Electronic textiles for military personnel

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R. Nayak, L. Wang, R. Padhye
School of Fashion and Textiles, RMIT University, Melbourne, VIC, Australia

11.1 Introduction

Advancements in technology have led to the miniaturisation of electronics that can be embedded into textiles and used by civilians or special personnel, such as soldiers. The integration of electronics into military textiles could assist soldiers in achieving levels of performance and capabilities never realised before on the battlefield. Soldiers on active duty can face varying threats, often unpredictable. The special programme "Soldiers of the Future" was launched by the United States in the 1990s and investigated the benefits of smart textiles for soldiers (Anonymous, 2014a). Many countries are now investigating the application of various electronic devices integrated into textiles for military use (Sahin et al., 2005). Two different training and education initiatives have been sponsored by North Atlantic Treaty Organization (NATO) on the application of advanced textiles for civil protection and defence (Scott, 2005).

Electronic textiles, or simply e-textiles, are textiles with embedded electronics and some fibre materials possessing electrical characteristics and providing some useful functions. Current research on military textiles includes the improvement in the ballistic protection level (which is the primary requirement), and the developments of new designs with integrated sensors and embedded sensing technologies in clothing, backpacks or tents for other functionalities.

The various functionalities where electronic textiles are making inroads include health monitoring, communication (both wired and wireless), enhanced mobility, survivability, reduction of heat stress, reduction of logistic burdens, camouflage and signature management (Scott, 2005; Wilusz, 2008). Developments in sensors and wireless technology have enabled improvement in the performance of personal combat equipment. Some of the recent functionalities achieved by integration of e-textiles include physiological status monitoring, wearable power supplies, and sensing of environmental conditions as well as the detection of chemical and biological threats.

The major objectives while designing future textiles for military applications will focus on combining high-tech electronics with light weight and comfort in textile garments. Furthermore, the application of nanotechnology in e-textiles can be used to endow soldiers with improved performance, endurance and communication capabilities. In this chapter, various applications of electronic textiles in military are summarised. Electronic textiles not only increase performance, but also add various other functionalities that have never been realised before. In addition, the difficulties

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associated with integrating electronic components in military applications are discussed. Furthermore, the future scope for electronic textiles in military use focuses on the selection criteria and functionalities of fit-for-purpose built electronics to be designed and integrated within military uniforms.

11.2 Applications of e-textiles in military hardware

The base fabrics used for body armour or inner garments worn next to the skin by soldiers can be fitted with integrated electronic, computing, sensors, and communication devices so that the clothing can react automatically to various stimuli from the environment or body. In addition, electric generation devices and analyzing software are being used to make integrated electronic devices fully functional. Different types of applications of e-textiles in military are listed in Table 11.1. Various methods such as weaving, knitting and embroidering can be used for the incorporation of sensors and circuitry into the fabric. For example, the simplest plain-weave structure can include individually addressable insulated metal filaments, which can be used as basic transmission lines or whole circuits. Data collected from sensors may need to be transmitted to a command post wirelessly or by other means. Table 11.2 summarises various types of sensors for military applications that can be embedded into textiles.

11.2.1 E-textiles for sensing the environment

In e-textiles, conductive metal or polymeric fibres need to be embedded in the fabrics to carry the signals, which are created by the sensors that react to various input parameters such as sound, light, movement and chemicals, as well as to certain gases and liquid vapours in the environment. The sensors can be classified as light sensors,

Table 11.1 **Applications of e-textiles in military hardware**

Type of application	Effect	Mechanisms
Monitoring health	Physiological process of human body	Electrocardiography (ECG), electromyography (EMG) and electroencephalography (EEG); sweat and body temperature measurement, and wounds detection.
Locating soldiers	Location identification	Global positioning system (GPS) and wireless devices
Communication	Exchange of information	Wireless and wired devices
Environmental temperature monitoring	Heat and cold stress	Active (e-textiles for cooling) or passive thermal management

Table 11.2 **Different types of sensors for military applications**

Sensor type	Input parameter	Input device	Output signal	Output device	Application
Biometric	Heart rate, body temperature	ECG, EEG	Electrical, mechanical	Digital display	Soldiers' health monitoring
Acoustic	Sound	Microphone, audio recording, speech recognition, ultrasonic detectors	Electrical	Headphones, loudspeaker, piezospeaker, speech synthesis, ultrasonic transmitter	Detection of approaching vehicles, enemies or aircraft
Temperature	Heat and cold	Resistance temperature detectors (RTDs), thermistors	Heat	Thermal devices	Detection of body as well as environmental temperature
Location	X, Y, Z and T collected by satellite	Wi-Fi, Bluetooth, Cell ID, ultrasonic, radio frequency identification (RFID), GPS, ultra-wideband radio	Electrical	Computer screen, digital display	GPS system can be used for detection of the location
Buttons/ touch input	Textile switch, fabric keyboard	Keypad, wristband	Electrical	Digital display	Sending information and biometric data
Optical	Infrared (IR) camera, image recognition, laser rangefinder	Cameras, light sensors	Electrical	Digital display, position display	Detecting the location of gunshots

acoustic sensors, heat sensors, motion sensors, activity recognition sensors, location detection sensors and chemical sensors. Although some of these sensors already are being used by the military for environmental sensing, research and development can improve existing technology and help integrate the remaining types into military applications.

Environmental sensing can also detect the presence of enemies or potential biochemical threats. Appropriate sensors can identify blast situations and report if there are any health risks. The use of conductive woven fabrics with embedded button-sized microphones to detect the sound of remote objects such as approaching vehicles has been reported (Berzowska, 2005; Uttam, 2014). A microcontroller compares and analyses the sound from each microphone to detect the direction of the sound.

11.2.2 E-textiles for soldiers' health monitoring

The incorporation of e-textiles into military uniforms has helped achieve sophisticated functions such as physiological status monitoring, wearable power supplies and electric resistive heating. A soldier should be in good physical condition to optimally perform his or her mission. Health monitoring can help to improve the promptness in provision of medical facilities in the treatment of casualties.

An e-textile-based wearable computer motherboard was developed by Georgia Tech to serve as a flexible information infrastructure platform and to monitor vital body signs such as heart rate, temperature, respiration rate and information about wounds (Park and Jayaraman, 2003). This principle can be extended for soldiers working in combat situations, where information can be collected and transmitted to monitoring equipment or the central control room.

For preparing complex conductive fabrics by weaving, a company named "Intelligent Textiles" has patented a number of techniques. One such example is the military uniform with a wearable computer (Berzowska, 2005). The uniform can be integrated with a fabric keyboard (Figure 11.1). Intelligent Textiles has been working on this

Figure 11.1 Military uniform with wearable computer and keyboard. Adapted from http://www.fastcompany.com/1552679/body-electric-britain-win-hearts-minds-powered-military-uniforms for first and second pictures and from https://www.pinterest.com/ingose/e-textile/ for third picture.

for several years with the British Ministry of Defence (http://www.cientifica.com/category/intelligent-textiles-limited/). Furthermore, the company is currently working with British Aerospace Systems to integrate other next-generation equipment into uniforms. Hence, British military uniforms may soon be getting an upgrade with the incorporation of e-textiles.

Electrophysiological signals such as electrocardiography (ECG), electromyography (EMG) and electroencephalography (EEG) can be received by conductive electrodes embedded in to a fabric, which is placed on top of the skin. Although the capacitive coupling principle can be used for this purpose, the integration of this type of sensor into textiles is difficult, as the dielectric thickness can change at any time with movement, hence changing the output. The following list details some examples of monitoring of various physiological conditions of soldiers.

- Due to high level of activity, soldiers can face dehydration and loss of sodium (Na) in sweat, which can lead to hyper- or hypo-natremia. Sensors can be used to detect dehydration, fatigue and exhaustion of soldiers under combat conditions. Dehydration sensors measure the sodium concentration in the sweat. Each sensor consists of electrodes carrying a host molecule that can selectively trap Na^+ ions. The electrodes are connected to a portable electronic board, which can drive the sensing part and process the signal to convert the electrical information into Na ion concentrations (Marchand et al., 2009).
- The heart rate can be measured by an ECG, and the posture and activity level can be measured by a three-axis accelerometer. In designing heart sensors, good contact with the skin is essential, and interference with the working environment should be as minimum as possible. The electrodes for measuring heart rate could be textile electrodes based on electrical conductive stainless steel yarns integrated into an inner garment. The electrodes can be knitted or woven in a double-face fabric so that the outer part of the electrodes does not contain any conductive yarn and insulates the electrodes from the outside environment (Sahin et al., 2005).
- The principle of measuring respiration based on inductive plethysmography can be incorporated into military uniforms (Cho et al., 2009). The necessary equipment and a wireless body sensor network unit for wireless transmission of data could be comfortably worn around the thorax or abdomen. The amount of oxygen carried by blood cells can be measured by non-invasive techniques involving pulse oximetry (Mendelson and Ochs, 1988). This technique uses an optical sensor placed around a suitable body part.
- A stretchable sensor band consisting of integrated copper wiring can be used to measure the body cross-sectional area by determining the self-inductance of a flexible conductor encircling the body (Cochrane et al., 2007).
- Smart socks with pressure sensors can alert soldiers to put their feet up to lower their blood pressure (Berzowska, 2005).
- Skin temperature can be measured by thermocouples placed under the armpit or in other strategic locations.
- An array of platinum sensors can be integrated into outer garments to monitor the environmental temperature, which can help in controlling the body thermal-regulations.
- A breathing rate sensor based on piezoresistive or piezoelectric principles can be integrated into an inner garment and positioned around the chest. The resistance of the sensor varies as its length and shape changes, even if slightly, due to thoracic and abdominal circumference changes during breathing.

- Similarly, different activities such as walking, running, standing and crawling of soldiers can be measured by accelerometers attached to various locations in clothing. A warning message can be sent when a soldier becomes inactive.
- Data for each group of sensors can be monitored, and the values that are not in the normal expected range could be indicated distinctly to get the attention of command personnel.

Military application of sweat sensors mounted on a printed electronic plaster are currently being investigated by a research cell at the United States Air Force (USAF) (Nelson, 2014). The label mounted on the skin (Figure 11.2) can actively analyse sweat for biological information. This method will provide sweat results directly instead of the current practice of taking blood and examining it in a laboratory.

SmartLife Technology (Anonymous, 2014b) has developed e-textiles by integrating knitted ECG electrodes, respiratory sensors and conductive pathways for interconnection and health monitoring. Sensatext (Anonymous, 2014c) has developed a smart shirt for the US Navy by using different sensing elements to expedite diagnosis and medical intervention for wounded soldiers on the battlefield. The functions of sensing, monitoring and information processing are networked together within a fabric. The protective clothing can detect the penetration of a projectile, monitor the soldier's vital signs and alert medical triage units stationed near the battlefield. A smart shirt is considered a shirt that thinks, measures and/or monitors individual biometric data and provides readouts via a personal digital assistant, voice synthesis or a wristwatch.

When there is a need to achieve elasticity in the fabric containing the sensing elements, core-sheath yarns can be used with Lycra® in the core. Clothing in close contact with the skin should be comfortable, which is a key factor in the acceptance of the clothing. The inner clothing can be prepared from blends of high-performance fibres and cellulosic fibres (cotton/viscose) to provide both comfort and performance.

The outer garments should provide the necessary ballistic protection and could accommodate a different set of sensors and other electronic components, including temperature sensors, accelerometers, a GPS module and a textile antenna. The sensors and electronics needed for monitoring the environment should be fitted into the outer

Figure 11.2 Wearable label for sweat analysis. Image source: www.plusplasticelectronics.com

garment. The outer garment should be designed to protect the sensors from environmental factors (rain, heat and moisture). Furthermore, different components of a sensing system should be fixed into a separate protected fabric layer and avoid affecting the performance of the body armour.

Existing weaving and knitting processes can be used to prepare very large computing systems with integrated sensors, actuators and power supplies. The batteries to power the systems may be held in pockets within fabric. It is ideal that future designs would be developed with the circuit boards and batteries directly woven/knitted into the fabric structure. In the future, appropriate tools should be developed to estimate emotional and psychological stress from physiological measurements (Westerink et al., 2009). The psychological stress can be indicated by EMG measurement systems (Taelman et al., 2007). Heart rate variability is now being used for stress estimation, which in the future could be used for assessment of a soldier's emotional condition.

11.2.3 Early warning systems

One of the most important tasks to be accomplished by the integration of e-textiles into military is early warning. Various systems could be designed to provide early warning of ballistic missile attack, aerial attack or other potential threats. The primary purpose of an early warning system would be to detect potential threats before they reach the targets. This can save the lives of soldiers and civilians or prevent other similar mass-scale devastation, provided that enough warning is given for evasive action to be taken.

Sensors and actuators can be used for the detection and signalling (light, sound, haptic feedback) of threats such as bombs, improvised explosive devices (IEDs), mortars, toxic gases or even unexpected attacks from enemies (Chapman, 2012). The sensors and actuators can be integrated into military uniforms, accessories or vehicles and linked to the warning systems.

The nature of recent threats is shifting from lethal weapons to nuclear, biological and chemical (NBC) attacks. NBC attacks can lead to mass destruction—not only of the people on the battlefield, but also of civilians. Hence, the development of early warning systems that can detect NBC threats is an emerging challenge for future research and development. Sensors need to be designed with sufficient sensitivity and robustness so that they can be integrated not only into textiles, but also into transportation vehicles, buildings, hubs and equipment for use on the battlefield.

Conventional equipment for detecting toxic substances needs careful handling and is expensive. In addition, these items cannot be used for *in situ* and remote sensing. However, optical sensors might be used as wearable technology to provide solutions to these difficulties. Optical sensors are flexible, small and compact in size and can be multiplexed easily. These sensors are not affected by electromagnetic interference and have high sensitivity (Boczkowska and Leonowicz, 2006).

11.2.4 E-textiles for communication

The integration of communication devices into textiles is rapidly increasing in civilian as well as military applications. Developments in both local and wide area networks (WANs) have enabled faster and more accurate data transfer and analysis to be carried out. Technologies such as Wi-Fi, WiMax, Bluetooth, RFID, GPRS, 3G/4G and real-time communications are being incorporated into communication and network systems (McCann and Bryson, 2009). Of the technologies available, the most appropriate one seems to be the Bluetooth, which is the cheapest and the most energy efficient.

Developments in communication devices have occurred in three main areas: personal communication networks (PCNs), WANs and information systems (IS). PCNs are involved with the collection and storage of information provided by sensors and converting the data into signals that can be transferred for analysis. WAN systems deal with the information collected from PCNs and transfer it to remote locations. IS help in the analysis, storage and interpretation of results (Figure 11.3).

Textile antennae can be incorporated into clothing systems for long-distance communication (Salonen and Rahmat-Samii, 2006). They can be directly printed onto a textile substrate or a micro-patch antenna attached to a vest. Depending on the environment, such antennae can operate in the range of 10–100 m. Longer-distance communication can be achieved by improved technology and the use of laptop computers or mobile phones. Very short distance connections can be made by wireless links using induction. Data can also be transferred by Bluetooth modules if the soldiers are located close to a central control facility.

In modern warfare, the importance of individual soldiers as sources of information will increase. New systems and equipment will be designed to enhance a soldier's role as a link in a local surveillance network. There will be increased importance placed on communication between soldiers and other units on the battlefield such as armoured vehicles and unmanned aerial vehicles (Figure 11.4). To cater to all these needs, the personal equipment of a soldier could include head-mounted displays, GPS, digital radio and video cameras. When designing these systems, textile antennae will play a role in optimising the system performance.

Gorman (1990) suggested the concept of integration of a powered exoskeleton into a soldier's battle dress that would augment the load-bearing capability of the soldier. In addition to providing protection from ballistic, chemical and other threats, the exoskeleton would help in communicating with fellow combatants via a personal computer. Although this concept was proposed for DARPA (Defence Advanced Research Projects Agency) funding, no fielded products have been reported.

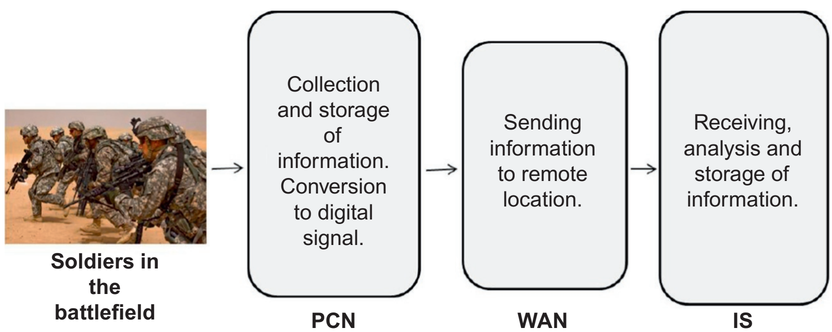

Figure 11.3 Three areas of communication devices for military applications.

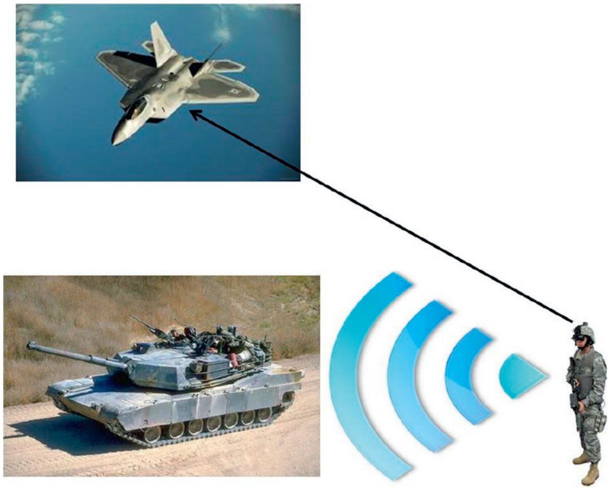

Figure 11.4 Modern soldier as a link in a local surveillance network.

11.2.5 E-textiles for camouflaging

E-textiles can be included in the development of camouflage uniforms with chameleon-like properties. The clothing could change its colour, for example, when a soldier moves from a desert to an urban area. Similarly, the clothing colour could change according to the time of day or other environmental factors. This can be achieved by the integration of e-textiles and shape memory materials. However, much research has not been done in this area.

In the future, military vehicles may be able to change colour on the battlefield using active chemical agents or biological molecules (as found in octopus skin) with the assistance of high-speed electric pulses generated by sensors. This phenomenon could help adapt the colour of the vehicle to its environment. The development in technology can help achieve camouflage by the use of sensor fabrics.

11.2.6 E-textiles for thermal regulation

Appropriate protective clothing can be designed using e-textiles for protection from extremities of hot and cold. Thermocouple-based temperature sensors are available in wire form, which could be integrated into the textiles for thermal regulation.

Military operations in extreme climates could benefit from the integration of active or passive heating or cooling systems into clothing. The integration of traditional electric resistive heating wires or conductive fibres can achieve active heating of uniforms, socks and gloves. The mechanism involves applying a controlled voltage to a series of conductive wires/yarns. Actively heated commercial vests, jackets, boots, socks and gloves are now available. While active heating is possible, necessary provision of a power supply could be an issue, in particular when a soldier needs to carry batteries for heating.

Passive heating can be achieved for a short duration by the use of multiple layers, phase change materials and insulation materials. Active cooling can be used in hot weather. An active cooling vest uses tubing sandwiched between two fabrics. Cold water is circulated through the tubing. A vapour compression cooling unit, powered by batteries or a power supply from a vehicle, is used to cool the water. Such a vest is more energy efficient than a conditioned room. However, integration of this unit increases the weight of the uniform substantially to already overburdened soldiers.

11.2.7 E-textiles for position detection

The sensors used for monitoring the movement and position of soldiers are based on GPS, MEMS (microelectromechanical systems) accelerometers and in some cases gyroscopes. These elements could be placed as small pockets on textiles for wearable applications (Zephyr, 2010). The mounting of these devices on flexible structures needs optimisation for comfort, robustness and proper functioning. The position of soldiers may be detected and displayed by a graphic interface, such as that based on Google Earth software. The boots worn by soldiers can also be fitted with sensors to detect their position and measure their movement.

11.2.8 E-textiles for armoured vehicles

Armoured vehicles are often used under harsh conditions. Hence, general wear and tear can affect the reliability of a vehicle and the systems contained in it. It is essential to regularly monitor vehicle systems for reliability and safe operation during its service life. This is performed by non-destructive evaluation (NDE) techniques based on ultrasonic scanning, shearography, acoustic emission, fibre Bragg grating sensing, infrared thermography and vibration sensing (Scott, 2005).

The recent trend is to develop low-cost techniques to assess the quality and structural health of composite structures in a vehicle, starting from the fabrication of the composite structure to actual service in the field. While NDE techniques are not yet ideal for online monitoring of structural health, investigating the stress–strain history from locally stored data prior to failure can help in understanding the causes of the irreversible damage (Wang and Chung, 2006).

The use of smart e-textiles and structures can provide a solution for online *in situ* monitoring of structural health. The special properties of sensors can be achieved by coating or finishing filament fibres, yarns or fabrics with nanoparticles or conductive and semiconductive polymers (Dharap et al., 2004; Lorussi et al., 2004). Several sensing mechanisms such as nanotube networks, semiconductive coatings and carbon tow can be used for measuring the stress–strain behaviour of composites (Cochrane et al., 2007; Zhang et al., 2006). However, none of these systems have been universally accepted either for the fabrication of intelligent textiles or for structural health monitoring. In particular, carbon nanotube (CNT) based sensors and actuators are being investigated for use in the fabrication of intelligent textiles or for structural health monitoring (Wilusz, 2008). However, several difficulties are associated with their fabrication, involving the controlled growth of CNTs on desired substrates, durability of the sensors and actuators and effective dispersion and orientation in the polymer matrices. Hence, more research is needed for their optimisation and successful use inside mesoscale (tow) or macro-scale (fabric) composites.

Carbon fibre-reinforced composites prepared from carbon tows can be used in sensing networks due to their conductivity. Other conductive fibre-based composites can also be used for this type of application. It is essential to understand the deformation mechanism of the reinforcement before adopting such an approach for structural health monitoring. The efficiency and validity of the sensing mechanism can be affected by any anomaly in the deformation mechanism (Wilusz, 2008).

In the future, armoured vehicles could be better protected against conventional, non-conventional and NATO-certified ammunitions by using adaptable armour. The shape of an armoured vehicle could be made auto-adaptable so that it could change form when threats are detected by sensors. This would enable a vehicle to actively manage mechanical stress and energy absorption during an impact. Different smart active and passive materials could be used to resist various types of ballistic impacts.

Vehicle conditions could be easily monitored by the use of *in situ* fabric-based sensors, which could detect damaged zones and the amount of damage. These e-textiles could help to reduce maintenance costs, minimise downtime and avoid undue personal and material loss on the battlefield.

Furthermore, structural modifications may be achieved using auto-adaptive materials such as shape memory materials including shape memory alloys (SMAs) and shape memory polymers (SMPs). For example, SMAs may be able to change from the martensitic to austenitic phases in iron under different conditions (including mechanical stress and temperature). The main challenges lie in the ability of these materials to be effective against high-speed impacts, as their reaction time may be greater than the blast time.

11.3 Difficulties in designing e-textiles for military use

Several difficulties, such as manufacturing cost, performance, comfort, and functionality of uniforms in selected applications and the power consumption associated with the design of military e-textiles, may be expected. There are other difficulties, such as networking, software execution, maintenance and storage of the uniforms. Some of the major problems are discussed in the following sections.

11.3.1 Design difficulties

The integration of sensors and actuators can increase the functionality of military uniforms. However, this also may lead to a decrease in the real protection for the soldiers from weapons and other related threats. The introduction of sensors and actuators into the military uniforms should not compromise a soldier's capabilities in terms of mobility, survivability, lethality and sustainability. The uniform should maintain its performance, durability, flexibility and comfort.

While designing e-textiles for military use, parameters such as the size of the human body, the type of interior clothing and dynamics of the human body in motion are major design issues. Body size and the interior clothing are static (design time) issues, whereas the body in motion is a dynamic (runtime) issue. A uniform designed for a specific body size may not be appropriate for different body sizes, as the position of sensors and actuators may be displaced. Similarly, uniforms designed to be in direct contact with skin may not work as intended due to the presence of some inner clothing. In addition, body movements might affect the relative positions of the sensors and, hence, their performance.

Design variables such as type and number of sensors, location of conducting materials in the fabric, and the communication network topology may affect the accuracy of sensing, comfort and power consumption, as well as the cost. The level of protection required is also a major factor when designing military uniforms with e-textiles. It is comparatively easier to design uniforms with low levels of protection than high levels. As the protection level increases, the complexity of the structure increases, and hence there may be a long lead time for the design and validation process.

After integrating e-textile devices into military uniforms, the performance properties (e.g. mechanical and electrical) must be evaluated to ensure reliability and stability. Another challenge is to incorporate the sensors and actuators in appropriate and optimal places for maximum performance. Abrasion of textiles can also lead to improper functioning due to deterioration in conductive contacts. The areas where clothing gets a large amount of bending, such as at the elbows and knee joints, can lead to early wear and tear on textiles. During the useful life of a uniform, the fabric will experience a large number of flex cycles. Hence, the fatigue life of the conductive materials and sensors also should be taken into consideration during the design.

The insertion of sensors and actuators into textiles may require modifications to fabric production processes. Similarly, cutting, assembling of the cut components and final finishing processes may need to be altered for these uniforms. Special care is also needed while packaging, transporting and storing the e-textile integrated uniforms for their proper functioning.

The process of miniaturisation (i.e., manufacturing ever-smaller mechanical, optical and electronic components) offers opportunities to include several functionalities in a tiny space. However, comprehensive evaluation is essential for any newly developed e-textiles, due to the complexities involved in integrating the functionalities.

The incorporation of sensors, actuators and other electronic components into military uniforms increases the overall cost of the final products, depending on the number and types of additional functionalities incorporated into the clothing. As the application of e-textiles for military use is still in its infancy, the initial cost involved in the design and development may be high. The cost should be reduced when the technologies become mature and e-textiles are integrated into bulk military items. Furthermore, the increase in cost could become less significant when various life-saving features are added to military clothing.

11.3.2 Energy consumption

E-textiles require sources of energy to keep the systems working. Two areas, namely energy storage and energy scavenging, can be considered to provide solutions to this problem. Energy can be stored by the means of electromechanical or capacitive storage. However, both of these storage methods cannot provide high energy densities. Hence, alternative approaches such as flexible thin electromechanical batteries and capacitive batteries can be used to resolve the problem. No batteries work properly when wet, hence they need to be shielded from water. Lithium polymer batteries can be flexible and are better candidates for textile integration. Rechargeable batteries also can be used with integrated charging systems or wireless power supplies, based on the inductive contactless energy transfer principle. Simultaneous charging of batteries by an inductive link and bidirectional data communication has been demonstrated (Carta et al., 2009). A maximum power of 200 mW can be provided by a power link at up to a maximum distance of 10 cm, and data can be transferred at a rate of 4.8 kbps.

Energy scavenging devices derive power from available sources such as sunlight, wind, and temperature differences. Harvesting a sufficient amount of energy is always a challenge. For solar energy, a sufficient area is needed to capture sunlight. Similarly, in the case of wind power, as the wind speed can change frequently, generating enough energy at slow wind speeds is a real challenge. Thermal energy scavenging needs high temperature differences and large surface areas. Wearable textiles can provide a larger surface area than a handheld device, and higher temperature differences can be achieved due to metabolic heat dissipated from the human body. Films of piezoelectric or thermoelectric material can be printed onto a textile base, which can be used to harvest energy as electric power. Developments in scavenging techniques and improvement in the efficiency of power usage by electronic devices can help improve the duration of power usage.

The Centre for Defence Enterprise (CDE) in the UK has developed a military uniform made with integrated e-textiles that can route power and data through conductive yarns (Rincon, 2012; Robertson, 2012). The manufacturer “Intelligent Textiles” designed the fabric and is now involved in the planning and field-testing of the uniforms. Hence, it is likely that current uniforms soon will be upgraded to more advanced uniforms with more embedded sensors and electronics.

Currently, a combat soldier may carry several different electronic devices powered by a range of battery types. The new uniform designs should be integrated with a single central power source with energy storage, generation and management technologies. This would replace the batteries that soldiers must carry and recharge, and reduce the soldier’s power-related burden. This would allow soldiers to recharge one battery instead of many, and lighten their load. It would also eliminate cables for power transmission. In addition, a centralised power management system could efficiently distribute power to end devices and provide information on power usage and indicative performance throughout a mission.

11.3.3 Comfort

When designing e-textiles for military applications, the comfort of soldiers should never be forgotten. However, the inherent nature of the clothing integrated with electronics to achieve desired levels of protection for soldiers may also affect the degree of comfort. The thickness, type of material used and design aspects of the clothing tend to retain body heat and perspiration inside the garment, which can all lead to heat and moisture build-up and subsequently compromise the body's ability to maintain thermal balance, resulting in discomfort and fatigue. The maintenance of thermal balance is one of the most important aspects of apparels (Nayak et al., 2009; Das and Alagirusamy, 2010). Almost all the high-performance fibres currently used in military fabrics are synthetic, and have poor heat and moisture management capability. Furthermore, the integration of electronic components and sensors tends to make clothing bulkier and increases the overall weight. In addition, electronic components generate heat. All the above factors can lead to thermal discomfort.

Comfort attributes depend on thermal regulation, physical sensation, water regulation, nature of the material (fibre and finishes), design aspects and the fit of the clothing. Although research has been done to improve the comfort attributes of synthetics, the improvements have not met the high standard of requirements for soldiers' uniforms and armour. Hence, future research on the development of smart e-textiles for soldiers should focus on the optimisation of comfort, robustness and proper functionalities.

11.3.3.1 Thermal comfort

The overall thickness of fabrics for ballistic protection must be high to achieve the desired level of performance. In turn, the increased bulk and thickness of body armour reduces the level of thermal comfort. However, the performance of these textiles for ballistic protection is still the essential requirement.

11.3.3.2 Tactile comfort

When integrating electronic components, sensors and actuators into military textiles, care should be taken so that these components do not irritate the skin and produce tactile discomfort. This in turn can affect soldiers' ability to remain focused on their work, or result in rejection of the clothing. Placing the sensors and actuators in appropriate locations can assist in this respect.

11.3.4 Limited mobility

The integration of electronics can make clothing and other military textiles bulkier and stiffer. This in turn can affect the ease of movement of body parts of soldiers, and hence their performance. Care should be taken to incorporate the electronic elements in specific locations of the body, such as the abdomen, upper back or shoulders, depending on the battle conditions and the combat tools to be used during the battle, such that the mobility of body parts is not restricted.

11.3.5 Issues related to maintenance

Military uniforms integrated with e-textiles may not be easy to clean and maintain after wearing (Nayak and Padhye, 2014). Some e-textiles could be detachable for special cleaning and care. However, the use of water or other chemicals for washing and dry-cleaning will pose potential threats to the sensors and actuators integrated into the structures of e-textiles. Even a small breakage in the continuity of a circuit can alter its proper functioning. Hence, advanced methods may need to be developed for e-textile care. Ideally, the integrated electronic components should be able to withstand washing and dry-cleaning. Furthermore, care should also be taken during packing, transportation and storage of these products, as conducting materials, sensors and actuators may be damaged. In addition, ageing of electrical materials could be another issue for the durability and reliability of e-textiles. Special maintenance may be required to ensure they retain optimum performance.

11.4 Future trends

Future military uniforms will be designed with high-tech functionalities by integration of smart e-textiles. The materials and technologies of the past, present and future will be used in military uniforms and other accessories to protect soldiers and military personnel. The main aims in the design and production of military uniforms with e-textiles should be functionality, low cost, long useful life, easy maintenance and durability. Furthermore, compatibility, interoperability, ergonomy and modularity are other important factors to be taken into consideration when designing military uniforms integrated with e-textiles.

The designing of military uniforms is becoming more complex due to the changing nature of risks, which are becoming variable and unpredictable. In addition, when integrating electronics into military textiles with a high level of protection or when protection against multiple risks is needed, the design complexity increases. In the future, military uniforms will need to be designed with high levels of adaptability, so that effective protection can be achieved when needed. Although sensors and actuators are making their way into military uniforms, they should be optimised for size and performance. Advancements in wearable computing and wireless data transfer can facilitate the collection, transmission and analysis of personal health data. Many of the sensor networks will need to be miniaturised and incorporated as small sensors into clothing systems. The sensors and actuators for early warning need to be miniaturised and integrated into the clothing or accessories of soldiers. In addition, the use of modelling and simulation can help in predicting the performance properties of the military textiles integrated with electronic devices (Nayak and Padhye, 2011). The development of suitable algorithms will be required for data acquisition and transmission, as well as processing the recorded information and extracting key results for decision making. Hence, future research will focus on the miniaturisation of these components with improved functionality.

Current communication systems are based mainly on wired e-textiles, but wireless systems are gradually being introduced. The power to these e-textile devices is provided mainly by rechargeable batteries, which can require recharging at intervals from several hours to a few days. Technological advancements in battery design and advanced devices with lower power consumption can help achieve extended battery life. At present, wired devices consume less power than wireless devices (Jones et al., 2003). However, in the future, wireless systems could become more energy efficient, and energy consumption may be reduced. Higher energy efficiency will help in the long running of electronic components. The durability of wired e-textiles is also a concern, as normal wear and tear can result in breakage or shorting of wires in the fabric. This can result in improper functioning or may end the useful life of the e-textiles. Improving the wear-and-tear resistance and making them wash-proof and easy to maintain are also some of the challenging tasks that need to be taken care of in future designs.

The ultimate goal when designing futuristic combat suits will be combining high-tech capabilities with light weight and comfort. Research in textiles, communications and health care is needed to improve the performance of military uniforms by integrating nanotechnology, biosensors, micro-systems and mobile telecommunication. The data obtained from physiological measurements can be used in the future for estimating the emotional and psychological state of the soldiers. The soldiers suffering from problems can be withdrawn for rest or given suitable advice to overcome the problems.

11.5 Conclusion

The application of electronic textiles to military systems is still in its infancy. Intensive research and development are needed for mass applications with a range of functionalities as well as for ballistic protection. The new generation of military textiles will need skilful amalgamation of textiles, electronics and computing. As the functionality of military uniforms increases with the integration of electronics, smarter power supplies will be needed to keep them operational. The challenges involved are not only in the production processes, but also in maintaining the integrity of the e-textile structures during use to withstand laundering, bending and flexing. It has been shown that the use of protective textiles with multiple functionalities can reduce the awareness and ability of soldiers to perceive various dangers, which may lead to more risks than can be justified by the acquired benefits. Hence, when designing uniforms and other similar tools for the military by the integration of e-textiles, care should be taken so that these items do not impair the cognitive performance of soldiers, rather, they should improve it.

11.6 Sources of further information

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b. Centre for Advanced Materials, School of Fashion and Textiles, RMIT University, Australia (http://rmit.edu.au/).
c. National Textile Center, USA (www.ntcresearch.org).
d. The US Army Natick Soldier Research, Development and Engineering Center, USA (http://nsrdec.natick.army.mil/).
e. Nanoscience and Nanotechnology Initiative, National University of Singapore, Singapore (www.nusnni.nus.edu.sg/).

f. Materials Science and Engineering Division of CSIRO, Australia (http://www.csiro.au/en/Organisation-Structure/Divisions/CMSE/Index.aspx).
g. School of Materials, University of Manchester, UK (www.materials.manchester.ac.uk/).
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i. McCann, J. and D. Bryson, *Smart Clothes and Wearable Technology*. 2009: Woodhead Publishing (UK).

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