder development costs. Ethical and social issues including safety need to be addressed. Furthermore, high production and selling costs and the need for increased user acceptance also are important factors.

At present, commercial smart textiles still utilize commercial sensors and integrated circuits to achieve their purpose. In the future, more and more uniquely textile sensors demonstrated by academic research labs need to be transitioned to commercial products. This will result in a blurring of electronic and textile properties to the point where electronics become fully integrated into the textile architecture. As smart textile technologies become more mature, production processes will need to become more automated and large scale. These products require combinations of electronics and textile manufacturing capabilities and at this scale the full product can only be made by industries with access to suitable technologies.

From a technology perspective, a key issue is that clothing fabrication is still a labor-intensive activity and remains concentrated in countries where labor costs are low. Furthermore, the integration of electronics into textiles is far from automated, and large-area, low-cost smart textiles will only be achieved if large-area fabrication methods from the electronic and textile industries are combined more seamlessly. Electronics and textile technologies have very different characteristics and requirements; electronic processes are expensive and precise, often requiring accuracy down to sub-mm dimensions. In comparison, textile processes are typically used to produce large textile surfaces at low cost, but with less accurate requirements in terms of minimum dimension and yarn placement. It is therefore likely that integrators will play a role, to help combine and translate the requirements from both industries into a complementary process. Smart fabrics research will follow the above trends, with a focus on integration, reliability, and product usability. The latter is often forgotten in research projects but is extremely important. The end-user should be involved in all phases of the research, from design to validation, to guarantee the usefulness of the proposition. Sustainability will become an increasingly important research topic, leveraging the efforts and knowledge existing in the textile industry.

Critically, more fundamental research is needed to enable the next wave of smart fabrics products. We are still far from fully utilizing the capabilities available from the textiles industry within a smart textile environment. In particular, 3D textiles promise new and hitherto unexplored opportunities. Power and comfort, especially cooling, are important areas where current smart textiles capabilities are insufficient. High energy density thin film or fabric batteries and efficient solar cells need to be developed that can be used to power portable textile applications in a more comfortable way. Cooling materials such as phase-change materials should be developed further to cool the body in hot environments, and to cool the electronics worn close to the body.

From the discussion above it becomes clear that there are many gaps that need to be filled before smart textiles become a mainstream technology. However, this fact also represents a unique opportunity to develop a new skill-set and expand the knowledge available to engineers and scientists. Smart textiles are unique in that they require the combined experience from very different disciplines. Their development will result in the formation of interdisciplinary teams of people from materials science, physics, chemistry, process engineering, and people from the textile and electronics manufacturing communities. Therefore, this type of research will lead to increased dialogue between groups of people that generally would not interact, and this in itself may result in the discovery of new opportunities based on combining their knowledge. Smart textiles research represents a new model for generating creative and novel solutions for integrating electronics into unusual environments and will certainly result in new discoveries that push the boundaries of science forward.


See http://www.ifmachines.com/ for “Amazing soft switches.”


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