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An Overview of Recent Developments in the Field of Wearable Smart Textiles

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Abstract

Wearable smart textiles are fabrics that provide the wearer with enhanced functionality by displaying a set of favourable properties or by sensing, reacting, and/or adapting to stimuli in the environments to which they are exposed. Electronics are often integrated into these fabrics and the integration provides enhanced functionality to the wearer's clothing. Functionality enhancements can be engineered for specific applications, thus permitting the development of smart textiles for many specific requirements such as enhancing the safety of the wearer, sensing and reporting of the biometrics of the wearer, heating or cooling of the body based on external requirements or contributing to enhanced performance in sports and related activities. This paper focuses on smart textiles that are worn by the user.

Keywords: Smart textiles; Wearable electronics; Smart technology

Introduction

Smart textiles are fabrics that contain technologies which sense and react to the conditions of the environment they are exposed to, thus allowing the wearer to experience increased functionality. The conditions or stimuli can be of mechanical, thermal, chemical, or of combination nature [1]. Smart textiles can be classified as passive, active, or ultra (or very) smart textiles [2]. Passive smart textiles do not respond to the environment; in other words, the design of the textile does not allow it to instantly alter the measured condition one way or the other. For example, antistatic fabrics developed by companies such as Sophitex Ltd. are designed in such a way that their electrostatic discharge (ESD) properties are not influenced by the environment to which they are exposed [3]. Active smart textiles, which are newer relative to passive smart textiles, are those that adapt to changes in the environment and contain built in actuators and sensors. In recent years, smart textiles have become capable of sensing, reacting, and adapting to the environment or stimuli. These advanced fabrics are known as ultra-smart textiles. For example, these ultra-smart materials can sense the temperature outside and consequently warm up or cool down, based on the measured temperature [4]. Many smart textiles that have electronics incorporated in them are called e-textiles [1]. Smart textiles can be designed to have applications in health monitoring, sportswear, temperature control, and increased comfort, in addition to other functionalities in many other end-uses.

Applications/Examples

There are numerous applications of wearable smart textiles currently available or in development. Many products have been designed to collect data on the specific body conditions of the user, mainly for health management or sports applications. Sensors are commonly employed in these fabrics to collect data such as heart rate, sweat rate, breathing rate, muscle tension, posture status, location, and temperature. Some smart textiles just report the data, while others adapt and change their properties to provide the wearer with more appropriate or acceptable functional performance.

One of the most common applications of smart textiles is in the area of health and fitness management. DuPont Advanced Material's (DuPont) Intexar™ smart clothing technology is capable of sensing and reporting heart rate, breathing rate, form awareness, and muscle tension [5]. Companies that have biometric-sensing technologies such

as Intexar™ market their technologies to many sports wears and athletic apparel manufactures. For example, OMsignal, a Canadian smart textiles manufacturer, uses IntexarTM technology in their line of fitness bras. These bras capture and report the biometric information of the wearer to a smartphone app [6].

Health management is important in all stages of life. Owlet has created a smart sock particularly for babies [7] (Figure 1). The baby-care company has released two models of smart sock. The sock works with Owlet's smartphone app which allows caretakers to have a constant and accurate reading of the baby's heart rate and oxygen level

Figure 1: The owlet smart sock (Version 2), which only needs to be worn on one of the baby's feet.

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with the help of a pulse oximetry device positioned within the sock. The data is also transmitted to a base station, where a green light remains lit as long as the measured parameters remain within the desired range.

In addition to the medical and healthcare applications, electrical devices have applications in designing smart clothing for use in entertainment and comfort. Prototypes of fabrics with implanted MP3 players, LED and OLED textile displays, GPS technology, and the ability to accept or dismiss phone calls have been demonstrated in recent years [8-10]. It has been shown that it is possible to place microphones and speakers into clothing, allowing the possibility of voice recognition technology or gesture-activated technologies. This allows for commands to be given to the clothing in order to perform tasks.

Jacquard™ by Google is a technology that interacts with the smartphone and the technology has been implemented in the Levi's® Commuter™ Trucker Jacket (Figure 2) [10]. This jacket allows the user to manage calls, texts, GPS, and music without the need to actually pick up the smartphone. The jacket has LED lights and vibration options to communicate alerts, and it even has the capability to read out messages. A removable snap tag is placed on the sleeve of the jacket which is capable of recognizing gestures to control the technology.

Safety smart textiles are a big concern, especially in laboratory and industrial settings. One way designers of smart clothing are able to increase workplace safety is by making the fabric material antistatic. These smart antistatic materials can be utilized to make garments with extended life and durability. Sophitex Ltd. is a company which focuses on creating woven and knitted electronic discharge (ESD) fabrics. Their line of antistatic garments includes coats, jackets, button-down shirts, polo shirts, t-shirts, sweatshirts, cardigans, pants, and coveralls. Sophitex Ltd. produces fabrics for everyday wear as well as industrial wear. They claim that Jarden Applied Materials is an advanced materials company which has a specialized line of passive smart textiles called the Restistat® fiber collection. These fibers are engineered to be conductive and antistatic and are suitable for clean rooms, military applications, electronics manufacturing, medical and other applications. They are designed to maintain their conductivity and antistatic properties during normal wear in an industrial workplace. Restistat® fibers are marketed for their "superior static decay and surface resistivity characteristics" [11].

Companies have found many different ways to utilize smart textile functionality. TexTrace has a woven RFID (radio frequency identification) brand label technology which is sewn onto apparel products (Figure 3) [12]. This brand label contains an RFID chip that is resistant to home washing and dry cleaning. The TexTrace woven RFID brand label can be used to prove authenticity, assist stock management, and discourage theft through its built-in EAS (electronic article surveillance) technology. The label can act to identify the exact number of the product that has been purchased, speeding up checkout and return procedures [12].

Utilizing fibers that contract and expand with heat, it has become possible to create shape-changing smart textiles. Using yarn made of these temperature-sensitive fibers, companies like Grado Zero Espace (GZE) have created shape-changing smart clothes. GZE's Oricalco fabric uses Nitinol, a lightweight alloy of nickel and titanium (55% and 45%, respectively), which has shape memory and super-elastic properties. Nitinol, when exposed to different levels of heat, contracts or expands to pre-programmed shapes [13]. Using the orthogonally-weaved Oricalco fabric, GZE created the Shape Memory Shirt (Figure

Figure 2: Jacquard™ by Google, a fashionable smart jacket capable of managing calls, texts, location, and music.

Figure 3: The TexTrace brand label, which adds functionality without being more bulky or unattractive than regular brand labels.

Figure 4: The shape memory shirt (left) created using oricalco fabric and the k-cap created using shape memory polymers (right), both designed by grado zero espace.

4). This shirt has sleeves which change length instantly based on the room temperature.

In addition to Oricalco, GZE has also designed the K-Cap [14]. The

K-Cap is a balaclava which is being developed to aid in the exploration of Mt. Everest. It can keep the wearer warmer than alternatives at high altitudes. The K-Cap uses shape memory polymers as opposed to shape memory alloys such as Nitinol (Figure 5) [15]. Like Nitinol, the shape changing polymers also change their shape and size with changes in temperature. The purpose of the K-Cap is to provide maximum insulation to the wearer without making the balaclava too heavy or uncomfortable. The K-Cap is comprised of one layer of a memory membrane fabric and two layers of bi-elastic fabric. These bi-elastic fabric layers make the balaclava malleable and allow the wearer to move freely.

One less common application of smart textiles in personal health management is aromatherapy [2]. Wearable smart textiles can be designed so that they release a pleasant smell that increases the well-being of the wearer. Dr. Jenny Tillotson's eScent® technology emits various fragrances and essential oils for purposes including alleviating allergies and improving the wearer's mental state. Dr. Tillotson designed a dress called second skin (Figure 6) [16]. The technology in the second skin dress releases fragrances which claim to treat depression and improve the overall well-being of the wearer.

Temperature control is a common consideration in smart textile production. Companies such as DuPont and Wendu have products for this purpose [17,18]. DuPont™ Intexar™ Heat is a multi-layer
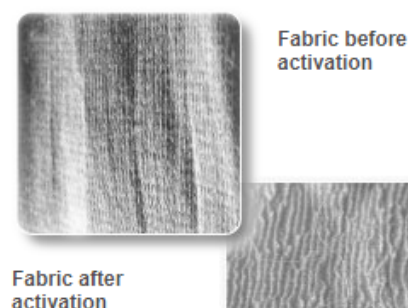
advanced heating technology that provides the wearer with a more comfortable temperature in cold environments (Figure 7). The technology is effectively a heater built into a fabric by utilizing a resistor layer of carbon in addition to a conductor layer of silver. Fabric type varies based on the manufacturer's specifications [17]. Wendu takes things a step further in temperature control, by allowing the wearer to choose a temperature in the range of 68-104°F. Both cooling and heating are provided by a battery-powered Bluetooth device called the Wendu Station. The Wendu Station is attached magnetically and can be controlled using a thermostat within a smartphone app [18].

Temperature regulation is important in sportswear. Sportswear companies such as Under Armour have been doing research to get the most out of smart materials in their lines of sports clothing [19]. Under Armour has many different technologies they are marketing to athletes for specific performance measures such as temperature control, sweat wicking (helping to evaporate sweat more easily), staying dry, increased comfort, and increased performance. The cooling technologies utilized by Under Armour create a cooling effect using several different methods: pulling heat away from the body (Coolswitch, Iso-Chill), using maximum breathability fabrics (Heatgear®, Heatgear®Armour, Heatgear® Armourvent™), reflecting heat and infrared rays (Coldblack®), or moisture wicking (MicroThread). Many of the cooling clothes have some form of moisture control, acknowledging that removing sweat from the body quickly is a good way to regulate temperature. Under Armor has heat-retaining clothing as well; technologies are used to increase retention of body heat using increased insulation (Amour® Fleece, Coldgear®, Coldgear® Infrared, PrimaLoft®), circulated body heat using a negative grid pattern (UA Base™), and changing the amount of heat retained based on sensed temperatures (Coldgear® Reactive). The adaptive nature of the Coldgear® Reactive makes it of particular interest. This technology is marketed as being "your own personal thermostat" [20]. The fabric cools down when the wearer is running and it heats up as the wearer slows down or comes to a stop so as to keep a comfortable temperature. It senses both the outside temperature and body temperature and acts as a heat regulator [19].

In addition to the smart garments mentioned above, Under Armour also created a smart shoe. Their line of smart shoes, HOVR™, uses Under Armour's Record Sensor™ technology to connect to the smartphone app called MapMyRun (Figure 8) [21,22]. The app tracks you through the course of a run and reports details such as pace, cadence, stride length, and distance travelled.

Another company interested in developing smart running shoes

Figure 5: Grado zero espace's thermo-responsive shape memory polymer, which changes structure depending on the temperature it is exposed.
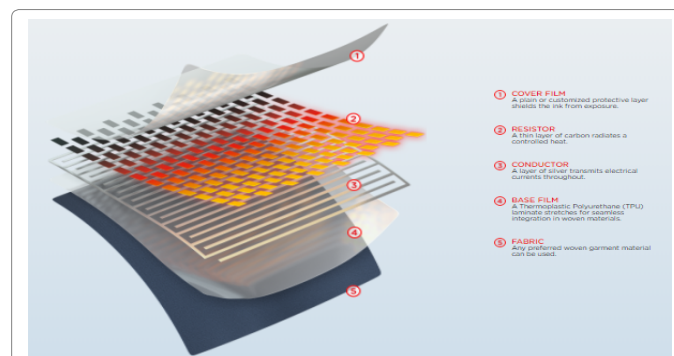

Figure 6: Dr. Tillotson's second skin dress. It emits a "scent bubble," which the wearer constantly smells.

Figure 7: DuPont™ Intexar™ Heat, a multi-layer technology capable of maintaining smart textiles at a specific temperature.

is Sensoria [23]. Sensoria produce smart fitness clothing and it has smart t-shirts, sports bras, and socks available (Figure 9). They are currently taking pre-orders for their smart shoe (Figure 10). The t-shirts and sports bras have a dock for a heart rate monitor, and they are compatible with third party monitors in addition to Sensoria's own model. The shirt/sports bra and heart rate monitor connect to a smartphone app in order to report a constant heart rate reading to the wearer. The smart socks have built in textile sensors on the bottom of the foot and are made from fabric designed to be comfortable during walking and running. Conductive fibers are utilized to connect the sensors to a removable anklet. The socks send information including speed and distance travelled directly to the wearer's smartphone while the anklet is attached. Sensoria smart shoes rely on the Sensoria® Core, a small and light device which attaches to the back of the shoe. It is waterproof and contains a rechargeable battery, 9-axis motion sensor, and Bluetooth capability. The shoe itself contains textile-based pressure sensors and can detect and report information including distance, pace, speed, ascent/descent, altitude, steps taken, distance travelled, and calories exhausted.

Figure 8: An example of a HOVR™ smart shoe: the UA HOVR phantom connected women's running shoe.

Figure 9: From left to right: sensoria men are smart t-shirt, sports bra, and socks. The heart rate monitors are placed near the center of the wearer's torso, and the anklet can be seen magnetically attached to the sock.

Figure 10: The sensoria smart running shoe, which is currently un-released for consumer purchase.

Hexoskin Wearable Body Metrics launched their own line of smart clothing in 2012 [24]. Hexoskin is capable of monitoring ECG and heartbeat data, stress, fatigue, heart rate recovery, breathing rate, and breathing volume, in addition to other health parameters. The technology can also be used to measure workout intensity and running statistics including peak acceleration, steps taken, and cadence. Hexoskin smart garments also have integrated sleep trackers. Collected data can be viewed in real-time by downloading the Hexoskin smartphone app. The clothing is durable enough to be washed, while still maintaining properties such as being breathable, lightweight, anti-odour, chlorine resistant, and UV resistant.

Current Research, Projects, and Recent Advancements

Medical applications of wearable smart textiles include the monitoring of patients' vitals and temperature. Humidity and temperature sensors can be placed within smart clothing to better analyze the condition of the patient. The humidity sensor can recognize excess sweating or abnormal wetness [25]. DELTA, ARPA-E (US Department of Energy) is a program funded in part to reducing domestic greenhouse gas emissions. Researchers at Cornell University are working within the DELTA program to develop clothes which can change thermal properties to account for uncomfortable temperatures without the need for heating and cooling the entire environment. The goal is to produce clothes which allow for higher individual comfort levels and decrease the need for large amounts of heating and air conditioning [4]. Researchers at the University of California, Berkeley (UC Berkeley) are working to make the integration of the individual-focused thermal control systems easier to implement by developing wireless charging systems [26].

Smart textiles can sense important health information about their wearers using sensors that are knitted or woven into clothing. Fabric electrodes used to monitor Electrocardiogram (ECG) have been successfully implanted into wearable shirts. These electrodes allow for the monitoring of medical patients over extended periods of time, as the fabric electrodes are reporting the data while the electrode-infused clothing is being worn. Piezoresistive fabric sensors that have been knitted into shirts have been used to collect respiratory signals (Figure 11). These sensors also allow for the detection of movement and can be used to monitor the posture and movement of the wearer [27].

Wearable smart textiles have the potential to redefine medical rehabilitation techniques. The sensors within the smart garments can track the mobility and biometrics of the patient, and this data can be used to judge how effective the chosen rehabilitation method is for the patient. These sensors need to be minimally obstructive to the patient, and it is important to implement them into the clothing of the patient as seamlessly as possible. The placement of the sensors is important because the data needs to be accurate and continuously collected [28]. The effectiveness of prostheses can be analysed by using sensors to record the amount and pattern of movement in rehabilitation patients. For example, the movement of a prosthetic arm can be analysed directly or in comparison to the movement in the patient's other arm [28].

BIOTEX was an EU-funded project which focused on biosensing textiles for use in health management which started on September 1, 2005 and ended on May 31, 2008 [29]. The project aimed to increase the number of physiological parameters that could be measured using smart garments. Because sweat provides an ample amount of physiological information, without being invasive, the project worked to create an efficient sweat-analysing textile system. The BIOTEX project successfully created a textile system that can be easily incorporated into

everyday clothing (Figure 12). The BIOTEX system involves a complex system of textile sensors including pH, sodium, conductivity, and sweat rate sensors integrated into a waistband positioned on the lower back [29]. ECG, respiration, and pulse oximetry sensors are implemented using a chest band. The textile-based pH sensor, able to detect pH values in the range of 4 to 8, uses a pH sensitive dye and a pair of optical LEDs for optical detection (Figure 13). Three textile electrodes and silicone cushions are incorporated into the chest band and are used to collect ECG data. The chest band also has a piezoresistive sensor which responds to ribcage movement to measure respiration rate. These sensors are based on knowledge gained from two other EU-funded projects, MyHeart and WEALTHY [30,31].

The WEALTHY project started on September 1, 2002 and ended on February 28, 2005 and it focused on the design and development of a wearable smart textile system of the same name (Figure 14) [32]. The textile system included "strain fabric sensors based on piezoresistive yarns" and "fabric electrodes realized with metal yarns" to record the physiological data of the wearer [31]. These sensors could record the patient's breathing patterns, activity patterns, and temperature, in addition to the patient's ECG and EMG data. Additionally, after

Figure 11: Piezoresistive sensors implanted in a shirt for monitoring respiratory conditions.

Figure 12: The BIOTEX system with sweat-analyzing sensors in a waistband (right) and a chest band (left) which collects ECG, respiration, and pulse oximetry information.

recording the data, the system was able to transmit the data to a computer or mobile phone.

MyHeart was a project which started on December 31, 2003 and ended on September 9, 2007 [30]. The purpose of the MyHeart project was to design and develop wearable smart textiles with integrated health sensors. Smart clothing was designed to monitor patients' health status and report measured information to health professionals [30]. It is important in the design of medical smart textiles to ensure the garment is still comfortable and affordable for the patient. Within the MyHeart project, four concepts were explored: Activity Coach, Take Care, Neural Rehabilitation, and Heart Failure Management [33]. The Activity Coach concept used the "Body Signal Sensor (BSS)" textile-based sensor to collect all necessary health data from the wearer. A device, the "Personal Mobile Coach," receives the collected data from the sensor via Bluetooth and provides feedback to the wearer and a service center. Similar smart clothing was used in the Take Care concept. The Neural Rehabilitation concept focused on using wearable smart textiles to provide aid in rehabilitation to patients who have recently experienced a cerebrovascular event. Sensors in an upper-body smart garment are used to record patient movement during exercise. In the Heart Failure management concept, a smart vest with health sensors was used to collect data relating to the health status of the heart.

Researchers at the Hong Kong Polytechnic University in Hong Kong, China, considered wearable smart textiles for phototherapy. For this purpose, they used side-emitting polymer optical fiber (POF). Using LED light sources and POF, they developed "a flexible luminous fabric device for wearable three-dimensionally fitted low-level light therapy" (Figure 15) [34]. The wearable device showed promising results, and it was determined that the POF fabrics caused no harm when it was in direct contact with the wearer's skin.

Piezoelectric materials are materials which are physically deformed when they are exposed to an electric field and produce energy when subjected to mechanical strain [35]. One potential use of piezoelectrics in smart wearables is the idea that they can be used to generate energy from normal human motions. It has been shown that energy can be captured using a polyvinylidene difluoride (PVDF) piezoelectric energy harvester that was implanted in the sole of a shoe and prototypes were able to generate enough energy that they could power low-energy wearable sensors (Figure 16) [36]. If enough energy is produced by an energy harvester, the need for physical batteries to supply power to the wearable sensors can be diminished or eliminated.

Another prospective way to eliminate the need for a battery is the integration of a thermogenerator. A prototype created by the smart textile company Infineon has shown that it is possible to generate electrical power from human body heat. The thermogenerator is stored in a smart garment and it generates energy using the temperature differential between the wearer's body surface and the surrounding fabric [8]. The Infineon prototype used a silicon-based thermogenerator chip to generate and supply electric power up to several microwatts/cm^2. It was shown that this generator has the potential to power some medical sensors and thus it can reduce the cost of batteries needed to power smart clothing technologies.

Textile cabling can be used to better implement electronics in smart clothing (Figure 17). Companies such as Ohmatex have shown that these cables can be integrated into fabrics while still maintaining the original properties of the clothing, such as softness or color [37]. Ohmatex has also developed a connector solution specifically for smart clothing. Textile cabling can be useful in connecting devices
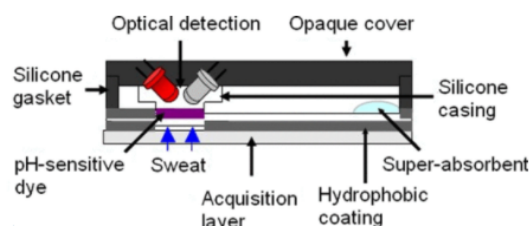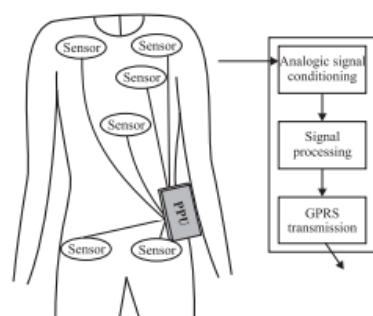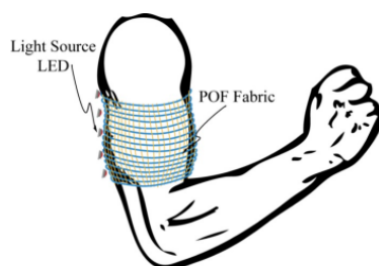
Figure 13: Configuration of the textile-based pH sensor used in the BIOTEX project.

Figure 14: The wealthy system, showing sensor placement and data transmission process.

Figure 15: A schematic of the fabric device consisting of POF fabric with LED light sources.

Figure 16: Two different piezoelectric-operating energy harvester prototypes created during research conducted at Tsinghua University.

across wearables. A problem with clothing which contain electrical components and wiring continues to be the washing factor. Research still needs to be done to determine the most efficient way to protect the electrical devices without causing a detrimental increase in the difficulty of washing the clothing [38].

Ping is a concept garment designed by Jennifer Darmour which allows the wearer to connect to and communicate to Facebook through a garment [39]. The prototype garment, a sleeveless hoodie, senses the wearer's motions and translates them into messages to be sent online. Different everyday motions such as putting the hood on are used to send programmable messages. There is a built-in notification system where the shoulder alerts the wearer of a message through soft vibrations. The concept claims to allow for the wearer to create an entire personalized language through the motions detectable by the garment. The problem the fashion industry often faces with electronic textiles is the appearance of the circuitry connecting the electrical components. Ping attempted to solve this issue by creating a pattern of circuitry which can be found on the left and right panels of the garment (Figure 18).

Philips Research has developed the smart textile technology, Lumalive which allows manufacturers to create self-illuminating smart clothing [40]. This technology could be incorporated into clothing to insure the visibility of the wearer; applications include illuminated sportswear or the clothing of first responders. There is a large amount of customizability that comes with incorporating Lumalive technology into clothing. In the fashion industry, designers can produce clothing which changes colors or patterns instantly. Companies can use this technology to produce clothing with moving images including logos or advertisements.

One important aspect to consider with smart clothing is that different technologies can be combined/improved to fit the individual need of companies. Lumalive technology, for example, has been combined with proximity sensors and either a local or global


Figure 17: Oham[tex] has developed textile cabling that does not affect the feel or properties of textiles.
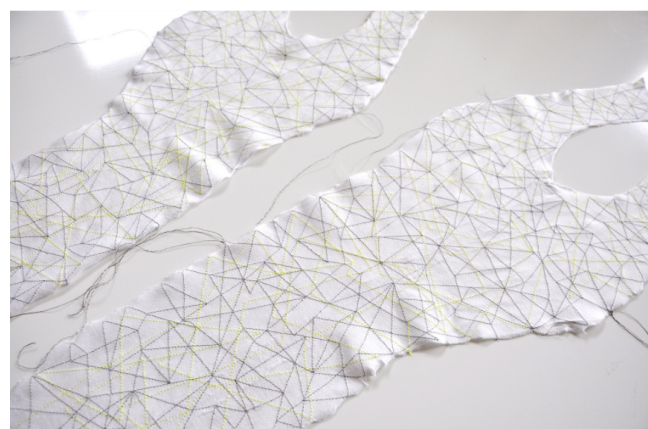
Figure 18: The side paneling for the prototype ping garment by electric foxy which has a pattern formed from the garment's electrical circuitry.

positioning systems (LPS or GPS) to create an entertaining game. Researchers from Queen's University in Canada created a modified game of tag called TagURIt [41]. The players wore interactive t-shirts with Lumalive displays that show through the fabric on the front of the shirt (Figure 19). Proximity sensors are placed on the front and back of the shirts. One participant, deemed the chaser, must touch one of the proximity sensors of a "player," or non-chaser participant, who holds a token. The team has one chaser and two players. This token can be transferred between players when the chaser gets close to the token-holding player. This three-person proof of concept could be expanded to accommodate a larger number of people and it serves as an example of the widespread applications possible when combining technologies in wearable smart textiles [2].

PLACE-It was a project focused on creating stretchable and adaptable smart textiles for human and automotive applications (Figure 20) [42,43]. The wearable smart textile part of the project worked to design a "cyber skin" for use in numerous applications [43]. The cyber skin could adapt to the movement of the wearer without causing a decrease in the functionality of any integrated electronics. The project also considered LED and OLED displays to create illumination in wearable textiles [42]. In addition to the safety factor of having illuminated smart clothing, light has also been used to increase overall wellness. Philips Lighting, Ohmatex, and ten other partners participated in the project [37]. PLACE-It designed wearable smart textiles applicable for blue light therapy, OLED technology, biomedical technology, and automotive lighting [44,45].
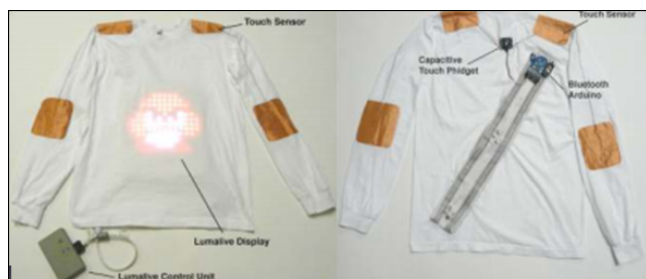
LED lights on garments have appeal for fashion, entertainment, sports, and safety applications. Clothing with incorporated LED displays has many different applications, ranging from smartphone-linked notifications to glow-in-the-dark clothing [10]. The fashion and sports industries are expected to continue to explore different ways in which electronics can be implemented into clothing. Displays can be stitched into the arms of a garment and used to relay information including biometric data or programmable designs [2,41-45]. The entertainment industry uses LED costumes to attract and retain the attention of the audience. The costumes mainly consist of clothing that can change color with the beat in musical performances, clothing that change color to draw attention to certain performers, and clothing that create mesmerizing effects through the combination of light and colors [2].

Light is very important in smart clothing. In addition to illumination, it is possible to create clothing that charges electrical devices. Photovoltaic textiles that absorb light energy carry the potential to charge electrical devices [46]. Research to develop flexible solar cells for integration into smart clothing has been pursued at the University of Stuttgart (Stuttgart, Germany) [47]. Researchers acknowledge that one problem with using solar cells to power electronics lies in the need for sufficient exposure to ambient light. However, it is also believed that solar cells can provide sufficient power to most devices as their energy requirements are not too high. Charging of mobile devices through wearable clothing is believed to be one of the most convenient ways of charging these devices. However, wear comfort is an important consideration when choosing clothing, making it necessary for the finished product to be both convenient and comfortable. This means that the integrated solar cells must be highly flexible and lightweight as to not cause discomfort. Maier Sports, in conjunction with the University of Stuttgart and others, produced a prototype jacket using integrated photovoltaic (Figure 21) [48]. The jacket was designed to power an mp3 player and has a maximum output of 2.5 W. It is capable of generating enough power for 40 hours of music in three hours, assuming sufficient exposure to the sun [47]. It is important to consider durability when considering solar power in clothing. For clothing to be feasible, it must be sufficiently resistant to wear and must permit repeated cleaning. There is still much research that needs to be done to produce a wearable smart textile with incorporated solar cells to find the correct balance between comfort and durability.

Figure 19: The TagURIt t-shirt, including a Lumalive display and proximity sensors on the front (left) and a bluetooth arduino computing framework and proximity sensors on the back (right).

Figure 20: An example of a stretchable electronic system from the PLACE-It project.

Figure 21: An example of a jacket with integrated solar cells. This model was designed to power an mp3 player.

BauBax has also considered the possibility of charging electronic devices through smart clothing [49]. Instead of solar power, BauBax proposed a two-pocket system held within a jacket. The wearer would need to purchase a power bank, and it would need to be placed in a concealed pocket within the garment. A fabric circuit would transport the power from the battery pack through the jacket and to the phone, which would be held in an easily accessible pocket. The phone would be charged wirelessly, thus eliminating the need for visible cords or wires. However, the product was never realized as the idea was postponed in August 2016 due to lack of public support.

Humavox a company which focuses on making charging personal devices simpler, has proposed that their ETERNA platform for wireless charging could be used in smart clothing [50-52]. The ETERNA platform is an ambitious wireless charging platform which consists of the Thunderlink™ power receiver, NEST™ power transmitter, and Charging Optimizer (Figure 22) [53]. Its small size allows for the possibility of it being incorporated directly into smart clothing to charge the electrical components of the smart system. The ETERNA platform is essentially waterproof as it does not require a USB port. Humavox provides their technology to companies looking to integrate wireless charging into their smart clothing.

MicroLED technology has been considered as the illumination technology for wearable smart textiles. MicroLEDs have the potential to serve in a more energy-efficient way to create flexible fabric displays as compared to LEDs or OLEDs [46]. Companies which are invested in MicroLED technology include Apple (LuxVue), Facebook (Oculus), Samsung, and Sony [54].

Corning, a company known for its research in glass science, ceramics science, and optical physics developed the Fibrance® Light Diffusing Fiber (Figure 23) [55,56]. This thin glass optical fiber can be implanted into clothing to add light. Fibrance® Light Diffusing Fiber eliminates the bulkiness that comes with incorporating more traditional illumination devices. This technology utilizes a silica core to spread light throughout the fiber to maintain an even, bright color. The fiber is flexible and durable enough to be used in smart clothing applications.

The EU-funded project PROeTEX was active from February 1, 2006 to January 3, 2010 [32] and it focused on designing wearable smart textiles to aid in the protection of first responders [57]. The goal was to create a garment which could monitor the vital signs, environment, and location of first responders and communicate this information to their headquarters. Both inner and outer garments were designed to enact these functions (Figure 24). The inner garments integrate health monitoring sensors to detect information such as heart rate, respiration rate, sweat composition, and temperature. Boots were also designed to have built-in gas sensors. The outer garments, which are connected to the inner garments via a wired link, incorporated accelerometers, thermosensors, a GPS device, the data processing unit, a battery, and an LED that shows if the wearer is in danger. Two textile antennae are used to send data back to the headquarters.

Seebo® a company which mainly focuses on Internet of Things (IoT) products and development, proposed a new way of using smart technology in work wear (Figure 25) [58]. The idea of an automatic alarm being held within the garment improves safety greatly, and it works well in tandem with the LED indicator light. Sensors held within the jumpsuit could be configured based on the individual needs of the industry. For example, lab workers will probably need more chemical sensors present in the jumpsuit than maintenance workers.

Seamless integration of circuits and electronics into wearable textiles has shown to be useful in safety applications. Bulletproof vests have been found to greatly increase the safety of the wearer. It has been shown that fabric circuit boards (FCBs) can be integrated into bulletproof vests to create a "smart bulletproof vest" (Figures 26 and 27). Strain and deformation sensors were placed between layers of energy absorbing materials so that the vest can sense and report the strain and deformation experiences throughout a ballistic impact. The smart bulletproof vest is thus able to determine when it has been shot, as there will be a spike in strain upon impact [59].

The FCBs within the vest were able to flex upon impact and were not destroyed due to the large amount of strain incurred when shot. There is potential here that the FCBs could be used to send for help whenever the wearer is shot while also keeping track of how many times the wearer has been shot [60].
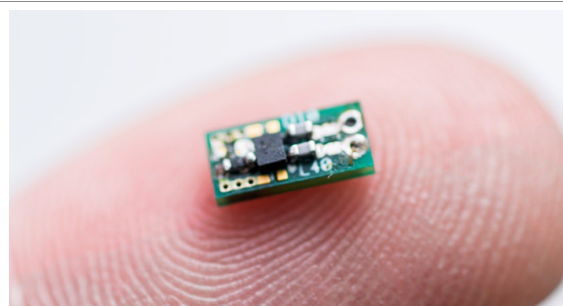
Figure 22: The Thunderlink™ is an extremely small power receiver which is integrated into the device to be charged.
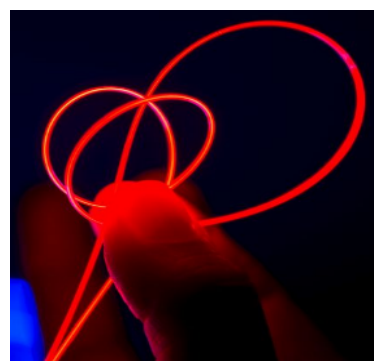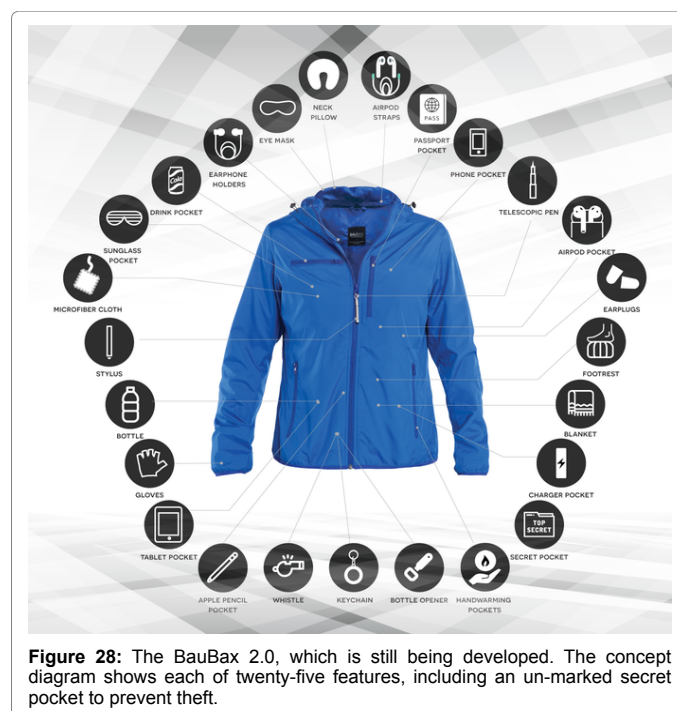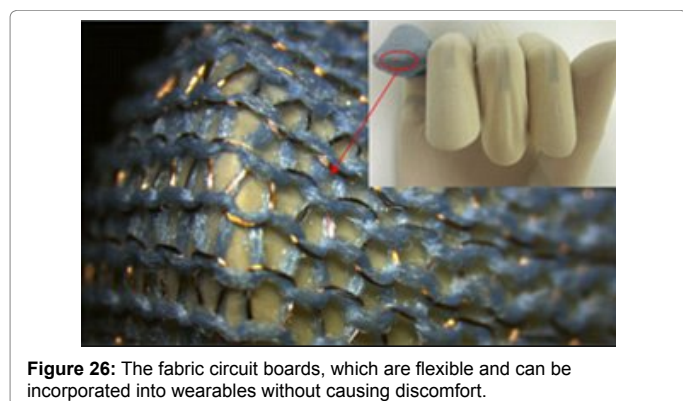

Figure 23: An example of corning's fibrance® light diffusing fiber, showing its flexibility and high color uniformity.
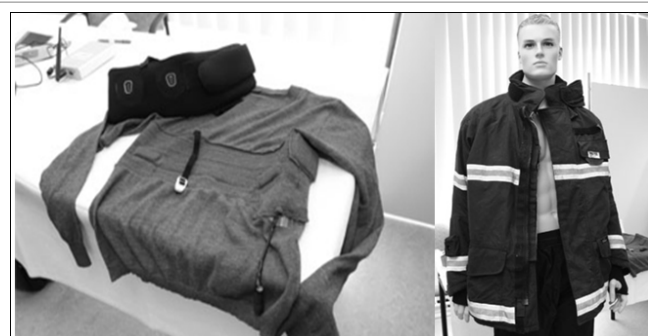
Figure 24: The protective clothing developed during the project PROeTEX included inner (left) and outer (right) garments.

Besides physical safety, it is also important to consider the safety of one's belongings. BauBax [61] is currently developing a line of smart clothing that has twenty-five features (Figure 28) [19]. Among these features is a secret pocket, which is RFID-proof to prevent the electronic theft of credit cards. One can also place sensitive belongings in this pocket. It has increased safety when compared to the rest of the garment in part due to the changing location of the pocket, which is based on the style of jacket chosen. The location of the pocket is not shown online. The jacket is designed to make traveling more comfortable-it has features such as retractable gloves, a retractable eye mask, a travel blanket, an inflatable neck rest, and an inflatable footrest. Hand-warming pockets and pockets for specific travel-related items are also included in the list of features. These include pockets for a drink, power bank, phone, tablet, stylus/pen, headphones, sunglasses, and passport.

Figure 25: A concept protective workplace smart jumpsuit designed by Seebo® Interactive LTD.

Figure 26: The fabric circuit boards, which are flexible and can be incorporated into wearables without causing discomfort.

Figure 27: A prototype kevlar smart bulletproof vest using FCBs created by researchers at the Hong Kong Polytechnic University.

Figure 28: The BauBax 2.0, which is still being developed. The concept diagram shows each of twenty-five features, including an un-marked secret pocket to prevent theft.

Conclusion

As smart textile technologies became increasingly advanced in recent years, new applications have come to light. Smartphone to clothing communication is becoming increasingly popular versus other methods of reporting data from the sensors within wearable smart textiles. Companies including Wendu, Google, and Infineon have implemented some form of smartphone app for easy viewing and analysis of reported data.

Wearable smart textiles are becoming increasingly advanced and helpful in increasing the functionality of both everyday clothing and work wear. They have applications in health management, sportswear, industrial work wear, temperature control, safety, and entertainment.

The technologies developed for wearable smart textiles are still being improved and developed. Many designs can still be streamlined to decrease bulkiness and improve the overall integrated feel of the technology.

Implementation of wearable smart textiles in the workplace increases the overall safety through favourable antistatic and conductive properties. It is important for industrial applications to ensure that the clothing will not decay quickly due to static, washing, or normal wear for the job. An important role smart clothing fills extremely well is the monitoring of biometric data of an individual. Sensors can be placed throughout the fabric of the clothing in order to get a detailed report of the status of the individual including heart rate, breathing rate, sweat rate, posture, and movement related information. Wearable smart textiles have been shown to enhance the functionality of the wearer in everyday life with designs exhibiting functionality for music play, calling, messaging, and location tracing (GPS). These smart clothing technologies have been implemented in products without having to sacrifice the appearance and durability of normal clothing. LED and OLED displays have been used to increase the visual appeal of clothing without causing an increase in bulk. Illuminated clothing also improved visibility of the wearer, a common safety concern. It

is important to consider how the integrated electronics impact the comfort and appearance of the base clothing. With companies such as Google starting to design smart clothing for everyday use, it is not farfetched to believe that smart clothing will continue to become more advanced and seamless.

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