1
Introduction

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1.1 Overview

Revolutionary changes have been occurring at an unprecedented rate in many fields of science and technology. The invention of electronic chips, computers, the internet, wireless communication, the discovery and complete mapping of the human genome, rapid advancements in nanotechnology, and many other developments, have transformed the entire world and affected nearly every human being on this planet. Looking ahead, the future promises even more. The technology of the future will have new features such as terascale, nanoscale, complexity, cognition and holism. The new capability of terascale takes us three orders of magnitude beyond the present general purpose and generally accessible computing capabilities. In a very short time, we will be connecting millions of systems and billions of information appliances to the internet. Technologies will develop to an incredible speed of over one trillion (1×10^9) operations per second. The technology in nanoscales will take us three orders of magnitude below the size of most of today's human-made devices. It will allow us to arrange atoms and molecules inexpensively in most of the ways permitted by physical laws. It will let us make supercomputers that fit on the head of a fibre; impart sensing and actuating mechanisms in micrometre- or nano-structures; allow wireless communication between devices, our body and environments; and make fashionable, intelligent clothing with built-in electronic and photonic functions.

The classical definition of electronics and photonics is the science and technology related to the generation, transmission, modulation and detection of electrons and photons, respectively. A wearable is a device that has the above functions, is always attached to a person and is comfortable and easy to keep and use. In other words, it is apparel with unobtrusively built-in electronic and photonic functions.

Wearable electronic and photonics have evolved from continuous technological advancements. An example is the evolution of a timing device. The carriage clock of three hundred years ago became a pocket watch and then a wristwatch. Now, personal electronic and photonic devices have been built into items that can be worn as jewellery and accessories. A recent development is the 'wrist camera watch'. This wearable digital camera is able to capture grey-scale photos anytime and store up to 100 pictures, view them instantly, or upload them to any computer via infrared red transmission. Another case is 'the wrist-type MP3 player', which can store and play up to 66 minutes of songs in MP3 (MPEG audio layer 3 or motion picture experts group audio layer 3) format downloaded from a computer using a universal serial bus (USB) connection. One more example is 'on hand PC', containing a 16-bit 3.6 MHz central processing unit (CPU) and 30 different built-in applications such as an address book, calculator, sound player and even games.

The first commercial range of wearable electronics apparel ICD+ was released in 2000 by Industrial Clothing Design Plus. It was co-produced by Philips NV and Levis Strauss with the collaboration of the designer Massimo Osti. One particular jacket design consists of ear gear and a microphone integrated into the collar with a simple 'body area network' made up of wires integrated into the design of the jacket. The jacket is also integrated with a global service mobile (GSM) phone and an MP3 player, which are operated using unified remote control. A book by Koninklijke Philips NV (2000) illustrates many such design concepts.

The examples mentioned above use quite simple and conventional technology but represent a step towards the incorporation of electronics into wearable items. There are at least three levels of sophistication in wearable technology: block-based technology, which connects all available devices and adds them to clothing as detachables; embedded technology, which is integrated into clothing by micro-electronic packaging technology; fibre-based technology, which are all devices in the form of fibres or fabrics. These examples belong to the first group of block-based systems.

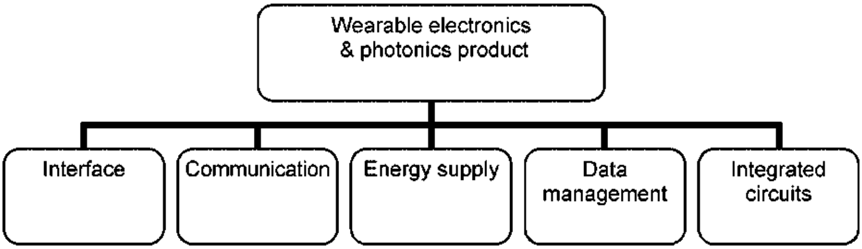
Four years have passed since the introduction of the first commercial product in 2000. There are not many successful commercial products currently in the market. One of the major reasons for this is that most currently available technologies and materials are simply not suitable for commercial products. Electronics companies, together with university research laboratories, have devoted a great deal of effort and funding to developing the technological foundations for wearable electronics and photonics. It is the intention of the author of this chapter to provide an overview of various existing and emerging technologies for wearable electronics and photonics.

1.2 Current and future wearable technology

A typical system architecture design of a wearable electronic/photonic product is shown in Fig. 1.1. It comprises at least several basic functions: interface, communication, data management, energy management and integrated circuits.

1.2.1 Interface technologies

Devices such as sensors are often used to obtain information, for instance,



1.1 General system configuration of a typical wearable electronics and photonics product.

environmental sensors, physiological function sensors, antennae, global-positioning-systems receivers, cameras and sound sensors. The information needs to be processed somehow by the wearer. An interface is a suitable medium for transacting information between devices and the wearer as well as between the wearer and outside world.

Input interface

A wearer may input information to the devices, for example, to control which sensor to use. The most common input interface for this purpose involves buttons or keyboards because simple button interfaces are easy to learn, implement and use with few errors. As the complexity of wearable electronic devices increases, however, the need for more complex interfaces arises. Another input interface is voice recognition and writing pads. However, current technology has a number of drawbacks. First, the influence of background noise is so large that incorrect information may be processed. In addition current technology requires more processing power than previous technologies. Furthermore, current technology has difficulty recognising and distinguishing between different people's voices.

Fabric-based interface devices are very attractive for use in wearable electronics and photonics. Keyboards and buttons have been made from either multilayered woven circuits or polymer systems. Fabric-based sensors made from conductive fabrics or fibre optics have been used to measure movement and temperature. By designing appropriate fabric structures, various fabric electrodes and antennas have been successfully developed and applied to a few commercial products.

Output interface

Wearable devices have output interfaces by which information is presented to the wearer. Vibration (tactile) interfaces have been used. An example of this is the vibration function in mobile phones, by which the user is silently alerted to an incoming call. Many portable devices use audio interfaces. In both cases, the amount of information given is quite small. Voice synthesis (the opposite of voice recognition) via earphones is an alternative, as the wearer does not need to decode the message and can understand it directly. A third category of output interface is the visual interface. These include, for instance, seven-segment or dot matrix displays, liquid crystal displays (LCDs), organic and polymeric light-emitting diodes (OLEDs and PLEDs), and fibre optic displays (FODs). The displays may take two forms: wearable flat panel displays or head-mounted displays.

The main display technology used in portable electronics today is the LCD screen. It is neither flexible nor lightweight. Moreover, it can be bulky and its angle visibility is poor. Holographic polymer dispersed liquid crystals (HPDLCs) are still in their infancy; however, they may offer better performance in terms of flexibility. Polymer light-emitting diodes (PLEDs) are very promising candidates for future wearables, as they have high contrast, a high level of brightness, require much less power and are flexible. Flexible displays based on polymeric fibre optics are also being investigated by a number of researchers.

Electroactive polymer actuators take the form of fibres, yarns and structures based on thin film. They are used as artificial muscles for robotics. According to their actuating mechanisms, they can be broadly divided into two groups: electronic and ionic. The electronic polymers include electrostrictive, electrostatic, piezoelectric and ferroelectric polymers. They can hold induced displacement when a DC (direct current) voltage is applied and have a high level of energy density in air. However, a high activation field greater than 150 V μm^{-1} is required. Ionic polymeric materials include polymer metal composites, conducting polymers and polymer–carbon–nanotube composites. They normally perform actuation in a solution and have a low activation voltage of 1–5 V μm^{-1}. All of these actuators have limitations for use in wearable devices. A promising new technology is based on the dielectric elastomer, which is activated with low voltage in the air and is very robust and flexible. Books by Tao (2001) and Bar-Cohen (2001) provide very comprehensive accounts of dialectric elastomers.

1.2.2 Communication technologies

Communication refers to the transfer of information. This can be between two wearable devices on the user (short-range communications) or between two users via the internet or a network protocol (long-range communications).

Long-range communications

The technologies have been well developed in the mobile phone revolution. Portable devices such mobile phones or personal digital assistants (PDAs) have always used radio frequencies to enable communication. This is understandable, since it is just not viable to have long wires or optical links. A variety of communication systems are already available, the main one being GSM. While this system is presently very suitable for voice transmission, a substantial amount of research has recently been undertaken on allowing data to be transmitted (requiring a greater bit rate) through this system. GSM generally allows files or data to be transmitted and faxes to be sent at 9.6 kbps. Third-generation (3G) wireless systems are now being commercialised. They are capable of handling services of up to 384 kbps, sufficient to transfer pictures and videos. If the transmission of voice or low-content information is required, the present GSM system is sufficient.

Short-range communications

This is the area that particularly needs to be developed, since the techniques that are presently available are not adequate. Several approaches have been considered, including embedded wiring, infrared, Bluetooth technology and personal area network (PAN).

Embedded wiring is very cumbersome and constrictive to the user. Infrared, as used on remote controls, requires direct lines of sight to be effective but this would be difficult or impractical for devices located inside wallets, purses and pockets. Bluetooth technology is a newly developed technology. It is a new standard that will allow any sort of electronic equipment – for instance, from computers and cell phones to keyboards and headphones – to make its own connections without wires, cables, or any direct action from the user. Bluetooth components may interact without help from the user and are wireless. Another important advantage is their ability to minimise interference by sending very weak signals (limiting their range to about 10 m) and using a technique called spread spectrum hopping.

Personal area network or PAN was first developed by the MIT Media Lab in collaboration with IBM. This technology turns the human body into a network, taking advantage of the natural salinity of the human body, which makes it an excellent conductor of electrical current. PAN has a data transmission rate of 2400-bauds, sufficient to carry identification, financial or medical information but not good enough for audio or video information. A PAN rejects interference very well because it is mostly limited to transmission through the human body. However, touching a person equipped with a PAN is like tapping a phone line, i.e. security is a problem.

1.2.3 Data management technologies

The storing and processing of data are topics relating to the management of data. In wearable electronics and photonics, the storing of data is a problem that requires special attention. Storage technologies are used to keep information such as music, pictures or data banks. The following three storage technologies are the most commonly used. First are magnetic storage systems, from music tapes to hard disk drives, which are the most common form of storing information. This is due to their low cost and ease of use, and to their long MTBF (mean time before failure) of over

10 years. The second group consists of optical storage systems, which use a laser beam and optoelectronic sensors to read and store data. This technology has been the backbone of data storage for nearly two decades, with compact discs (CDs) (which are now rewritable using magneto-optic technology), and also digital versatile discs (DVDs) as the primary methods of storing data for music, software, personal computing and videos. The third are solid-state storage (flash memory storage) systems, the most recent medium of storage, which makes use of an EEPROM (electrically erasable programmable read-only memory) chip. Solid-state means that there are no moving parts – everything is electronic instead of mechanical. Their robustness, small size, weight and low power consumption make them well suited for application in wearable electronics.

Much research on more advanced means of storing information is based on magnetic and optic media. For instance, IBM manufactures a 1 GB (giga byte) magnetic drive as small as a compact flash card, but much cheaper. Optical storage using holographic memory can reach one terabyte (TB) of data in a sugar-cube-sized crystal, more than can be contained in 1000 CDs, while CDs and DVDs only make use of the surface area of the recording medium. Success in this kind of research would help spur growth in the wearable industry and the cost of producing wearable devices would fall.

1.2.4 Energy management technologies

The power supply for wearable electronics and photonics must be light and discreet, to be capable of being incorporated into clothing. Such a supply must be either long lasting or easy to recharge on the move. It should be robust enough to endure wearing and caring conditions. At present, batteries in the form of standard AA batteries or lithium batteries are the most common type of power source. Unless current levels of power consumption by electronic devices are reduced phenomenally or battery energy density increases drastically, other sources of power are likely to be required for wearable electronics and photonics.

A potential alternative lies in the ongoing miniaturisation of fuel cell technology. The smallest fuel cell so far has been developed by Toshiba and a team from MIT. It uses methanol, and is less than 2 inches (5 cm) long and weighs a fraction of an ounce. Similar to batteries, fuel cells generate electrical power by converting the chemical energy of a given type of fuel (e.g. hydrogen and oxygen) into electrical energy. However, fuel cells have far longer lives than conventional batteries of a similar size since oxygen does not need to be stored and only hydrogen is stored in metal hydrides or methanol. Recharging refills the fuel cells with hydrogen or methanol.

Another alternative is to harvest a small fraction of the kinetic energy from human movement. The kinetic Seiko watch has a miniature electric generator that is driven by arm movements, as well as a capacitor to store some charge so that the watch will run for intervals when the watch is stationary. Piezoelectric inserts in a shoe can harness walking power. Piezoelectric materials, such as PVDF (polyvinylidene fluoride), create an electrical charge when mechanically stressed. The deformation of the shoe during walking provides the necessary compression to generate power from piezoelectric piles. Apart from generating electricity, storage devices may be needed if the supply of kinetic power is used in electrical storage devices such as capacitors or in mechanical storage devices such as flywheels, pneumatic pumps or clock springs.

Other forms of power supply have been considered and investigated. Photovoltaic cells harvest the energy of the sun and semiconductor thermal couples generate electricity from the difference in temperature between the human body and the environment. These technologies have yet to produce sufficient power for wearable electronics. Alternatively, power may be transmitted to wearable devices remotely via microwaves, an area on which much research is being performed today. The greatest advantage of such an approach is that there would be a constant supply of power without the need for recharging.

1.2.5 Integrated circuits

Nowadays, most integrated circuits are made with silicon because of its superior semiconductor properties. Current chip fabrication processes exert limitations on the size of the chips or on the number of transistors on a chip. It has been speculated that a solution may lie in molecular electronics superseding silicon in the future. Molecular electronics employs devices based on a single molecule or single molecular wires to process signals and information. Molecules have the capability to conduct and transfer energy between one another and act like switches. If this process can somehow be manipulated and controlled, it would be possible to have these molecules and molecular structures perform tasks such as encoding, manipulating and storing information.

An important drawback is that silicon is not flexible. In contrast, conductive or semi-conductive polymeric materials are flexible, lightweight, strong and have a low production cost. These properties make them perfect for wearable electronics. The electronic properties of the conducting polymers may not match those of extremely pure and monocrystalline silicon. The polymeric chip would not be competing with the conventional silicon chip (at least not in the immediate future), but rather complementing it. At present, properties such as the switching speed and durability of the silicon chip are far superior to those of the polymeric chip, but the latter has the advantages of low price and flexibility (the ability to be folded double without affecting performance).

Wearable electronic devices might be incorporated into clothing, but still need to be connected together on the garment where the devices are allocated. A number of conductive fabrics have been made by using intrinsically conductive fibres or yarns. This allows the yarn to be sewn or embroidered with industrial machinery. Individual strands of yarns can be addressed so that a strip of this fabric can function like a ribbon cable. These fabrics have notable characteristics, including high conductivity, high tensile strength and good thermal stability.

1.3 Applications of wearable electronics and photonics

In the past few decades, many desk electronic appliances have been made portable because of constant miniaturisation in electronics. It is reasonable to assume that, in the future, some of these portable devices will become so small and convenient to carry that they will be wearable. Applications of the technology will be widespread and far reaching.

1.3.1 Information and communications

An evolution in lifestyles in recent years has led to increased mobility and, at the same time, a strong desire for instant access to information and communications. The tendency is towards ease of use/comfort: people want devices that are more unobtrusive and less inconvenient to use. A friendly and comfortable wearable computer or a wearable mobile phone integrated into some form of apparel will have a market if it is priced at an affordable level.

1.3.2 Health care and medical applications

In affluent societies, people are becoming increasingly health conscious. Meanwhile, the ageing of the population in many developed societies is bringing a heavy burden to bear on medical, especially hospital, systems as well as government budgets. Wearable electronics may provide personal systems for having our physiological status monitored. If necessary, medical advice can be given or treatment administrated anywhere, not just in a hospital, thereby leading to more mobility as well as to more efficient and effective health services.

Some noticeable examples can illustrate the applications. The Wearable Cardioverter Defibrillator by LifeCor Inc. has a chest harness and a hip pack, which provides immediate emergency medical aid to people prone to heart attacks. As soon as electrodes of the defibrillator sense the irregular beating of the heart, an audio warning is given before electricity is discharged. Then, the nearest hospital is notified. Another example is a wearable artificial kidney, which serves as a haemodialyser but has the advantage of being able to be fitted around the neck. In a form of undergarment, the wearable motherboard by Georgia Tech has sensors that are detachable so that they can be positioned at the right locations for users of different sizes. Such sensors can be used to monitor vital body signs (such as the heartbeat, respiration rate or temperature) of patients recovering from specific illnesses or to monitor patients at home rather than in a hospital. The Wearable Polysomnograph by Advanced Medical Corporation is a wearable ECG (electrocardiograph), which allows patients to be monitored at home with data being sent to a hospital via an internet connection.

Many people live their lives with a physical handicap, such as the loss of a sense like vision and hearing, or a loss of mobility in one part of their body or in all of it. Some future wearable electronic devices could help alleviate the suffering of such people. For example, wearable devices equipped with artificial muscles can be deployed to help limbs and arms become more mobile. Personal guidance systems are being developed to help the blind use the global positioning system (GPS) and the computer's geographical information system (GIS) to keep track of locations with the aid of a highly detailed map. Cochlear implants are being developed to help the deaf replace the lost functionality of damaged or missing hair cells by sending signals to the intact underlying nerve structure.

1.3.3 Fashion, leisure and home applications

Wearable electronics has a very exciting but challenging market in this sector as wearable and fashionable clothes must make people want to wear them and to feel good when they do wear them.

The Philips/Levis ICD+ can be viewed as the first generation of smart clothing because they integrate mobile phones and music players, which try to enhance the 'organizer' functions of clothes. Until now, the closest wearable mobile communications has been Ericsson's Bluetooth headset. Nokia's prototype of the mobile snow jacket is an attempt to have devices such as the mobile phone fully incorporated within clothing. France Telecom has developed a phone coat equipped with an extra-flat (100 g) mobile telephone integrated in its lining. The keypad is placed on the sleeve of the jacket and a microphone is discretely placed on the collar. Infleon's MP3 jacket is an application in the area of infotainment, a combination of information and entertainment.

Cloth has always acted as an interface between the body and the external world. Wearables are no exception. They offer ample opportunities for the creation of intelligent clothing that perform functions according to the body's needs and requirements, and that adapts to the environment. Some of the functions are described as follows. Intelligent clothes can give reminders to people, identifying and memorising different objects to take with them, such as keys and wallets. They may perform temperature feedback and control mechanisms in a smart jacket, adjusting its interior temperature accordingly. Wearable medical devices can be integrated into a biosensor layer to monitor body conditions such as heartbeat, blood pressure and temperature. Another function is called the Virtual Doctor, which would assess and give advice on the overall health of the individual. In the future, such clothing may detect the user's feelings, moods, aches and pains, and so forth by monitoring brain activity and changing its colour, pattern, shape, and even its smell. However, fashion items worn by ordinary consumers require a high standard of quality and easy care. They should be washable in addition to being flexible and robust, and ideally foolproof. This is a real challenge to most electronic devices today.

1.3.4 Military and industrial applications

This is a very promising market where earlier penetration of the technology is expected to take place. In combat, soldiers must use their hands at all times to control weapons and machinery. Wearable devices to assist them would be very useful. The soldiers may be connected to navigation systems via wearable computers to guide them through difficult terrain and unknown areas. The systems may also let them know the positions of enemy and allied soldiers using satellite systems. Soldiers would also be in constant touch with their superiors. Others in nearby areas can be notified if a soldier falls down. Soldiers can look up on a stored database of information how to fix any damaged equipment and even how to apply first aid to injured soldiers. Other people, such miners and mountaineers, may need navigation and detection systems to guide them in avoiding dangerous areas and reaching safety.

Wearable electronic and photonics are likely to be expensive, initially only affordable by the military and by industrial sectors where performance is in great demand. The high costs of wearable technology could easily be outweighed by its efficiency and by the competitive edge it gives the user.

1.4 Implications of wearable technology

1.4.1 Economic impact

Wearable technology opens a door to many exciting applications and may lead to another technological revolution similar to the internet and mobile communication industries. The potential economic impact is enormous. It could lead to great opportunities for both the electronics and fashion/textile industries, each of which represents approximately 450 billion US dollars in world trade. The Venture Development Corporation estimated in 2003 that global market volume for smart fabrics and intelligent clothing, which includes wearable electronics and photonics, will reach 720 million US dollars in 2008, for an impressive annual growth rate of 18.8% between 2003 and 2008. The detailed estimation is given in Table 1.1.

1.4.2 Social and cultural factors

We are living in an exciting era and are feeling the great impact of technological advancement. In the past, the inventions of paper and the computer had profound influence on our society and culture, as well as on our lifestyle. It is expected that wearable technology will exert more influences in addition to those already made by portable electronic devices. Will social interaction increase or decrease when

Table 1.1 Market estimation for smart fabrics and intelligent clothing (Venture Development Corporation, 2003)

Market	$US × 1000		
	2003	2008	Annual increase rate (%)
Consumer sector	122 205	251 691	15.5
Professional and industrial sectors	150 884	388 086	20.8
Government	30 751	80 223	21.1
Total	303 840	720 000	18.8

most people possess clothing with wearable electronics and photonics? This may reduce the time to collect and communicate information, thus leaving more time for leisure and a social life.

The boundaries between science and engineering, which have traditionally been separate and distinct fields, have become blurred and the results of multidisciplinary and interdisciplinary research have been astonishing. Wearable electronics and photonics represent some of these results. This will have a profound influence on the future development of education and research. In the future, children may need to depend less on such abilities as reading and writing, if they are to be brought up in an environment where multimedia communication is made much easier for them. Meanwhile they may develop other abilities. Classes of the future may not take the present form, as people can learn things *in situ* with the aid of wearable computers and databases. The evidence indicates that face-to-face interactions reduce the levels of hormones involved in producing stress, fear and worry and increase levels of trust, bonding, attention and pleasure hormones. Hence, the technology of wearable electronics can be developed in such a way as to promote such face-to-face interactions, for instance, videophones.

In the future, people may not have as much privacy as they have today, as long as the problem of network security remains unsolved. A real threat is that people equipped with wearable electronics can outsmart other people who do not have such devices. What would happen if such technology falls into the wrong hands? A self-destructive trigger may provide some safeguard.

1.4.3 Health issues

The widespread use of mobile phones has led to a substantial amount of public concern over the possible adverse effects of electromagnetic waves on human brains. Many surveys and studies have been carried out, but no evidence has been found to support the view that mobile phones are harmful to human brains. Nevertheless, in order to avoid this possible hazard, new technologies employ an intelligent antenna to cut radiation by continually adjusting its characteristics to ensure that the power transmitted and received by mobile phones is directed away from the brain.

Another issue is the interference to normal operations of the human body by the wearable electronic devices. Humans have attained their current anatomy through a long process of natural evolution spanning tens of thousands of years. Current wearable computers need a head-mounted display as an output interface. Because the wearer's eyes always focus on the same spot on the screen, he/she may feel dizzy. Due attention will be paid to the biological and physiological aspects of humans when designing wearable products.

1.5 References

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