Recent developments in flexible wearable electronics for monitoring applications

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With the technology miniaturization and wireless revolution, electronics have found new applications in the form of flexible wearables for monitoring purposes. Ongoing research on wearable electronic systems has resulted in a number of prototype garments that can monitor and relay various types of data. As a review of the latest development in this area, this paper outlines and discusses the various components required for such a system, including sensors, actuators, circuitry and power management.

Key words: monitoring; smart; textiles; wearable electronics.

1. Introduction

In the continuous pursuit of innovation, academic and industrial researchers alike have opened up floodgates in the development of wearable electronics. The progress was distinctly stepwise. First, there were large non-portable electronics, computing and communication devices. Then came the smaller and lighter portables, with integration of some multiple functions. Now, we are in the era of the multi-purpose unobtrusive wearable, where criteria such as weight, comfort, durability, energy management and wireless communication are the essential building blocks of the product.

Before going further, a clarification of the definition of wearable electronics for this paper is necessary. The term has been used extensively recently to include various types of electronic devices that can be 'worn' on the body and used during physical activity. This broad definition includes common accessories such as pedometers and heart straps, as well as more complex interactive items such as monitoring rings

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(Yang and Rhee, 2000), armbands (Teller, 2004) and head-mounted computers (Mayol *et al*., 2002; Ockerman *et al*., 1999). This review does not, however, include such technologies, but rather, focuses on electronics integrated within items of clothing, to create 'flexible' wearable systems.

Tao's definition of wearable electronics is that of 'apparel with unobtrusively built-in electronic functions' (Tao, 2005a). More specifically, Ko *et al*. (2005) sum up various functions as providing '... intelligent assistance that augments memory, intellect, creativity, communication and physical senses'.

In the last few years, such types of electronics have been developed for various applications. In the entertainment industry, garments with integrated iPods, speakers, radios, etc. have already been commercialized by the likes of Gap, O'Neill, Rosner, Spyder, Textronics or Scottevest, working in collaboration with Philips, Infineon, Eleksen, SOFTswitch, Konarka Technologies and others. This review will not cover these already marketed products, which have been well documented in trade magazines and online. In the health and safety industry, a number of research groups have more challengingly developed monitoring garments, which, when worn, should be able continuously or discreetly to sense physical bodily or positioning data and relay them to a communication centre. Practical issues about the 'wearability', accuracy and reliability of the developed prototypes are being considered and addressed, and early steps for the commercialization of some of these products have been taken. While this is still in its infancy, it is perhaps now timely to bring together the various research results from the international community, and review the current progress in flexible wearable monitoring electronics.

2. Textiles and clothing as flexible supports

Textiles are ubiquitous in our society, and provide the ideal base or support for wearable monitoring electronics. Because textile garments or accessories can be worn close to the skin, integrating electronics within the textiles gives benefits unrivalled by other systems. Measurements of data requiring close contact with the skin are possible, with minimal effects on the comfort of the wearer, and with minimal disruption to his/her day-to-day activities.

To date, a number of wearable electronic textiles have been developed. Many are multi-layer systems, consisting of at least an internal layer (in contact with the skin) and an external one, with connected electronics and circuitry. The torso garment of Dunne *et al*. (2005) is an example of a double-layer prototype. Stylios and Luo (2003) by contrast describe a multiple layer system consisting of an innermost layer for comfort, an electromagnetic mask layer to shield the body from radiation, an electronic layer and an outermost layer, where power management systems such as solar cells can be incorporated. Rantanen and Hännikäinen (2005) describe a three-layer system, consisting of a skin layer for physiological measurements, an inner clothing layer as a platform for the electronic components and an outer layer for environmental and positioning sensors and equipment.

Structurally, both knitted and woven fabrics have been used for wearable electronic clothing for monitoring applications. The main advantage with textiles is their flexibility, which relates to some extent to wearing comfort. Knitted fabrics have the advantage of being stretchable and deformable to some extent, and have been used where the fabrics need to be close to the body, or close fitting, such as for leotards or other sportswear. Comparatively, woven fabrics provide more dimensional stability, and are more suitable where large movements of the body are not an essential factor to consider. Exploring the duality of functions, the interlacing of warps and weft in woven fabrics have been explored as networks for electrical circuits, in addition to being the supporting material for the integrated electronics (Dhawan *et al*., 2004a). This will be discussed in the forthcoming sections.

At this point in time, the influences of fabric structure and geometrical construction and of fibre type on the monitoring performance and accuracy have not been considered to be of significance. Most of the research has instead focused on constructing systems and ensuring that it works efficiently. Fabrics of reported prototype monitoring garments have been made of various types of fibres, including natural fibres, polyester, acrylic, elastane, Nylon and optical fibres (Beith, 2003; De Rossi *et al*., 1999; Dunne *et al*., 2005).

3. Sensors

A key component for wearable electronics systems for monitoring applications is the sensor, which gathers data from the wearer and relays the information to a processing unit. Recent works in monitoring vests and garments have integrated multiple sensors that provide physiological data such as body temperature, heart rate, skin conductivity, etc., and location data, using satellite facilities. Depending on their size and requirements, a number of traditional sensors made of conducting materials such as metals or carbons can be incorporated in smart clothing. Current research trends, however, are to develop flexible sensors out of textile materials, making use of the new range of polymers capable of changing properties with the environmental conditions, eg, change in pressure, moisture, temperature, etc. Novel flexible sensors have thus been developed specifically for use in smart clothing or textiles and will be discussed throughout this paper. The type, position and number of sensors used naturally depend on the application end-use of the smart clothing. Recent examples of integrated sensors include the LifeShirt (tracking physiological measurements), an electronic bra for breast cancer detection and baby pyjamas to assist in preventing cot death (Hibbert, 2004).

3.1 Detection of posture and movement

Various prototypes for the monitoring of posture and movement have been developed for improving body postures, reducing sports and other injuries, and assisting in rehabilitation. Previously, such types of monitoring were done by applying sensors directly on the body, with the disadvantages of being cumbersome, uncomfortable to wear as well as easy to displace. With the advent of the concept of smart textiles, sensors are now being integrated within textiles, or securely attached to it. Most are based on the principles that the electrical resistance of the flexible sensor changes during stretching. Neilly (1986) gave a good account of early attempts at developing strain and stress sensors for fabrics, and was one of the firsts to investigate flexible strain sensors from piezo-electric polyvinylidene fluoride (PVDF) polymer films. However, the developed films exhibited limitations such as sensitivity to temperature and electromagnetic interference, tensile stiffness and transient output signals, which precluded their use in wearable garments. A more recent, simple but successful example is a fabric strain sensor attached to a knee sleeve that acts as a biofeedback device, monitoring the wearer's knee movements during physical activity, and sending back information via a beeping sound (CSIRO, 2001). This type of sensor is, however, limited in its lifespan and has been developed as a disposable device.

Prototypes of more complex and durable garments and accessories such as jackets, leotards and gloves with surface-attached sensors have also demonstrated the ability to sense the position of different parts of the body and monitor physical activity (De Rossi *et al*., 2003, 2005; Farringdon *et al*., 1999). Normally, a number of sensors have to be positioned over specific points of the body, where angles of joints and stretch distances can be measured. From a design point of view, the surface attachment of many strips of sensors on the garment be capitalized as a decorative element, but is also a source of design limitations and restrictions. Other systems have been developed whereby the sensors are embedded between fabric layers (Dunne *et al*., 2005) or into the fabric itself (Kirstein, 2004).

Many of the developed flexible strain sensors are based on using coated fabric technology. The discovery of conducting electro-active polymers such as polypyrrole (PPy), polyaniline and polythiophene has opened doors in the development of various types of textile sensors. PPy has been particularly well explored in coated fabrics (De Rossi *et al*., 1999, 2003, 2005) and foams (Dunne *et al*., 2005). Such materials have been found to have transducing properties as strain gauges, exhibiting a drop in electrical resistance with a physical deformation and topology change. De Rossi *et al*. (1999, 2005) reported gauge factors similar to that of nickel. However, they also reported that the sensor resistance shows strong variations with time, and that the material has a high response time.

Other elongation sensors include conductive fibre potentiometers, conductive fluids and carbon-filled rubber coated fabrics, which have been shown to have some properties similar to that of metals in the 1–13% strain range (De Rossi *et al*., 2005).

Kirstein (2004) summarizes the pros and cons of each system, highlighting the simple and cheap manufacturing process of PPy-coated fabrics and carbon-filled rubber, but their high hysteresis and dependence on pre-history and stretch velocity. Conductive fluids (strain gauges made from liquid metals such as mercury, or electrolytes such as copper sulphate contained in a rubber tube) are claimed to have better transducer performance, but the potential problem of permeability of the rubber tube, its limited lifespan and its lack of textile quality are the main drawbacks.

3.2 Biometric measurements

A number of smart wearable electronic garments have incorporated existing, adapted or developed sensors for the measurement of biometric factors such as body temperature, heart rate, respiration rate, skin conductivity, etc. (BBC, 1999; Catrysse *et al*., 2004; De Rossi *et al*., 2003, 2005; Dunne *et al*., 2005; Goulev *et al*., 2004). Applications for such types of garments or accessories cover the healthcare, clinical, military, rescue or sports sectors, where the monitoring of vital signs is essential. In the medical field, smart monitoring suits can be used for long-term continuous monitoring of patient's conditions, and can also be a potential aid in the fight against cot death in babies (Hibbert, 2004). In the military field or in a rescue situation, acquiring and relaying the vital signs of a soldier or fire fighter in action can help the medical team prepare for any required treatment. In sports, smart suits can be used as a tool to study conditions for optimum performances, but can also be used as tools in extremes and life-saving situations such as avalanches (Michahelles *et al*., 2003).

Unlike posture and movement sensors, in most cases for biometric sensors, they have to be positioned next to or very close to the skin, which limits their incorporation in large loose garments such as jackets. For the majority of prototypes, the smart garment is close fitting and worn as an undergarment. As such, textile sensors, with better tactile and comfort properties are being developed in order to improve the 'wearability' of the electronics.

Textile electrodes, also called 'Textrodes' have been developed out of knitted stainless steel fibres for the measurement of electrocardiograms (Catrysse *et al*., 2004). Trials showed that the Textrodes are less irritating to the skin (in contrast to gel electrodes), and that they are able to provide reliable monitoring despite having high skin-electrode impedance. In the same spirit, Catrysse *et al*. (2004) also developed a textile alternative to conventional methods of measuring respiration rates. Made of stainless steel yarn and knitted in an elastane-containing belt, their 'Respibelt', when worn around the thorax, is able to measure thoracic changes in perimeter and cross-section, through changes in inductance and resistance. In another approach, Dunne *et al*. (2005) investigated the use of PPy-coated pressure-sensitive polyurethane foams as sensors for breathing. Limitations with regards to ageing of the material, oxidative degradation and hysteresis effects have been observed; however, the coated foam still showed interesting promises for the monitoring of breathing rates.

PPy-coated materials have also been shown to have good thermal sensitivity for temperature monitoring. De Rossi *et al*. (1999) found that the temperature sensitivity of PPy-coated Lycra is of the same order as that of ceramic thermistors. Pre-oxidized carbonized woven polymers such as the trademark Gorix can also be used as a temperature sensor (Kirstein *et al*., 2005).

3.3 Location monitoring

The incorporation of unobtrusive tracking devices in garments to monitor the location and whereabouts of the wearer is now being explored commercially. Thanks to rapid development in mobile phone technology and in long-range communication, the technology for remote localization is well established and can be readily transferred to wearable electronics. The Japanese were amongst the first to explore openly the Global Positioning Systems (GPS) technology in clothing. Small GPS tracking devices have already been integrated in school uniforms and prisoners' outfits, as a safety and security measure. There is no doubt that a GPS positioning system can be useful in certain situations (kidnapping, prisoner escape, avalanche or other types of rescue, accidents, etc.); however, given the inconspicuous nature of the devices, some issues can be raised on privacy and human and moral rights.

3.4 Pressure sensors

Pressure sensors integrated in apparel can have different applications – detecting pressures during day-to-day, physical or sports activities, or providing an input interface for the wearer, for example in the form of an integrated keyboard or touch pad (Jones, 2004; Swallow and Thompson, 2001). Significant development in the field of flexible pressure sensors, with improved tactile properties and weight (compared to conventional keyboards and pressure sensors) has been achieved and commercialized, based on various types of technologies.

Dunne *et al*. (2005) investigated the use of PPy-coated polyurethane foam as pressure-sensitive materials, and applied them for the monitoring of body movement and breathing monitoring. Most other textile pressure sensors work from multi-layer principles, eg, two conductive textile layers sandwiching a non-conductive one. The middle layer can be an electro-resistive composite that changes resistance when compressed, eg, as per the commercially available Softswitch technology (Jones, 2004; Softswitch, 2005), or a mesh-type structure, which would allow physical contact between the two conductive layers with pressure (Swallow and Thompson, 2001). Another commercial system comprises a five-layer structure with conductive carbon fabric layers and insulating separation mesh layers separating a partially conductive layer that conducts locally when compressed (Eleksen, 2006; Gilhespy, 2004). The technology is now developed enough to provided detailed information on the pressure positions and forces. Most applications of pressure sensors to date have been for textile electronics for the entertainment industry, but applications in the medical and healthcare fields are also being explored.

3.5 Ballistic penetration and fabric damage

The military and safety sectors have been key stakeholders in the development of smart monitoring textiles. The functionalities provided by sensors described above are attractive for the support of frontline personnel, and much work has been carried out in the pursuit of smart clothing for fire fighters, rescue workers, policemen, soldiers and other special forces. In one smart garment prototype developed with the military in mind, optical fibres form a conductive circuit backbone in a grid of rows and columns (Lind *et al*., 1998). Upon penetration of a bullet, the conductive path of the thread is broken, and detected by the microprocessor, which can identify the exact coordinates of the penetration. The information can then be quickly relayed to medical teams. A similar concept can potentially be used for other type of fabric damage, including for chemical and biological protective garments, whereby a warning signal can be emitted when a hole or tear occurs in the fabric.

4. Actuators and output signals

Various types of textile-based or other actuators that can transform electrical signals into a physical phenomenon have been incorporated in wearable electronics to generate some form of output, which can be audio, visual or tactile. In the piloted sensing knee sleeve (CSIRO, 2001), the output of the information sensed (angle of knee bent) is in the form of an audible sound, warning the wearer when the correct knee angle is achieved during landing. Audio signals are simple but effective warning signals, which can also be varied by changing pitch, tone and other audio factors, to convey different messages.

A vast amount of research is ongoing in the area of flexible visual displays, which are able to provide more information to the wearer. One group of flexible visual displays uses colour-changing mechanisms in dyes and pigments to create colour, and hence visual outputs. In this respect, many sensors can also act as actuators and automatically respond by a physical change, when sensing an environmental change, eg, chromatic dyes changing colour with temperature, light, pressure, etc. Other chromatic materials can also react with an electric current and hence change colour as and when required to create a colourful output (Gregory *et al*., 2004).

Tao (2005b) and Philips Research (2002) provided a brief overview of current technologies in flexible displays, from the academic and industrial points of view. Displays made of polymer light-emitting diodes (polyLED) produced on flexible plastic substrate can lead to extra flexibility, but has the disadvantage that the plastic backing permits degradation of the light-emitting properties of the polyLED. Various semi-conducting polymers have been found to have potential as polyLEDs, eg, polyanilines, polythiopenes and polypyridines (Dawson, 2003) and much work still continues in this area. Textile-based display prototypes have been produced using electro-luminescent materials that are triggered with an electric voltage, as with the commercially developed Visson displays. The electro-luminescent material is used to thinly coat wire conductors, which are then woven into a rows-and-columns electrodes network. Emission of light is triggered when a voltage is applied to a specific row and column, hence creating an electric field at their intersection. Another technology is to use encapsulated charged particles within microcapsulses, and attract or repel them using an electric field. Yet another system is to use optical fibres in woven textile structures. Koncar *et al.* (2005) describe an optical fibre flexible display (OFFD) that has been prototyped on a jacket. Using a patented process to generate microperforations in optical fibres such as poly(methylmethacrylate (PMMA)), fibres with multiple point lateral illumination are obtained (Bernasson and Vergne, 1998). These fibres are woven into a number of surface units, or large 'pixels', that can be lit individually to create specific shapes, texts or logos.

A final visual and tactile type of actuator are shape memory materials such as alloys and polymers, which change shape upon receiving a stimulus such as temperature or electrical field. Such materials have been explored for use in apparel and interior textiles (Chan and Stylios, 2003; Winchester and Stylios, 2003), but not yet in a function related to monitoring. As with chromatic materials, shape memory materials can act as both sensors and actuators, and may thus have interesting uses in the wearable monitoring field.

5. Data management and communication

With basic sensing/actuating materials such as chromatic dyes and shape memory materials, the wearer may be able to monitor specific parameters without the need for a processor for the data, and communication network to relay the information. As example, consider a photochromatic patch on an outdoor vest, swimwear or sportswear. The patch may be able to monitor the level of ultraviolet rays responsively by sensing and reacting with the incident light. With this type of system, no data management, storage and communication are necessary.

In the case of wearable electronics, the complexity of the system is higher because the electronic components will need to convert electrical signals into output and/or input into electrical signals. Processors such as transistors, diodes and other non-linear devices are needed to amplify signals, process simple arithmetic operations and store data gathered. Attempts have been made to create electro-active textile fibres that can act as transistors. Lee and Subramanian (2003) demonstrated the patterning of transistors directly on fibres using a novel weaving-based lithography, a technique that lends itself to textile manufacturing. The fibre transistors showed good and stable electrical characteristics, with performance suitable for applications in smart textiles, but were limited by enhanced dielectric leakage and reduction in reliability.

Central processing units for smart clothing systems often include small 8–16-bit microcontrollers (Rantanen and Hännikäinen, 2005). The monitoring system can consist of a combination of several such units, positioned at different locations to perform specific functions, and communicate with each other.

5.1 Short-range communication

One of the challenges of interactive wearable electronic textile systems is the effective transfer of data or power between different modules of the system. For practicality, weight and design purposes, it is often convenient to spread out the sensors, actuators and microcontrollers over different strategic locations on the body. This distribution of information micro-hubs requires an effective and comfortable network of communication. Earliest attempts included the use of wires. Infrared and Personal Area Networks (PAN) such as Bluetooth technology were also suggested as possible alternatives. Recently, a Fabric Area Network (FAN), and the transfer of information through the human body have been investigated (Hachisuka *et al*., 2003; Hum, 2001). A summary of the various short-range options is given in Table 1. The various PAN systems have attracted much attention in the area of wireless interactive wearable electronics, but security and privacy still need to be worked on. The need for good data encryption systems, and for a universal communication and encryption standard to enable different products to work together wirelessly, has been identified as essential areas of research (Gould, 2003). For inter-device physical connections, a large amount of work has been carried out in the area of conductive fibres, yarns and textile circuitry.

5.2 Textile circuitry

The development of flexible circuitry to interconnect various elements of wearable electronics has explored various approaches across the world. Conductive yarns and coatings played a significant role in enabling various textile circuitry technologies. Anderson and Seyam (2002) have provided an account of the various methods of imparting conductivity and semi-conductivity to textiles. Conductive textile circuits are now in a position to compare favourably to conventional flexible circuits

As mentioned by Post *et al*. (2000), there are various methods for making flexible circuits, most of which relying on the metallization of a flexible high-temperature resistant polymer substrate such as polyimides, which can withstand soldering temperatures. The flexibility of such circuitry is, however, generally limited to the substrate – soldered joints are the weak points during mechanical stress.

Table 1 Short-range communication

System		Benefits	Disadvantages
Wired	Traditional wires	Minimal cost	Cumbersome to wear
		Reliable technology	Constrictive and restrictive
		High capacity for information and power transfer	Inflexible and prone to environmental ageing
			Heavy
	Advanced wires (eg, conductive fibres, yarns, optical yarns)	Practical two-in-one or multi-functional approach	Technology still under development
		Minimization of number of components required in the system	Lack of natural insulation in conductive yarns causing unwanted conductivity
		Optical fibres are insensitive to electromagnetic irradiation and do not generate heat during data transfer; conductive fibres benefit from being able to conduct electrical signals directly	More sensitive to breakage at soldering connections
Wireless	Wireless Local Area Networks (WLAN)	High capacity communication within a limited geographical area	Power requirements
		Reliable and low-cost data transfer	
		Multiple users are possible	
	Personal Area Networks (PAN)		
	Bluetooth	Cost and power consumption more favourable for wearable electronics	Smaller operational area than WLAN
		Devices can find each other and communicate without the user	Lower data rate and fewer terminals per network than WLAN
		Enables communication in any direction (no alignment of devices necessary)	Effect of the emission of radio frequency fields through the body is under debate

Infrared	Simple	Devices have to be aligned, making it impractical for many smart clothing applications
	Low cost	Data transfer size limited
Intra-body communications:	Little interference from electromagnetic noise and obstacle	A wire is necessary outside the body
1) The body as a circuit,	Signals do not leak	Transmission quality for electrostatic coupling systems is affected by surrounding systems
2) Electrostatic coupling		
3) The body as a waveguide		
Fabric Area Networks (FAN)	Radio frequency fields restricted to the fabric surface only (emission-safe)	Data transfer limited by distance
	Low cost	
	Easy to maintain	
Radio Frequency Identification Technology (RFID)	Low cost	Transfer restricted to the surface of the clothes
	No requirements for alignment of devices	
	Potential solution for transferring data between pieces of clothing	

The challenges of creating circuitry that can be mechanically stressed in all directions and positions led to the development of textile-based circuitry.

The earliest attempts suggested the use of printing and coating technologies to create a circuit pattern on a textile substrate using conductive polymers such as PPy, polyaniline and polythiophthene. Adams *et al*. (1994) illustrated a technique of creating a patterned conductive surface by coating with conductive polymer and physically removing the coating on selected areas, eg, using high-velocity water jets. De Angelis *et al*. (1997) described a method of chemically etching away patterns from a conductive film deposited on a textile substrate to create selective conducting paths.

Post *et al*. (2000) outlined various alternatives to create textile-based circuitry. In one line of research, the use of metallic silk organza was explored, and electrical components were soldered directly on the fine fabric. A particular characteristic of organza that makes it ideal for conducting electrical signal is that its silk warp threads are wrapped in a metal foil helix, which has a high conductivity. The labour-intensive piecework produced, however, highlighted several limitations, including the fragility of the metal wrap and its propensity for corrosion. Further, soldering components still led to poor mechanical properties at joints (considering the stresses expected in apparel), and raised issues of toxicity when worn next to the skin.

Embroidery proved to be a good solution to textile-based circuitry. While stitching on the metallic organza was not an option because of the fragility of the wrapping foil, using conductive yarns on other types of fabrics gave good results. A number of conductive yarns were shown to have varying degrees of conductivity, durability and performance: yarns made of continuous or short stainless steel fibres, blends of stainless steel and polyester, nylon-stainless steel core-wrapped structure and metal-clad Aramid fibres. However, in the case of embroidered circuitry, the yarns of continuous metal fibres were not suitable for machine stitching because of the low yarn elasticity and built-up of tension during stitching. Post *et al*. (2000) remarked that with embroidery, multi-layer textile circuitry becomes easier to develop, compared to conventional multi-layer circuitry.

In addition to embroidery, weaving has also been shown to be a potential solution for flexible circuitry, including multi-layer ones. The interlacing of conductive and non-conductive yarns can be used in complex networks, with the right interconnecting and disconnecting points for conductive yarns to route the electrical signals (Dhawan *et al*., 2004a). Interconnection of unconnected yarns for specific circuit designs can be done by resistance welding using microprobes and air splicing. Disconnection can be done with microcutters as well as during resistance welding, to cut and connect at the same time. One of the limitations of textile (and other flexible) circuitry is a lack of signal integrity under certain conditions. This happens for example when there is a rapid voltage change on a line, leading to cross-talk or electromagnetic interference to an adjacent line. Dhawan *et al*. (2004b) investigated the use of different types of yarn structures to reduce cross-talk, and found that interference is reduced when coaxial and twisted pair copper threads are used instead of bare ones.

Seyam (2003) reviewed the potential of the latest developments in woven fabric technology for electro-textiles, highlighting the possible automation, high-speed productions, versatility and quality. For disconnecting and interconnecting conductive yarns into a designed woven circuit, the incorporation of small robotic devices and optical sensors enables automation of the process. Further, advances in weaving technology, such as variable-speed weaving, filling selection mechanisms or 3D weaving technology facilitate the woven circuit technology development. One example is the Wearable Motherboard (Beith, 2003), which is woven in one piece, bypassing the cut and sew operation. The wearable computer incorporates and integrates plastic optical fibres, creating a whole garment circuit.

5.3 Long-range communication

For external data transfer, eg, via the Internet or a network protocol, the technologies have been well developed in the recent two decades. A range of communication systems is already available: the Global System for Mobile Telecommunication (GSM) is widely used for small sized data transfer (eg, voice transmission); the Third Generation (3G) wireless system is now being used to transfer larger files such as photographs and videos. On the downside, the energy requirements for the more powerful data transfer systems are higher, and as such efficient power management systems are required.

6. Energy sources

The main energy requirements for a wearable electronic textile system include low power consumption, light, easy to carry around, long-lasting and discreet power sources. In the case of monitoring systems that will encounter harsh environmental conditions or movement (eg, for use in sports activities, fire-fighting exercises, military conditions or extreme environmental conditions), the robustness of the system is also an essential criterion.

Batteries such as the lithium–polymer ones are at present the most common types of power sources, but because of the high consumption of energy for electronic components in wearable electronics, they may not be the most suitable source for long-term conditions, eg, mountaineering or rescue expeditions. Alternative solutions include using longer lifespan power sources such as microfuel cells, or harvesting continuous and semi-continuous power sources such as the sun (photovoltaics), the human body (kinetic or heat energy) or microwaves (Tao, 2005a). The smart textiles sector has taken a keen interest on the use of solar energy for powering the electrical components in outdoor clothing. Recently, commercially available flexible photovoltaic materials made from copper indium galium diselenide (CGIS) has been used in the development of a solar-powered jacket (Scottevest, 2004). Silicone-based thin photovoltaic films are also under investigation for use in woven military uniforms and other applications (Anon, 2004).

On the research front, various methods of producing textile-based photovoltaics are being investigated, including depositing nanocrystalline silicon on woven or non-woven substrates, weaving and knitting photovoltaic fibres developed with photoreactive dyes and titanium dioxide, and adapting multi-layer thin film technology for cylindrical materials such as fibres. Organic and polymer photovoltaics have also raised interest for applications in textiles (Krebs *et al*., 2005). Although still in its early stages of development, polymeric photovoltaics have been applied as coating on textiles, with encouraging performances, but with issues to be addressed regarding stability and durability.

7. Current status and future potential

In the last half of the 20th century, significant technological advances in various disciplines have led to a plethora of technologies designed to enhance our lifestyles. The 1990s and early 2000s created a multidisciplinary revolution, bringing in together technologies from a wide range of disciplines to create multifunctional products. The smart and interactive clothing is one typical example of the collaboration of a number of different experts and researchers in the electronics, information technology, material science, textile technology and textile and fashion design among others. The area of smart fabrics and intelligent textiles has been estimated at a global value of US$ 300 million in 2003, predicted to grow to US$ 720 million by the year 2008 (Fitzpatrick, 2004; VDC, 2003). Two of the major markets are the American and Japanese ones, both of which having invested (and still investing) large sums on research in this discipline. However, groundbreaking advances are also being reported in Europe, in particular the UK, Finland, France, Belgium and Italy. China, including Hong Kong, is also expected to bring in a large contribution to the research and industrial community in the area of smart clothing.

As it stands, significant progress has already been achieved in the design and development of smart interactive garments for monitoring applications. Research on the individual components required for such applications (sensors, actuators, microprocessors, etc.) continues with dynamism, fuelled by the interests shown by the industry. Research on the construction of interactive garments is also buoyant for applications such as clinical and general health monitoring, performance during sports and military uses, including life sign and injury monitoring, position and location tracking and communication systems. A number of working prototypes have already been produced, and clinical trials in the medical sector and field trials in extreme conditions have already started. Mass commercialization of some systems is not too far down the line, but work is still needed in order to resolve all the technicalities, particularly with regards to the following:

- accuracy and reliability of data measurement (noise reduction);
- reliability, safety and security of data transfer;
- minimization of the number of additional attachments (simplification of the systems by multi-functional textiles);
- efficiency of power management, including power generation;
- durability of the systems, including washability and long-term accuracy in performance;
- user-friendliness, including the ability to use/wear the garments without the essential need for assistance;
- mobility, including weight reduction;
- cost versus product lifespan or durability;
- comfort and physical aesthetics, including breathability, absorbency, drape, handle, etc.

The last point raises the importance of aesthetic and product design in what appears to be principally technical and functional textiles. The concept of product development includes the whole package of design, technology, functionality and logistics. While the technology has been established in many areas, creating the end-use functionality is still a subject of major continuing and maturing research. The design component of research for such applications by contrast is still in its early stages, but with the advent of a new generation of multidisciplinary researchers, is growing rapidly. The logistic and sociological aspects have not been fully explored, primarily because commercialization of such products has not yet occurred on a large scale.

As outlined by Gould (2003), privacy and security of data transfer is an issue that needs to be resolved by the research community. With the current systems for short-range communications, encryption and decryption systems have to be reinforced in order to prevent 'accidental' transfer of personal data between individuals wearing smart interactive devices. The rights to privacy and data protection are issues that are strongly felt by consumers and various human rights groups alike. In this line of thought, there have been some reactions against the inclusion of Radio Frequency Identification Technology (RFID) in high street clothing items due to privacy issues (Ilic, 2004). Concerns can also be raised with the illicit or non-consensual use of such devices.

8. Conclusion

As a growing sector, interactive smart textiles continue to generate interest from academia and industry alike, and new opportunities and applications are being investigated continuously. The technical and functional sides of research on wearable electronics for monitoring applications have been researched extensively and continue to progress. Issues such as launderability and deformation in use have been addressed for some applications (eg, SOFTswitch, 2005), and continue to be investigated for other more complex wearable electronics. While at the beginning, advances from specific fields were adapted into the textile and clothing research, at this point, the demands of industry and consumers have rallied researchers from various disciplines to collaborate, resulting in new textile sensors, processors and actuators, textile circuitry and inter-device communication and textile-based power generation systems. There are still many practical, technical as well as non-technical challenges that have to be met, and it is anticipated that the coming years will witness an even greater level of multidisciplinary collaboration, in particular bringing in now more design, sociological and legal aspects.

With the increasing interest of consumers in lifestyle products, it is expected that the applications for interactive monitoring garments will expand out of institutional use (hospitals, military, rescue services) where it is currently focused, into individual consumer use. The growing ageing population could be an influential factor: flexible wearable electronic clothing systems would facilitate the independence of the aged and disabled, by allowing them to get on with their day-to-day activities, while still being monitored. However, in order for this level of commercialization to be reached, convenience, reliability and accuracy have to be improved, costs have to be brought down, and the supporting infrastructure for the monitoring and assistance need to be developed. Again, this highlights the necessity for multidisciplinary industrial collaboration.

References

Adams, L.W. Jr, Gilpatrick, M.W. and **Gregory, R.V**. 1994: Method for generating a conductive fabric and associated product. US Patent No. 5,292,573.

Anderson, K. and **Seyam, A.M**. 2002: The road to true wearable electronics. *Proceedings of the Textile Institute's 82nd World Conference*, 23–27 March, Cairo.

Anon. 2004: USA: Solar fabrics could be used in military uniforms. Just-Style.com News, July, accessed from www.just-style.com

BBC. 1999: Computerised shirt could save lives, BBC News Online, accessed from http://news.bbc.co.uk

Beith, M. 2003: Wearable wires. *Newsweek International* (Special Double Issue, Inventions That Will Change the World), 30 June/7 July.

Bernasson, A. and **Vergne, H**. 1998: Optical fiber with multiple point lateral illumination. International Patent No. PCT/FR94/01475

Catrysse, M., Puers, R., Hertleer, C., Van Langenhove, L., Van Egmond, H. and **Matthys, D.** 2004: Towards the integration of textile sensors in a wireless monitoring suit. *Sensors and Actuators A* 114, 302–11.

Chan, Y.Y.F. and **Stylios, G.K.** 2003: Designing aesthetic attributes with shape memory alloy for woven interior textiles. In *INTEDEC 2003, Fibrous Assemblies at the Design and Engineering Interface*. Research Institute for Flexible Materials, Edinburgh.

CSIRO (Commonwealth Scientific and Industrial Research Organisation). 2001: Intelligent knee sleeve to save costly sporting injuries, CSIRO Media Release, accessed through www.csiro.au

Dawson, T.L. 2003: Developments in colour display devices. *Review of Progress in Coloration* 33, 1–14.

De Angelis, A.F., Child, A.D. and **Green, D.E**. 1997: Patterned conductive textiles. US Patent No. 5,624,736

De Rossi, D., Carpi, F., Lorussi, F., Scilingo, E.P. and **Tognetti, A.** 2005: Electroactive fabrics and wearable man-machine interfaces. In Tao, X., editor, *Wearable electronics and photonics*.

Woodhead Publishing in Textiles, Chapter 4, 59–80.
De Rossi, D., **Della Santa, A.** and **Mazzoldi, A.** 1999: Dressware: wearable hardware. *Materials Science and Engineering* C7, 31–35.
De Rossi, D., **Lorussi, F.**, **Mazzoldi, A.**, **Orsini, P.** and **Scilingo, E.P.** 2003: Active dressware: variable kinesthetics. In Barth, F.G., Humphrey, J.A. & Secomb, T.W., editors, *Sensors and sensing in biology and engineering*. Springer-Verlag, Chapter 26, 379–92.
Dhawan, A., **Seyam, A.M.**, **Ghosh, T.K.** and **Muth, J.F.** 2004a: Woven fabric-based electrical circuits. Part I: Evaluating interconnect methods. *Textile Research Journal* 74, 913–19.
Dhawan, A., **Ghosh, T.K.**, **Seyam, A.** and **Muth, J.F.** 2004b: : Woven fabric-based electrical circuits. Part II: Yarn and fabric structures to reduce crosstalk noise in woven fabric-based circuits. *Textile Research Journal* 74, 955–60.
Dunne, L.E., **Brady, S.**, **Smyth, B**. and **Diamond, D**. 2005: Initial development and testing of a novel foam-based pressure sensor for wearable sensing. *Journal of NeuroEngineering and Rehabilitation*, 2:4, accessed through www.jneuroengrehab.com
Eleksen Ltd. 2006: ElekTex® Smart Fabrics, accessed through www.eleksen.com
Farringdon, J., **Moore, A.J.**, **Tilbury, N.**, **Church, J**. and **Biemond, P.D**. 1999: Wearable sensor badge and sensor jacket for context awareness. *The Third International Symposium on Wearable Computers, Digest of Papers*, 107–13.
Fitzpatrick, M. 2004: Wired wear: intelligent clothing gets smarter. Just-style.com, August, accessed through www.just-style.com
Gilhespy, N. 2004: Enabling soft sensor solutions. *Proceedings of the Wearable Electronic and Smart Textiles Seminar*, Leeds.
Gould, P. 2003. Textiles gain intelligence. *Materials Today* 6, 38–43.
Goulev, P., **Stead, L.**, **Mamdani, E.** and **Evans, C.** 2004: Computer aided emotional fashion. *Computers & Graphics* 28, 657–66.
Gregory, R.V., **Samuels, R.J**. and **Hanks, T**. 2004: Dynamic color change chameleon fiber systems. *National Textile Center Annual Report, November* 2004, Project No. M01-CL07.
Hachisuka, K., **Nakata, A.**, **Takeda, T.**, **Shiba, K.**, **Sasaki, K.**, **Hosaka, H.** and **Itao, K.** 2003: Development of wearable intra-body communication devices. *Sensors and Actuators A* 105, 109–15.
Hibbert, R. 2004: *Textile innovation; interactive, contemporary and traditional materials*. Line.
Hum, A.P.J. 2001: Fabric area network - a new wireless communications insfrastructure to enable ubiquitous networking and sensing on intelligent clothing. *Computer Networks* 35, 391–99.
Ilic, C. 2004: Tracking fashion with RFID. *RFID Journal*, 15 November, accessed from www.rfidjournal.com
Jones, D. 2004: Wearable electronics enabled by Softswitch technology. *Proceedings of the Wearable Electronic and Smart Textiles Seminar*, Leeds.
Kirstein, T. 2004: Motion aware clothing. wearable computing lab, ETH Zürich, accessed from www.wearable.ethz.ch
Kirstein, T., **Cottet, D.**, **Grzyb, J.** and **Tröster, G.** 2005: Wearable computing systems – electronic textiles. In Tao, X., editor, *Wearable electronics and photonics*. Woodhead Publishing in Textiles, 177–97.
Ko, F.K., **Aufy, A.** and **Lam, H.** 2005: Electrostatically generated nanofibres for wearable electronics. In Tao, X., editor, *Wearable electronics and photonics*. Woodhead Publishing in Textiles, 13–40.
Koncar, V., **Deflin, E.** and **Weill, A.** 2005: Communication apparel, optical fibre fabric display. In Tao, X., editor, *Wearable electronics and photonics*. Woodhead Publishing in Textiles, 155–76.
Krebs, F.C., **Biancardo, M.**, **Winther-Jensen, B.**, **Spanggard, H**. and **Alstrup, J**. 2005: Strategies for incorporation of polymer photovoltaics into garments and textiles. *Solar Energy Materials & Solar Cells*, 90, 1058–67.
Lee, J.B. and **Subramanian, V**. 2003: Organic transistors on fiber: a first step towards electronic textiles. *Proceedings of the IEEE International Electron Device Meeting*, Washington DC, 0-7803-7873-3/03.
Lind, E.J., **Jayaraman, S.**, **Park, S.**, **Rajamanickam, R.**, **Eisler, R.**, **Burghart, G.** and **McKee, T.** 1998: A sensate liner for personnel monitoring applications. *Acta Astronautica* 42, 3–9.
Mayol, W.W., **Tordoff, B.** and **Murray, D.W.** 2002: Wearable visual robots. *Personal and Ubiquitous Computing* 6, 37–48.

Michahelles, F., **Matter, P.**, **Schmidt, A.** and **Schiele, B.** 2003: . Applying wearable sensors to avalanche rescue: first experiences with a novel avalanche beacon. *Computer & Graphics* 27, 839–47.

Neilly, D.G. 1986: The development of methods for the study of properties and performance in fabric for industrial and engineering end-uses. PhD thesis, University of Leeds.

Ockerman, J.J., **Najjar, L.J.** and **Thompson, J.C.** 1999: FAST: future technology for today's industry. *Computers in Industry* 38, 53–64.

Philips Research 2002: Flexible displays cast off rigid constraints. Password Magazine, 10, accessed from www.research.philips.com

Post, E.R., Orth, M., Russo, P.R. and **Gershenfeld, N**. 2000: E-broidery: design and fabrication of textile-based computing. *IBM Systems Journal* 39, accessed from www.research.ibm.com

Rantanen, J. and **Hännikäinen, M.** 2005: Data transfer for smart clothing: requirements and potential technologies. In Tao, X., editor, *Wearable electronics and photonics.* Woodhead Publishing in Textiles, 198.

Scottevest. 2004: Global solar prepare solar jacket for holidays. Press release, Scottevest Inc., September 2004, accessed from www.scottevest.com

Seyam, A.M. 2003: Electrifying opportunities. *Textile World*, February 2003.

SOFTswitch Ltd. 2005: SOFTswitch Technology, accessed from www.softswitch.com

Stylios, G.K. and **Luo, L**. 2003: The concept of interactive, wireless, smart fabrics for textiles and clothing. *Proceedings of the* 4th *International Conference Innovation and Modelling of Clothing Engineering Processes – IMCEP* 2003, Maribor, Slovenia.

Swallow, S.S. and **Thompson, A.P.** 2001: Sensory fabric for ubiquitous interfaces. *International Journal of Human–Computer Interaction* 13, 147–59.

Tao, X. 2005a: Introduction. In Tao, X., editor, *Wearable electronics and photonics*. Woodhead Publishing in Textiles, 1–12.

Tao, X. 2005b: Variable photonic based on integrated polymeric photonic fibers. In Tao, X., editor, *Wearable electronics and photonics*. Woodhead Publishing in Textiles, 136–54.

Teller, A. 2004: A platform for wearable physiological computing. *Interacting Via Computers* 16, 917–37.

VDC (Venture Development Corporation). 2003: *Smart fabrics and interactive textiles: global market opportunity assessment*, November.

Winchester, R.C.C. and **Stylios, G.K.** 2003: Designing knitted apparel by engineering the attributes of shape memory alloy. *International Journal of Clothing Science and Technology* 15, 359–66.

Yang, B.-H. and **Rhee, S.** 2000: Development of the ring sensor for healthcare automation. *Robotics and Autonomous Systems* 30, 273–81.