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Adaptive and responsive textile structures (ARTS)

SUNGMEE PARK AND
SUNDARESAN JAYARAMAN*

13.1 Introduction

The field of textiles has been instrumental in bringing about one of the most significant technological advancements known to human beings, i.e. the birth of the computer, which spawned the information/knowledge revolution being witnessed today. It is only appropriate that this field take the next evolutionary step towards integrating textiles and computing, by designing and producing intelligent textiles that can adapt and respond to the wearer's needs and the environment. In this chapter, we discuss the need for the new generation of adaptive and responsive textile structures (ARTS) and present the design and development of the Georgia Tech Wearable Motherboard™ (GTWM), the first generation of ARTS. We will discuss the universal characteristics of the interface pioneered by the GTWM, or the smart shirt, and explore the potential applications of the technology in areas ranging from medical monitoring to wearable information processing systems. We will conclude the chapter with a discussion of the research avenues that this new paradigm spawns for a multidisciplinary effort involving the convergence of several technical areas – sensor technologies, textiles, materials, optics and communication – that can not only lead to a rich body of new knowledge but, in doing so, enhance the quality of human life.

13.2 Textiles and computing: the symbiotic relationship

John Kay's invention of the flying shuttle in 1733 sparked off the first Industrial Revolution, which led to the transformation of industry and subsequently of civilization itself. Yet another invention in the field of textiles – the Jacquard head by Joseph Marie Jacquard (*ca.* 1801) – was the first binary information processor. Ada Lovelace, the benefactor for Charles Babbage who worked on the analytical engine (the predecessor to the modern day

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* To whom correspondence should be addressed.

computer), is said to have remarked, 'The analytical engine weaves algebraic patterns just as the Jacquard loom weaves flowers and leaves.' Thus, the Jacquard mechanism that inspired Babbage and spawned the Hollerith punched card has been instrumental in bringing about one of the most profound technological advancements known to humans, viz. the second Industrial Revolution, also known as the Information Processing Revolution or the Computer Revolution.[1]

13.2.1 The three dimensions of clothing and wearable information infrastructure

Humans are used to wearing clothes from the day they are born and, in general, no special 'training' is required to wear them, i.e. to use the interface. It is probably the most universal of human–computer interfaces and is one that humans need, use and are very familiar with, and that can be enjoyed and customized.[2] Moreover, humans enjoy clothing, and this universal interface of clothing can be 'tailored' to fit the individual's preferences, needs and tastes, including body dimensions, budgets, occasions and moods. It can also be designed to accommodate the constraints imposed by the ambient environment in which the user interacts, i.e. different climates. In addition to these two dimensions of functionality and aesthetics, if 'intelligence' can be embedded or integrated into clothing as a third dimension, it would lead to the realization of clothing as a personalized wearable information infrastructure.

13.2.2 Textiles and information processing

A well-designed information processing system should facilitate the access of information Anytime, Anyplace, by Anyone – the three As. The 'ultimate' information processing system should not only provide for large bandwidths, but also have the ability to see, feel, think and act. In other words, the system should be totally 'customizable' and be 'in-sync' with the human. Clothing is probably the only element that is 'always there' and in complete harmony with the individual (at least in a civilized society!). And textiles provide the ultimate flexibility in system design by virtue of the broad range of fibres, yarns, fabrics and manufacturing techniques that can be deployed to create products for desired end-use applications. Therefore, there is a need for research in textiles that would result in a piece of clothing that can serve as a true information processing device, with the ability to sense, feel, think and act based on the wearer's stimuli and the operational environment. Such an endeavour can facilitate personalized mobile information processing (PMIP) and give new meaning to the term man–machine symbiosis. The first step in creating such an intelligent or adaptive and responsive textile structure (ARTS) has been taken with the design and development of the Georgia Tech Wearable Motherboard™, also known as the smart shirt.[3]

13.3 The Georgia Tech Wearable Motherboard™

In the spring of 1996, the US Navy Department put out a broad agency announcement inviting white (concept) papers to create a system for the soldier that was capable of alerting the medical triage unit (stationed near the battlefield) when a soldier was shot, along with some information on the soldier's condition characterizing the extent of injury. As such, this announcement was very broad in the definition of the requirements, and specified the following two key broad objectives of the so-called sensate liner:

- Detect the penetration of a projectile, e.g. bullets and shrapnel
- Monitor the soldier's vital signs.

The vital signs would be transmitted to the triage unit by interfacing the sensate liner with a personal status monitor developed by the US Defense Advanced Projects Research Agency (DARPA).

13.3.1 The name 'Wearable Motherboard'

As the research progressed, new vistas emerged for the deployment of the resulting technology, including civilian medical applications and the new paradigm of personalized information processing using the flexible information infrastructure. Therefore, we coined the name Wearable Motherboard™ to better reflect the breadth and depth of the conceptual advancement resulting from the research. Just as chips and other devices can be plugged into a computer motherboard, sensors and other information processing devices can be plugged into the sensate liners produced during the course of the research. Therefore, the name Wearable Motherboard is apt for the flexible, wearable and comfortable sensate liners. The name also represents (1) a natural evolution of the earlier names sensate liner and woven motherboard, (2) the expansion of the initial scope and capability of a sensate liner targeted for combat casualty care to a much broader concept and spectrum of applications and capabilities – much like a platform to build upon, and (3) the symbiotic relationship between textiles and computing that began with the Jacquard weaving machine.

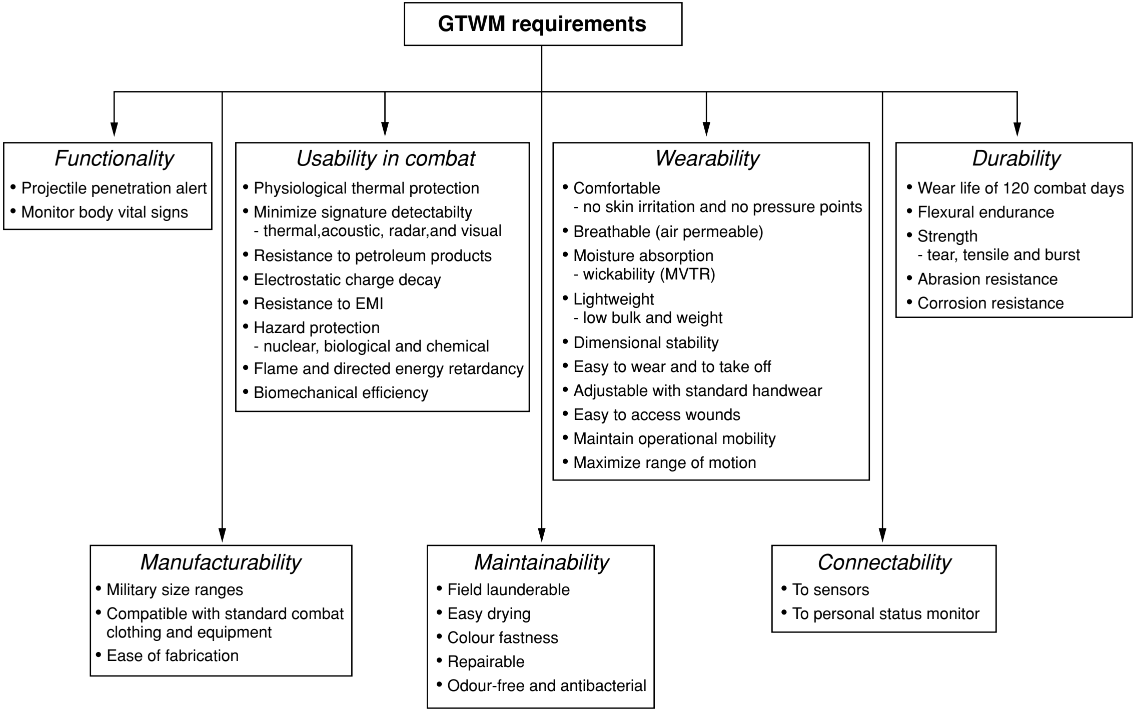
13.3.2 Detailed analysis of the key performance requirements

Quality function deployment (QFD) is a structured process that uses a visual language and a set of inter-linked engineering and management charts to transform customer requirements into design, production and manufacturing process characteristics.[4] The result is a systems engineering process that prioritizes and links the product development process to the design so that it assures product quality as defined by the customer. Additional power is derived when QFD is used within a concurrent engineering environment. Therefore, the QFD approach was adopted for the research that also served as an example of integrated product/process design (IP/PD) or concurrent engineering.

The first step in this QFD process is to clearly identify the various characteristics required by the customer (the US Navy, in this research) in the product being designed.[5,6] Therefore, using this information on the two key performance requirements, an extensive analysis was carried out. A detailed and more specific set of performance requirements was defined with the result shown in Fig. 13.1. These requirements are functionality, usability in combat, wearability, durability, manufacturability, maintainability, connectability and affordability. The next step was to examine these requirements in depth and to identify the key factors associated with each of them. These are also shown in the figure. For example, functionality implies that the GTWM must be able to detect the penetration of a projectile and should also monitor body vital signs – these are the two requirements identified in the broad agency announcement from the Navy.

Likewise, as shown in the figure, wearability implies that the GTWM should be lightweight, breathable, comfortable (form-fitting), easy to wear and take off, and provide easy access to wounds. These are critical requirements in combat conditions, so that the protective garment does not hamper the soldier's performance. The durability of the GTWM is represented in terms of a wear life of 120 combat days and its ability to withstand repeated flexure and abrasion – both of which are characteristic of combat conditions. Manufacturability is another key requirement, since the design (garment) should eventually be produced in large quantities over the size range for the soldiers; moreover, it should be compatible with standard issue clothing and equipment. The maintainability of the GTWM is an important requirement for the hygiene of the soldiers in combat conditions; it should withstand field laundering, should dry easily and be easily repairable (for minor damages). The developed GTWM should be easily connectable to sensors and the personal status monitor (PSM) on the soldier. Finally, the affordability of the proposed GTWM is another major requirement, so that the garment can be made widely available to all combat soldiers to help ensure their personal survival, thereby directly contributing to the military mission as force enhancers.

Thus, in the first step of the conceptual design process, the broad performance requirements were translated into a larger set of clearly defined functions along with the associated factors (Fig. 13.1).



13.1 GTWM: performance requirements.

13.3.3 The GTWM design and development framework

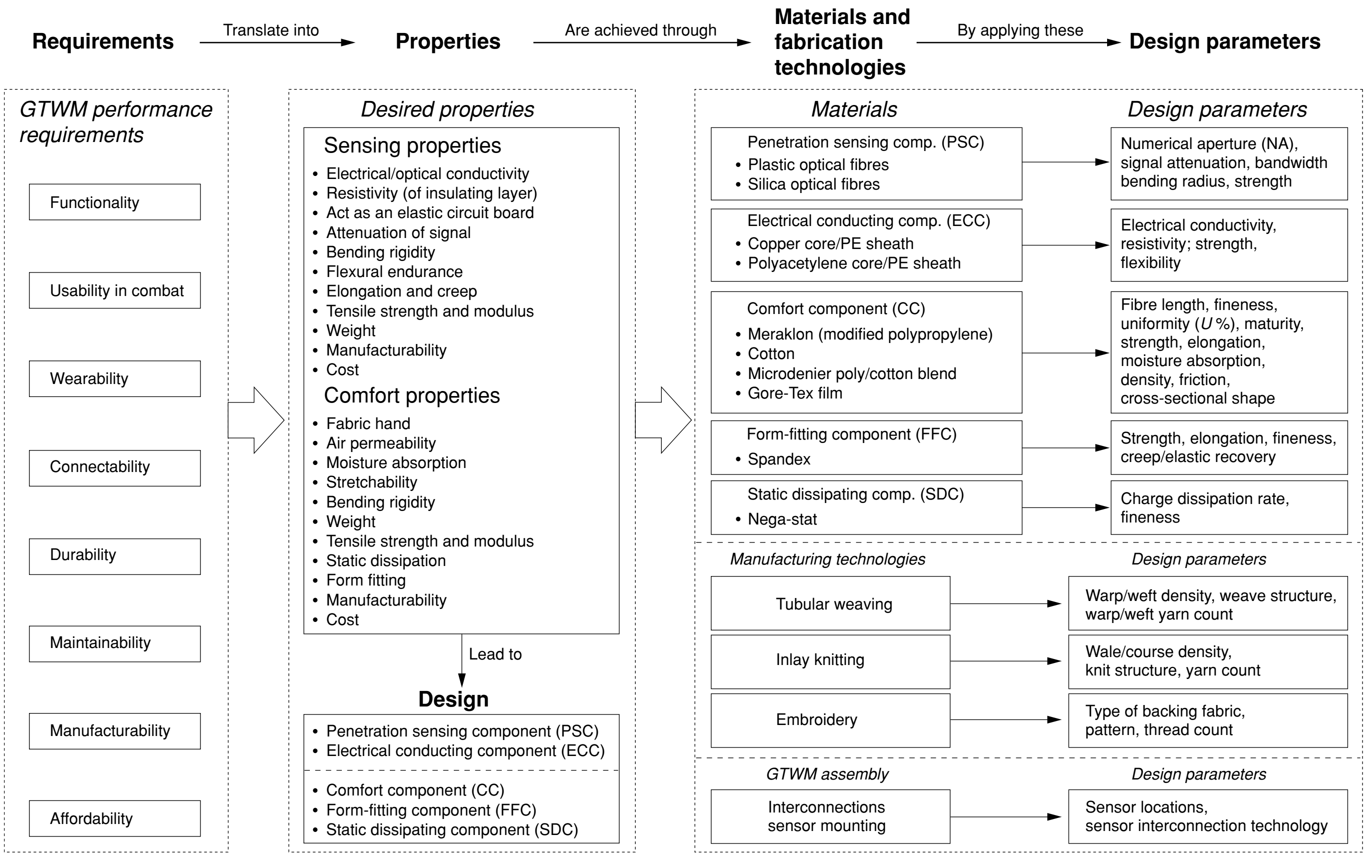
Once the detailed performance requirements were defined, the need for an overall design and development framework became obvious. However, no comprehensive framework was found in the literature; therefore, one was developed. Figure 13.2 shows the resulting overall GTWM design and development framework and encapsulates the modified QFD-type (quality function deployment) methodology developed for achieving the project goals. The requirements are then translated into the appropriate properties of GTWM: sets of sensing and comfort properties. The properties lead to the specific design of the GTWM, with a dual structure meeting the twin requirements of 'sensing' and 'comfort'. These properties of the proposed design are achieved through the appropriate choice of materials and fabrication technologies by applying the corresponding design parameters as shown in the figure. These major facets in the proposed framework are linked together as shown by the arrows between the dotted boxes in Fig. 13.2. The detailed analysis of the performance requirements, the methodology and the proposed design and development framework can be found elsewhere.[7] This generic framework can be easily modified to suit the specific end-use requirements associated with the garment. For instance, when creating a version of GTWM for the prevention of sudden infant death syndrome (SIDS), the requirement of 'usability in combat' would not apply.

13.3.4 The design and structure of GTWM

This structured and analytical process eventually led to the design of the structure. The Wearable Motherboard consists of the following building blocks or modules that are totally integrated to create a garment (with intelligence) that feels and wears like any typical undershirt. The modules are:

- a comfort component to provide the basic comfort properties that any typical undergarment would provide to the user,
- a penetration sensing component to detect the penetration of a projectile,
- an electrical sensing component to serve as a data bus to carry the information to/from the sensors mounted on the user or integrated into the structure,
- a form-fitting component to ensure the right fit for the user, and
- a static dissipating component to minimize static build-up when the garment is worn.

The elegance of this design lies in the fact that these building blocks (like LEGO™ blocks) can be put together in any desired combination to produce structures to meet specific end-use requirements. For example, in creating a



13.2 GTWM: design and development framework.

GTWM for healthcare applications, e.g. patient monitoring, the penetration sensing component will not be included. The actual integration of the desired building blocks will occur during the production process through the inclusion of the appropriate fibres and yarns that provide the specific functionality associated with the building block. In and of itself, the design and development framework resulting from this research represents a significant contribution to systematizing the process of designing structures and systems for a multitude of applications.

13.3.5 Production of GTWM

The resulting design was woven into a single-piece garment (an undershirt) on a weaving machine to fit a 38–40 in chest. The various building blocks were integrated into the garment at the appropriate positions in the garment. Based on the in-depth analysis of the properties of the different fibres and materials, and their ability to meet the performance requirements, the following materials were chosen for the building blocks in the initial version of the smart shirt:[7]

- Meraklon (polypropylene fibre) for the comfort component
- plastic optical fibres for the penetration sensing component
- copper core with polyethylene sheath and doped nylon fibres with inorganic particles for the electrical conducting component
- Spandex for the form-fitting component
- Nega-Stat™ for the static dissipating component.

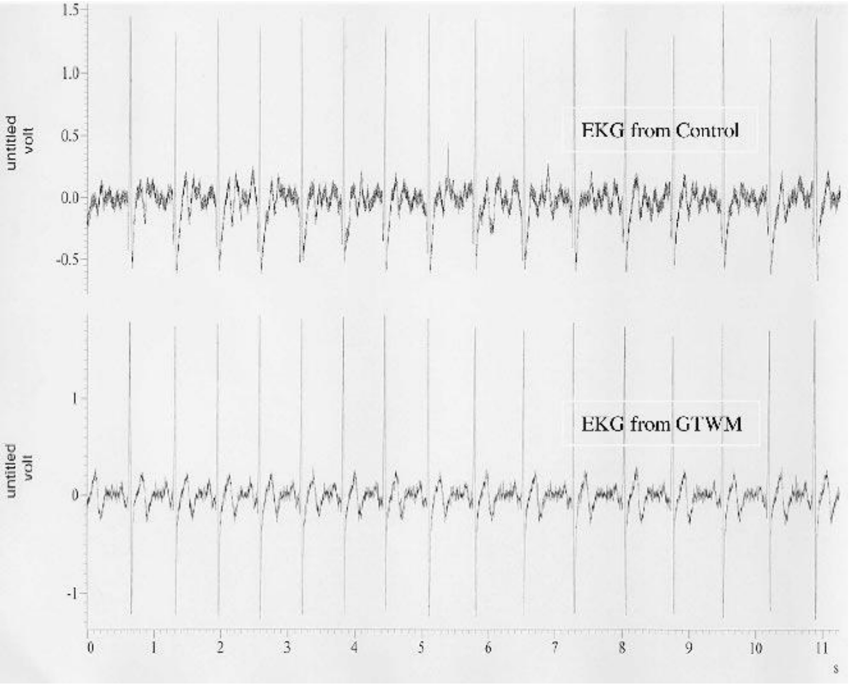
The plastic optical fibre (POF) is spirally integrated into the structure during the fabric production process without any discontinuities at the armhole or the seams using a novel modification in the weaving process. With this innovative design, there is no need for the ‘cut and sew’ operations to produce a garment from a two-dimensional fabric. This pioneering contribution represents a significant breakthrough in textile engineering because, for the first time, a full-fashioned garment has been woven on a weaving machine.

An interconnection technology was developed to transmit information from (and to) sensors mounted at any location on the body, thus creating a flexible bus structure. T-Connectors – similar to button clips used in clothing – are attached to the yarns that serve as the data bus to carry the information from the sensors, e.g. EKG (electrocardiogram) sensors on the body. The sensors plug into these connectors and, at the other end, similar T-connectors are used to transmit the information to monitoring equipment or DARPA’s personal status monitor. By making the sensors detachable from the garment, the versatility of the GTWM has been significantly enhanced. Since the shapes and sizes of humans will be different, sensors can be positioned on the right

13.3 Wearable Motherboard™ on subjects. The optical fibres are lit, indicating the shirt on the left is 'armed' for detecting penetration.

locations for all users and without any constraints imposed by the GTWM. In essence, the GTWM can be truly 'customized'. Moreover, it can be laundered without any damage to the sensors themselves. In addition to the fibre optic and specialty fibres that serve as sensors, and the data bus to carry sensory information from the wearer to the monitoring devices, sensors for monitoring the respiration rate, e.g. RespiTrace™ sensors, have been integrated into the structure, thus clearly demonstrating the capability to directly incorporate sensors into the garment.

Several generations of the woven and knitted versions of the Wearable Motherboard have been produced (see Fig. 13.3). The lighted optical fibre in the figure illustrates that the GTWM is 'armed' and ready to detect projectile penetration. The interconnection technology has been used to integrate sensors for monitoring the following vital signs: temperature, heart rate and respiration rate. In addition, a microphone has been attached to transmit the wearer's voice data to recording devices. Other sensors can be easily integrated into the structure. For instance, a sensor to detect oxygen levels or hazardous gases can be integrated into a variation of the GTWM that will be used by firefighters. This information, along with the vital signs, can be transmitted to the fire station, where personnel can continuously monitor the firefighter's condition and provide appropriate instructions, including ordering the individual to evacuate the scene if necessary. Thus, this research has led to a truly and fully customizable 'Wearable Motherboard' or intelligent garment.



13.4 EKG trace from the GTWM.

13.3.6 Testing of the GTWM

The penetration sensing and vital signs monitoring capabilities of the GTWM were tested. A bench-top set-up for testing the penetration sensing capability was devised. A low-power laser was used at one end of the plastic optical fibre (POF) to send pulses that 'lit up' the structure indicating that the GTWM was armed and ready to detect any interruptions in the light flow that might be caused by a bullet or shrapnel penetrating the garment. At the other end of the POF, a photo-diode connected to a power-measuring device measured the power output from the POF. The penetration of the GTWM resulting in the breakage of the POF was simulated by cutting the POF with a pair of scissors; when this happened, the power output at the other end on the measuring device fell to zero. The location of the actual penetration in the POF could be determined by an optical time domain reflectometer, an instrument used by telephone companies to pinpoint breaks in fibre optic cables.

The vital signs monitoring capability was tested by a subject wearing the garment and measuring the heart rate and electrocardiogram (EKG) through the sensors and T-connectors. In Fig. 13.4, the EKG trace from the Wearable

Motherboard is shown along with the control chart produced from a traditional set-up. Similarly, the wearer's temperature was monitored using a thermistor-type sensor. A subject wearing the smart shirt continuously for long periods of time evaluated the garment's comfort. The subject's behaviour was observed to detect any discomfort and none was detected. The garment was also found to be easy to wear and take off. For monitoring acutely ill patients, who may not be able to put the smart shirt on over the head (like a typical undershirt), Velcro™ and zipper fasteners are used to attach the front and back of the garment, creating a garment with full monitoring capability.

Thus, a fully functional and comfortable Wearable Motherboard or smart shirt has been designed, developed and successfully tested for monitoring vital signs.[3]

13.4 GTWM: contributions and potential applications

This research on the design and development of the GTWM has opened up new frontiers in personalized information processing, healthcare and telemedicine, and space exploration, to name a few.[8] Until now, it has not been possible to create a personal information processor that was customizable, wearable and comfortable; neither has there been a garment that could be used for unobtrusive monitoring of the vital signs of humans on earth or space, such as temperature, heart rate, etc. Moreover, with its universal interface of clothing, the GTWM pioneers the paradigm of an integrated approach to the creation and deployment of wearable information infrastructures that, in fact, subsume the current class of wearable computers.

13.4.1 Potential applications of the GTWM

The broad range of applications of the GTWM in a variety of segments is summarized in Table 13.1. The table also shows the application type and the target population that can utilize the technology. A brief overview of the various applications follows.

13.4.1.1 Combat casualty care

The GTWM can serve as a monitoring system for soldiers that is capable of alerting the medical triage unit (stationed near the battlefield) when a soldier is shot, along with transmitting information on the soldier's condition, characterizing the extent of injury and the soldier's vital signs. This was the original intent behind the research that led to the development of the GTWM.

Table 13.1 Potential applications of the Wearable Motherboard

Segment	Application type	Target customer base
Military	Combat casualty care	Soldiers and support personnel in battlefield
Civilian	Medical monitoring	Patients: surgical recovery, psychiatric care
		Senior citizens: geriatric care, nursing homes
		Infants: SIDS prevention
		Teaching hospitals and medical research institutions
	Sports/performance monitoring	Athletes, individuals Scuba diving, mountaineering, hiking
Space	Space experiments	Astronauts
Specialized	Mission critical/hazardous applications	Mining, mass transportation
Public safety	Fire-fighting Law enforcement	Firefighters Police
Universal	Wearable mobile information infrastructure	All information processing applications

13.4.1.2 Healthcare and telemedicine

The healthcare applications of the GTWM are enormous; it greatly facilitates the practice of telemedicine, thus enhancing access to healthcare for patients in a variety of situations. These include patients recovering from surgery at home, e.g. after heart surgery, geriatric patients (especially those in remote areas where the doctor/patient ratio is very small compared to urban areas), potential applications for patients with psychiatric conditions (depression/anxiety), infants susceptible to SIDS (sudden infant death syndrome) and individuals prone to allergic reactions, e.g. anaphylaxis reaction from bee stings.

13.4.1.3 Sports and athletics

The GTWM can be used for the continuous monitoring of the vital signs of athletes to help them track and enhance their performance. In team sports, the coach can track the vital signs and the performance of the player on the field and make desired changes in the players on the field depending on the condition of the player.

13.4.1.4 Space experiments

The GTWM can be used for the monitoring of astronauts in space in an unobtrusive manner. The knowledge to be gained from medical experiments in space will lead to new discoveries and the advancement of the understanding of space.

13.4.1.5 Mission critical/hazardous applications

Monitoring the vital signs of those engaged in mission critical or hazardous activities such as pilots, miners, sailors, nuclear engineers, among others. Special-purpose sensors that can detect the presence of hazardous materials can be integrated into the GTWM and enhance the occupational safety of the individuals.

13.4.1.6 Public safety

Combining the smart shirt with a GPS (global positioning system) and monitoring the well-being of public safety officials (firefighters, police officers, etc.), their location and vital signs at all times, thereby increasing the safety and ability of these personnel to operate in remote and challenging conditions.

13.4.1.7 Personalized information processing

A revolutionary new way to customize information processing devices to ‘fit’ the wearer by selecting and plugging in chips/sensors into the Wearable Motherboard (garment).

A detailed analysis of the characteristics of the GTWM and its medical applications can be found elsewhere.[2]

13.4.2 Impact of the technology

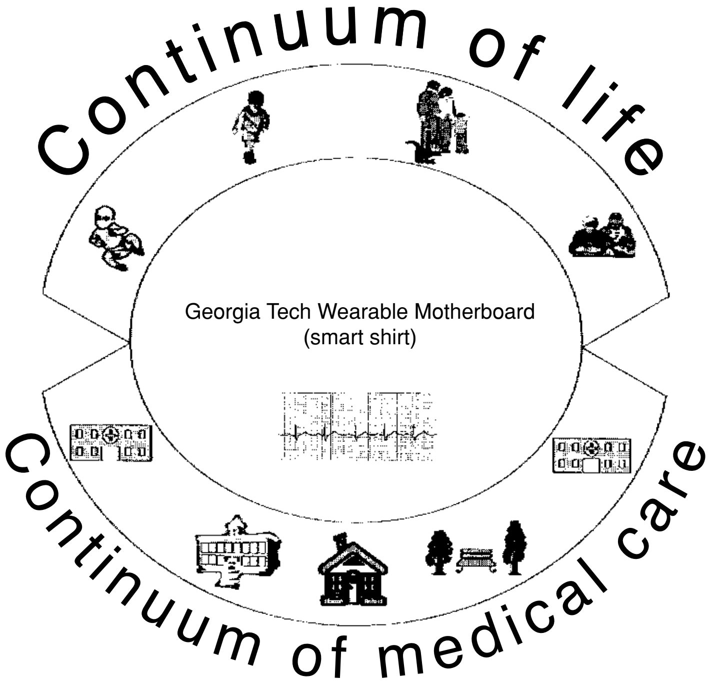
The Wearable Motherboard™ technology has the potential to make a significant impact on healthcare while enhancing the quality of life. For instance, patients could wear the GTWM at home and be monitored by a monitoring station (similar to home security monitoring companies), thereby avoiding hospital stay costs and reducing the overall cost of healthcare. At the same time, a home setting can contribute to faster recovery. As another example, when a baby version of the GTWM is used for monitoring infants prone to SIDS (sudden infant death syndrome), it can shift the focus from the treatment of infants who have suffered brain damage due to apnea to the prevention of the damage in the first place. Because the GTWM can be tailored, it can be used across the entire population spectrum, from infants to senior citizens of both genders.

13.4.2.1 Product versatility

The 'plug and play' feature in the GTWM greatly broadens its application areas. For instance, athletes can choose to have one set of sensors to monitor their performance on the field, while firefighters could have a different set of sensors, e.g. heart rate, temperature and hazardous gases for their application. Thus, the GTWM is a versatile platform and serves as a true motherboard.

13.4.2.2 Product appeal

The GTWM is similar to any undershirt and is comfortable, and easy to wear and use. By separating the sensors from the garment, the maintenance of the garment has been enhanced. The current versions of the garment can be machine-washed. Initial tests have demonstrated the reliability of the system to continuously monitor the various vital signs. In terms of affordability, the anticipated cost of producing the smart shirt is in the \$35 range. The costs associated with the required sensors and monitoring would vary depending on the individual application. Thus, conceptually, the smart shirt can be



13.5 The twin continua of life and medical care.

likened to a home alarm system. Just as the overall cost of the home monitoring system will depend on the number of points monitored, the types of sensors used and the desired response, the final cost of the smart shirt will also vary. This ability to customize greatly enhances the appeal of the GTWM to a wide cross-section of the population.

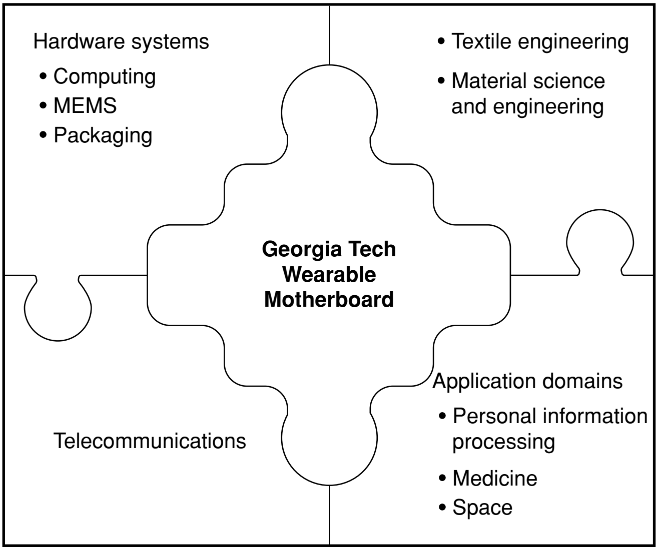
Thus, the smart shirt will have a significant impact on the practice of medicine, since it fulfils the critical need for a technology that can enhance the quality of life while reducing healthcare costs across the continuum of life, i.e. from newborns to senior citizens and across the continuum of medical care, i.e. from homes to hospitals and everywhere in-between as shown in Fig. 13.5. The potential impact of this technology on medicine was further reinforced in a special issue of *Life Magazine – Medical Miracles for the Next Millennium*, autumn 1998 – in which the smart shirt was featured as one of the '21 breakthroughs that could change your life in the 21st century'.[9]

13.5 Emergence of a new paradigm: harnessing the opportunity

One of the unique facets of the GTWM is that there are no seams or 'breaks' in the plastic optical fibre, which circumnavigates the garment from top to bottom. This pioneering contribution represents a significant breakthrough in textile engineering because, for the first time, a full-fashioned garment has been *woven* on a weaving machine. With this innovative process, there is no need for the conventional cut and sew operations to produce a garment from a two-dimensional fabric.

Although it started off as a 'textile engineering' endeavour, the research has led to an even more groundbreaking contribution with enormous implications: the creation of a wearable integrated information infrastructure that has opened up entirely new frontiers in personalized information processing, healthcare, space exploration, etc. Therefore, there is an exciting and unique opportunity to explore this new paradigm on two major fronts, i.e. mobile wearable information processing systems (MWIPS) and vital signs monitoring systems (VSMS) that can not only lead to a rich body of new knowledge but in doing so, enhance the quality of human life. The two fronts should eventually converge and give rise to a generation of personalized mobile information processing systems (PMIPS) with embedded intelligence that can sense, adapt and respond to the needs of the wearer and the environment. Thus, the Wearable Motherboard, with its truly universal human interface of a garment, can serve as the integration framework for the realization of affective and invisible computing.

Today, when a microwave oven is used, the individual is totally hidden from or unaware of the microprocessor built into the oven. Likewise, research in



13.6 An interdisciplinary research approach to personalized mobile information processing.

PMIPS should lead to smart clothing where the 'intelligence' is embedded into the clothing, and the user can harness the required information processing capabilities without being an expert in the domain of computer hardware or software. Thus, research must explore in depth the promise of the Wearable Motherboard technology, while simultaneously engineering the transformation from an innovative concept whose feasibility has been conclusively demonstrated to a robust system with a multitude of real-world applications including mobile personal information processing, multimedia-rich computing, medicine and space exploration.

13.5.1 Need for interdisciplinary research

Research in this area must expand on the symbiotic relationship between art, science and engineering pioneered in the development of the GTWM, where the fine art of weaving has been skilfully blended with scientific principles and engineering design to create a unique and innovative structure/system that is of practical significance to humankind. Furthermore, the design and development process involved a convergence of several technical areas – sensor technologies, textiles, materials, optics and communication – making it an ideal example of a multidisciplinary approach to problem-solving. This successful paradigm must be applied during the research for the realization of PMIPS. As illustrated in Fig. 13.6, it must bring together researchers from the complementary disciplines essential for exploring the new paradigm:

- textile engineering and materials science and engineering
- computing hardware, electronics packaging and microelectromechanical systems (MEMS)
- telecommunications
- application domain: medicine, space, information processing, networking, etc.

Such an interdisciplinary approach will not only lead to effective solutions but also to significant breakthroughs in the field.

13.5.2 A research roadmap

We will now identify key areas of research in ARTS, exploring the new paradigm that will lead to the realization of PMIPS.

13.5.2.1 Sensor development – design and development of wearable, interconnectable sensors/microchips

In the current generation of the GTWM, sensors for heart rate monitoring are affixed to the body and connected to the T-connectors on the garment. This could be uncomfortable/difficult for certain users such as invalid persons, burn victims and infants with sensitive skin. There is a need for a sensor that can be integrated into the structure and held against the user's body using the form-fitting component of the GTWM. New sensors that can be integrated into the GTWM must be identified, designed and developed. The sensors must be rugged enough to withstand laundering and 'field use', and/or should also be easily detachable from the garment. The sensors must also be interconnectable, compact and have a high degree of reliability. This research calls for collaboration between the fields of textile engineering, materials science and engineering, microelectronics, MEMS and biomedical engineering.

13.5.2.2 Interconnection technology development

The interconnection technology used in the present version of the GTWM is manual and represents the first attempt at realizing such interconnections in flexible textile materials. There is a need for an interconnection technology that can provide precise, rugged and flexible interconnections using an automated process suitable for mass production. An interconnection technology for mounting microchips on the GTWM and technology for coupling optical fibres to sensors (as opposed to interconnecting them) should also be developed. This research calls for collaboration between the fields of textile engineering, microelectronics, electronic packaging and material science.

13.5.2.3 Wireless communications technology development

Wireless transmission capability is critical for the effective use of the GTWM in the various applications (see Table 13.1) so that the data can be received, decoded and analysed, and appropriate action taken. For example, if the patient recovering at home from heart surgery is wearing the smart shirt, the EKG (electrocardiogram) needs to be transmitted to the hospital on a regular basis. This monitoring will help the patient feel 'secure' and will facilitate recuperation while simultaneously reducing the costs and time associated with recovery. Moreover, in the event of an emergency, the doctor can be notified instantaneously, leading to prompt and effective treatment. Since the current version of the GTWM does not have wireless transmission and reception capability, wireless technologies such as those used in cellular phones, radio modems and baby monitors must be integrated into the GTWM. Important factors that would determine the selection of this technology are cost, the ability to interface with existing computer hardware, bandwidth, speed and size. The technology must be capable of providing bidirectional, multimodal multimedia communications between the sensors, cameras and microphones mounted on the GTWM and remote monitoring stations. This research calls for collaboration between the fields of microelectronics, telecommunications and textile engineering (to ensure seamless integration of the communications device with the garment).

13.5.2.4 Development of decoding/image compression software

There is a need for software that can decode the transmitted data, e.g. vital signs, and display it in a meaningful format. The software should also have the ability to record the data for later analysis. The key considerations in the selection of this software are cost, the ability to run on multiple platforms and a user-friendly interface. The software system must also analyse the decoded data and automatically raise an alarm if the vital signs are beyond certain previously defined thresholds. The important factor that would be considered is the ability to automatically alert emergency medical personnel using telephones, pagers or the Web. This research calls for collaboration between the fields of telecommunications, electrical engineering and medicine.

13.5.2.5 Development of new materials

The required set of properties for the materials used in the GTWM (comfort fibres, conducting fibres, optical fibres, etc.) will depend on the application, the sensor suite, etc. For example, chemical resistance will be necessary for fibres used in fire-fighting applications; however, chemical resistance is not very important when it comes to using these fibres in baby clothes. Likewise, to build or embed ‘memory’ into clothing – that is analogous to the computer’s memory – there is a need for research in fibres and materials that can provide such characteristics eventually leading to ‘on-off’ capabilities being embedded in the fibres themselves. As yet another example, there is a need for fibres that can integrate properties of stretch, comfort and conductivity in the same single fibre. Research in this area calls for collaboration between the fields of textile engineering and materials science and engineering.

13.5.2.6 Development of next generation ARTS using MEMS devices

ARTS represent the new class of textile garments that can sense the vital signs of the individual wearing the garment (say, the GTWM), analyse the data using built-in intelligence and provide a suitable response based on the analysis. For example, some individuals are susceptible to anaphylaxis reaction (an allergic reaction) when stung by a bee, and need a shot of epinephrine (adrenaline) immediately to prevent serious illness or even death. Therefore, there is a critical need for research that could lead to the development and incorporation of (1) appropriate sensors on the GTWM to detect the anaphylaxis reaction (or a diabetes shock), (2) ‘adaptive’ mechanisms that can monitor the wearer’s vital signs and create a response, and (3) a built-in feedback mechanism, e.g. a MEMS device, that can effect the responsive action (administer an injection). This research calls for collaboration between the fields of MEMS, medicine and textile engineering.

Thus the research roadmap presented in this section can be utilized to build on the Wearable Motherboard concept and technology to create adaptive and responsive textile structures that will pave the way for PMIPS.

13.6 Conclusion

The Jacquard weaving machine was the precursor to today’s powerful computers. Similarly, the Wearable Motherboard is a versatile and mobile information infrastructure that can be tailored to the individual’s requirements to take advantage of the advancements in telemedicine and information processing and thereby significantly enhance the quality of life. Moreover, the Wearable Motherboard technology provides a strong foundation or platform for further advancements in the area of personalized mobile wearable information processing systems that will lead to pervasive computing. In short, clothing can indeed have the third dimension of ‘intelligence’ embedded into it and spawn the growth of individual networks or personal networks where each garment has its own IN (individual network) address much like today’s IP (internet protocol) address for information processing devices. When such IN garments become the in thing, personalized mobile information processing will have become a reality for all of us!

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14

Wearable technology for snow clothing

HEIKKI MATTILA

14.1 Introduction

Not so long ago, terms like 'intelligent textiles' and 'smart clothing' started to appear in seminar presentations and academic discussions. The aim seemed to be to develop textile materials which have temperature regulating, electroconductive and other advanced properties. Wearable computer research was focusing on how to link computer hardware to clothing, glasses and other accessories worn by the user. The armed forces both in the USA and Europe were carrying out their own projects in this field.

In 1998, representatives from two Finnish universities and some industrial companies discussed future research projects and recognized smart textiles to be both challenging and interesting. The problem was how to convince private and public sponsors to allocate enough funds for such a new and rather sci-fi research area. Therefore, an extraordinary approach was selected. Let's first make a prototype. By combining electronics and other unusual devices of existing technology to a garment, we could prove that such cross-scientific research and development is possible and worth funding in the future.

For the cross-scientific approach, a network of four university departments and four industrial companies was formed. The Institute of Electronics and the Institute of Textiles from Tampere University of Technology, the Institute of Industrial Arts and the Institute of Textile Design from University of Lapland, the snowmobile suit manufacturer Reima-Tutta Oy, compass and navigating systems producer Suunto Oyj, heart rate monitor producer Polar-Electro Oy, and DuPont Advanced Fibre Systems were the participants. In addition, Siemens and Nokia Mobile Phones assisted with GSM (global system for mobile communication) communications. Altogether, more than ten researchers worked on the project.

The snowmobile suit was selected as the prototype. A snowmobile is a vehicle used for work and leisure in harsh arctic winter conditions. The driver may be alone or in a group in remote areas. His health and even his life may depend on the vehicle and his clothing. In the event of an accident, he might need help fast. Reima-Tutta Oy is one of the world's leading snowmobile suit manufacturers. Thus, the team had expert knowledge of conventional snowmobile clothing and the problems associated with it.

Work started in the autumn of 1998 with a brainstorming phase which ended in the spring of 1999. A product design phase followed and the prototype was tested in Northern Lapland during the winter of 1999–2000. Maximum publicity was one of the objectives of the project. A well-planned press release and a show were organized for spring 2000, and the show was filmed by more than ten international TV stations. Finally, the experiences from the prototype and the smart clothing philosophy were displayed in the Finnish pavilion at the Expo 2000 World Fair in Hanover.

The budget for the project was approximately one million US dollars, half of which came from TEKES, the National Technology Agency, which is the main financing organization for applied and industrial R&D in Finland. The other half was paid by Reima-Tutta Oy, the snowmobile suit manufacturer. For a firm with an annual turnover of 40 million dollars, this was its biggest ever investment into a single R&D project. A management board was formed for the project, with representatives from each party. The board closely followed the work of the research team and offered advice and comments when needed.

14.2 Key issues and performance requirements

The targeted user for the suit was defined as an experienced snowmobile driver who knows how to move around in an arctic environment and who has basic first-aid skills. There were several problems that the suit should solve in the case of an emergency. Firstly, in case the person gets lost he must be able to locate himself and to know which way to go in order to reach a road or village. Also, the rescue units must be able to locate him if he needs help. He must have access to local weather forecasts as well as know the times of sunrise and sunset. In case his snowmobile breaks down, he must be able to walk away in deep snow or survive long enough to be rescued. In case he falls through ice into water, he must be able to get out of the water and to survive in sub-zero temperatures long enough to be rescued. If he has an accident and falls unconscious, the suit should send an automatic distress signal, together with enough information regarding his condition for the rescue units to know how quickly he must be found. Furthermore, the suit should provide shelter and make life as comfortable as possible in the arctic climate.

The objective was to design and build as many different features into the prototype as possible. The electronics and other devices should be part of the garment, rather than being inserted into pockets and picked out when needed. All wires and other devices must be hidden and the garment must look, inside and out, like a clothing product. The product must also be comfortable to wear. Besides the suit, underwear also had to be designed, in order to facilitate heart rate monitoring.

The maximum weight for the suit was agreed to be 4.5 kg. All the devices must work in −20 °C for 24 hours. Furthermore, everything should be operational if the person perspires or even if he falls into water. The user interfaces must be designed so that they can be used without removing heavy gloves or if the fingers are numb from cold. The product must be washable in a normal washing machine.

Budget and time limitations meant that no basic research could be done and the inventing of totally new devices should be kept to a minimum. This forced the research team to use existing technology, but applications could be new.

14.3 The prototype

The purpose of the suit itself is to keep the user warm and dry. A snowmobile suit is usually a two-piece garment consisting of high waistline pants and a jacket with hood. The suit must be warm and weathertight, breathable but watertight. All seams are usually taped for this purpose. Durable and watertight material is normally used at the seat and knee areas. Special shock-absorbing padding may be used in the knee, elbow and shoulder areas. The team selected a breathable material, which lets the humidity out but prevents water from getting inside. For comfort and safety, the suit should maintain thermal equilibrium. The possibility of using phase change materials (PCMs) was analysed. PCMs are materials containing, either in the fibre or in the coating, microcapsules with a substance which changes phases from solid to liquid and back, according to a certain temperature range. In this process, heat is either released or absorbed, and a more equal temperature is maintained within the wearer's personal microclimate. Materials like Outlast and Gore-Tex were selected for this purpose. In case of emergency, once the distress signal has been sent, the rest of the energy could be used for the signal light and for heating critical areas of the body. Heating, however, requires a lot of energy and in a practical environment it may not be feasible to use the portable energy sources for such a purpose.

Several sensors were used for monitoring the body functions and movements of the user. Sensors monitoring heart rate were attached to the underwear. The rest of the sensors were attached to the suit itself. There are six sensors for measuring the outside temperature and four for measuring the inside temperature. The temperature differences are used for analysing where and in which position the user is, i.e. is he on his back in the snow or is he just lying down by a fire? All the electronic devices were attached to the suit itself, including the processor and communications network, with interfaces in different parts of the garment for connecting the necessary components. The user interface and interface for recharging the batteries would also be part of the suit. This modular solution makes it possible to have different versions, thus giving the consumer the option to buy only the devices he needs. Also, only the user interface, the interface for power recharging, wiring and other interfaces must be washable, while the rest of the components can be removed. Even so, they must be resistant to shock, water and bending.

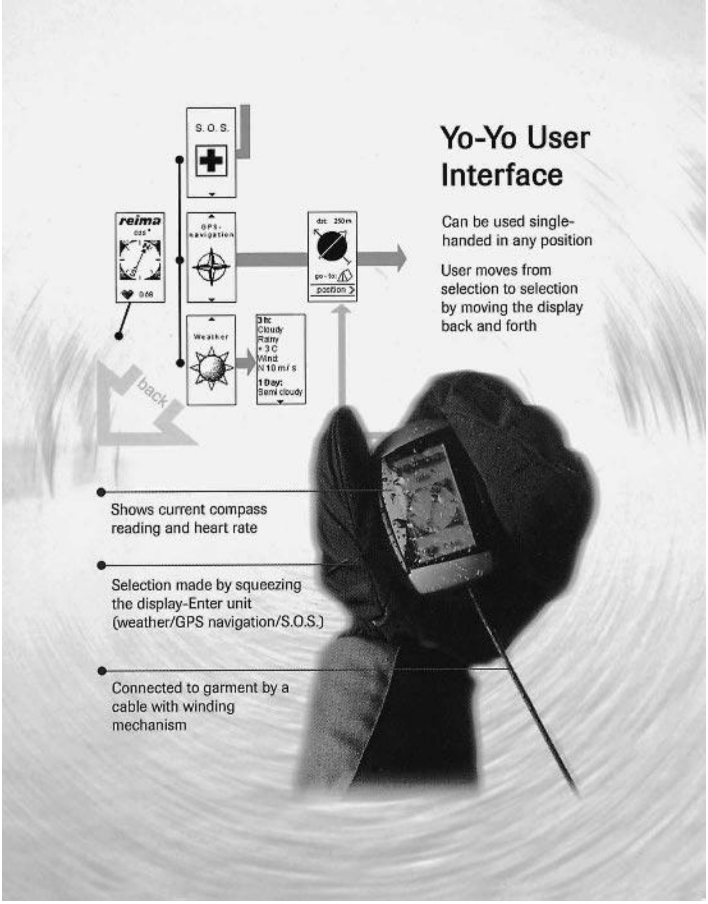
Sensors monitoring the heart rate had to be placed close to the skin. They were sewn permanently to the underwear. By monitoring the heart rate, it is possible to tell, for example, how much pain the user is suffering. Body temperature was measured in three different places. Other sensors were used for monitoring temperatures outside and inside the suit. By measuring the acceleration forces, it was possible to determine whether the user had been in collision with something, whether he is still moving or what position he is lying in. This information was gathered by an accelerometer developed by Polar Electro Oy. The CPU unit containing the programs needed for operating the whole suit and analysing various features was placed inside the jacket at the back of the user.

The global positioning system (GPS) uses several orbiting satellites for radio navigation, providing the user with the ability to pinpoint his exact position anywhere in the world. By receiving signals from a minimum of four satellites simultaneously, it is possible to determine the latitude, longitude and altitude of the user very accurately. The GPS system was installed into the central processing unit. The user could not only locate himself, but he could also be found by others. A compass with a GOTO arrow was included, with direction and distance to the desired destination also displayed. However, special development work had to be carried out in order to make the GOTO arrow operational, even if the person is standing or lying still. In a normal GPS, the GOTO arrow works only if the user is moving.

GSM was selected for data transfer. Instead of using a mobile telephone, the Siemens Cellular Engine M20 was installed as part of the central processing unit. This device is capable of sending and receiving short messages.

The power supply was the tricky part. After checking all the possibilities, from solar panels to utilizing static electricity, conventional batteries had to be selected. The smallest battery to guarantee power for 24 hours would weigh 600 to 700 g. The battery is rechargeable either at home or from the snowmobile during the drive.

The objective was to design a single user interface for all the electronics in the garment. The interface had to be part of the suit and usable with the left or right hand without removing gloves. This eliminated any solid or embroidered keyboards. In fact, nothing existed that fulfilled the requirements, and therefore it had to be designed for this project. The research team came up with



Can be used single-handed in any position

User moves from selection to selection by moving the display back and forth

Shows current compass reading and heart rate

Selection made by squeezing the display-Enter unit (weather/GPS navigation/S.O.S.)

Connected to garment by a cable with winding mechanism

14.1 The user interface.

a brilliant idea, a winding palm-size display unit attached with a cable to the chest of the garment. When the unit is pulled from the chest, the menu in the display changes accordingly. There are three steps, each about 5 cm apart. At the first step with the unit nearest the wearer, the display shows the time, heart rate, power level, the level of GSM signal and coordinates. The next step shows the second menu, and so on. To operate the system, it is only necessary to squeeze the unit, as shown in Fig. 14.1.

In addition to electronics, other survival equipment was developed. These features are displayed in Fig. 14.2. It is quite usual to drive over frozen lakes and rivers with a snowmobile, and sometimes the ice gives way. Two awls attached to the sleeves will help the user to get out of the water and back on to the ice. At the back of the garment there is an airtight sack, and by getting into

14.2 Survival features in the suit.

the sack the user can prevent hypothermia for as long as 4 hours. One of the thigh pockets is detachable and fireproof, and can be used for melting snow over a fire. In such situations, to avoid hypothermia, it is important to drink liquid. Waterproof matches, collapsible snow shoes, and a first-aid kit are also provided. A summary of all features is presented in Table 14.1.

In case of an emergency, the wearer of the suit can send a distress signal by squeezing the user interface for 30 seconds. The rescue team can confirm the signal back to him and also read his coordinates. Through various sensors, the suit monitors the condition of the user, for example, heart rate, ***g***-forces, temperature, pain, hypothermia, and so on. If a critical situation is diagnosed by the software, a distress signal will be sent automatically. The interface, however, warns the user first and he has 30 seconds to cancel the signal if necessary. In addition to just the signal and coordinates, the rescue team will be able to see whether the person moves around, and in what position he is lying, whether he is in the water, his body temperature, the outside temperature, etc.

Table 14.1 Features of the snowmobile smart suit

Problem	Solutions	Technology
Cold and wet environment	Breathable and waterproof outer fabrics PCM underwar for temperature regulation	Taslan, polyamide, Cordura polyamide fabrics Aracon, Gorix, Outlast underwear materials
Disorientation	Location by GPS Direction and distance to desired destination	Rockwell-Jupiter GPS system, Suunto electronic compass, real time GOTO arrow
Fall through ice into water, hypothermia	Get into hypothermia sack to maintain heat Melt snow for drinking water Send distress signal	Hypothermia sack, warming underwear Detackable fireproof pocket Siemens M20 GSM engine
Accident, health problem, unconsciousness	Monitor heart rate, body temperature, outside temperature, g-forces and body movement Send manual or automatic distress signal	Polar Electro heart rate monitoring system Specially designed Hitachi CPU unit Siemens M20 GSM engine
Snowmobile breaks down	Collapsible snow shoes	
Local weather conditions	Weather Service Finland report	Siemens M20 GSM
How to operate the features with one hand and gloves on	Winding, palm size display unit attached by a cable to the chest of the garment with changing menu according to distance. Operated by squeezing the unit	PIC processor controls power management Electronic compass Patented Yo-Yo user interface

14.4 Conclusions

The prototype snowmobile suit developed within this project is a smart garment. Cross-scientifically, electronic and textile innovations were combined, and the objectives were achieved. The suit works as planned. It is not likely that the prototype costing 1 million dollars to create will be commercially exploited in its exact shape and form. However, much was learned. Several innovations, including the user interface, were patented and will be commercially applied in the future. The garment manufacturer Reima-Tutta Oy launched snowboard clothing with electronic devices in the autumn of 2000.

Some of the objectives proved to be difficult to achieve at the prototype stage. For example, to make the garment fully washable could not be done. Only the wiring and interfaces could be treated so that it is possible to wash the product in a normal washing machine. All the other devices, including CPU, GSM engine, user interface, etc., had to be removed. What was, however, achieved was to guarantee that the suit and all electronics would remain fully operational even if the user falls into water. Gorix is a fabric that can be heated electrically. The idea of using extra power for heating critical body areas would have worked well except that the batteries used for operating the electronics could maintain heating levels for only a very short period. Therefore, this idea had to be abandoned.

The project received more publicity than expected. Magazine articles and programmes by ten European TV stations, including *BBC World*, spread the word worldwide. This has convinced the participating companies and universities that there is a demand for smart clothing. Similar ventures by Philips, StarLab's I-Wear and the haute couture fashion house Oliver Lapidus confirm this. As a result, Reima-Tutta Oy has set up a wearable intelligence laboratory called Clothing + with ten researchers. The lab will work as part of a network connecting the other firms and universities that participated in the original project. The objective will be to create new innovations for adding intelligent features to apparel products.

15

Bioprocessing for smart textiles and clothing

ELISABETH HEINE AND HARTWIG HOECKER

15.1 Introduction

The application of enzymes in food processing, in the paper and leather industries, as additives in washing powders, and in the desizing process of cotton is well established. However, biocatalysis has also entered textile processing. Enzymes, biocatalysts with specific and selective activity, are today produced by biotechnological processes in great amounts and constant quality, and are therefore applicable to large-scale processes.

In view of the new applications resulting from the design of enzymes for specific processes, there is a demand for extensive collaboration between bio- and textile chemists.

Besides natural protein fibres, like wool and silk, and natural cellulose fibres, like cotton, flax and hemp, synthetic fibres are also targets for biocatalysed processes. In cotton finishing, chemical processes are widely substituted by enzyme-catalysed processes. In addition to the well-known biostoning and biofinishing, attributes like ‘used look’ and ‘modified handle’ are realized by enzymatic finishing. Moreover, there is potential for replacing the alkaline scouring in cotton pretreatment by the use of enzymes like, for example, pectinases. Catalases are added to destroy the residual peroxide in bleaching baths, to make easy reuse of the liquor possible, leading to an environmentally friendly and cost-effective process. In wool finishing, enzymes, mainly proteases, are used to achieve shrinkproofing. The properties of wool textiles like handle, whiteness and lustre are modified by enzyme-catalysed reactions as well. In early wool processing stages, like raw wool scouring and carbonization, the prospects of enzyme application are assessed. Furthermore, bioprocesses are described leading to pilling reduction and dyeability improvement. The degumming of silk, traditionally performed by the aid of soap, alkali or acid, is achieved by proteases. To improve the quality and consistency of flax, microbial or dew-retting is replaced by a specific enzymatic retting. Moreover, the dyeability of flax is improved by the enzyme-catalysed degradation of pectic substances without damaging the cellulose components. Hemp is enzymatically modified with regard to crystallinity, accessibility and ‘pore structure’. Via the controlled enzyme-catalysed fibrillation of lyocell fibres, the so-called ‘peach-skin’ effect is produced. There is a broad range of applications and a multitude of prospects for the use of enzymes in textile processing, leading to a positive impact on the environment. This chapter surveys recent developments in the field of enzymatic textile processing and discusses the advantages and limitations of these finishing processes.[1]

The use of enzymes in food processing, in the paper and leather industry, as additives in washing powders, and in the desizing process of cotton is well established. In the meantime, enzymatic processes have been developed, which aim at modifying the appearance and handle of textiles made of wool and cotton.

Enzymes are biocatalysts with selective and specific activity, accelerating distinct reactions and remaining unchanged after the reaction. From an ecological and economical point of view, the moderate reaction parameters of enzyme-catalysed processes and the possibility of recycling enzymes are particularly attractive. Today, enzymes are produced by biotechnological processes in great amounts and constant quality, thus allowing the use of enzymes in large-scale processes. Advances in the field of genetic engineering enable enzyme manufacturers to design an enzyme for a special process, e.g. with regard to temperature stability or pH optimum. The design of an enzyme for a special purpose requires an understanding of the catalytic action of the enzyme on a specific substrate, i.e. in the case of natural fibre substrates, the designer of an enzyme process needs a certain knowledge of wool and/or cotton morphology, of the effect of a special enzyme on the fibre components, and consequently on the properties of the fibre material as a whole. Furthermore, to evaluate the enzymatic process, the results of the enzymatic treatment are to be compared to the results of usual chemical processing.

The first enzymatic process in textile finishing was the desizing process using amylases. Many areas of textile finishing have been conquered since then. Today, prospects lie in the field of developing new durable press finishes for cotton, e.g. by cross-linking, in the field of effluent colour removal, and in the field of composting synthetic fibres.[2] Due to the proteinic nature of the enzymes, safety in handling enzymes is often questioned because repeated inhalation of protein material can cause allergic reactions in some individuals. It is important to notice that there is no evidence to indicate that enzyme allergies are developed through skin contact.[3] Enzymes can be safely handled by using safe product design, by engineering controls, by safe working practices, and by appropriate personal protective equipment. In product design, enzyme aerosols and powdered formulations should be avoided, whereas granular (with low dusting capabilities) and liquid formulations (with low mechanical action or in closed vessels) can be recommended. The market potential of enzymes is considerable. A market study says that there should be growth from US$ 350 million in 1992 to US$ 588 million in 2000, and that the biggest potential concerns new applications in the paper, chemical and pharmaceutical industries and in waste treatment.[4]

15.2 Treatment of wool with enzymes

15.2.1 Morphology of wool

Wool as a complex natural fibre being mainly composed of proteins (97%) and lipids (1%) is an ideal substrate for several enzyme classes (e.g. proteases, lipases). The wool fibre consists of two major morphological parts: cuticle and cortex. The cuticle is composed of overlapping cells surrounding the inner part of the fibre, the cortex. The latter is built up of spindle-shaped cortex cells which are separated from each other by the cell membrane complex.[5] The cuticle is subdivided into two main layers: exo- (with a- and b-layer) and endocuticle, and an outermost membrane called the epicuticle, causing the Allwoerden reaction of wool fibres treated with chlorine water.[6] One important component of the cuticle is 18-methylicosanoic acid.[7] In a model of the epicuticle drawn up by Negri et al.,[8] this fatty acid is bound to a protein matrix to build up a layer. According to Negri et al.,[9] this layer, referred to as the F-layer,[10] can be removed by treating wool with alcoholic alkaline or chlorine solutions, thus enhancing wettability. Another important characteristic is the cross-linking of the exocuticle, e.g. the a-layer contains 35% cystine residues. In addition to the normal peptide bonds, the cuticle is cross-linked by isodipeptide bonds, ε-(γ-glutamyl) lysine.

The hydrophobic character of the a-layer, in particular, caused by the large amount of disulfide cross-links and the bound lipid material, is the origin of the diffusion barrier, e.g. for dye molecules. Therefore, the composition and morphology of the wool surface is primarily modified in fibre pretreatment processes.

15.2.2 Heterogeneous reactions – the catalytic action of enzymes on wool and cotton

Using wool or cotton as substrates for enzyme-catalysed reactions, a special type of enzyme kinetics is followed. In the heterogeneous system of the soluble enzyme and the solid substrate enzyme, diffusion plays a more decisive role than in a homogeneous system where both enzyme and substrate are soluble. In the heterogeneous reaction, the kinetics depend not only on the concentration of the reaction partners, and on the temperature and the pH value of the liquor; as additional parameters, the diffusion of the enzyme to and into the solid phase of the substrate and the diffusion of the reaction products out of the solid phase into the liquor have to be considered.[11]

The reaction products, e.g. peptides in the case of wool and oligosaccharides in the case of cotton, when diffusing out of the fibre, act as a substrate in the liquor. Thus, part of the enzymes is bound to the soluble substrate in the treatment bath.

The diffusion of the enzyme from the liquor into the fibre (wool) resembles the diffusion of a dyestuff. The following steps are to be considered:

1. Enzyme diffusion in the bath
2. Adsorption of the enzyme at the fibre surface
3. Diffusion from the surface into the fibre interior
4. Enzyme-catalysed reaction

The complex structure of natural fibres, especially of wool, complicates enzymatic fibre modification. Enzymes like proteases and lipases catalyse the degradation of different fibre components of a wool fibre, thus making reaction control difficult.

Once having diffused into the interior of the fibre, proteases hydrolyse parts of the endocuticle and proteins in the cell membrane complex, thus, if not controlled, leading to a complete damage of the wool fibre. Thus, at least for some applications, it is desirable to restrict the enzymatic action to the fibre surface, e.g. by immobilizing the enzyme.[11]

The results of treating wool with proteolytic enzymes will be unpredictable in the absence of detailed knowledge of (a) the processing history of the substrate and (b) how specific process conditions affect subsequent enzymatic treatments. To elucidate this point, the effects of adsorbed ionic species on enzyme/substrate adsorption and reaction kinetics were studied.[12]

For cotton, the restriction of the enzyme to the fibre surface is easily achieved, because cellulose, being a highly crystalline material and comprising only small amounts of amorphous parts, makes the diffusion of enzymes into the interior of the cotton fibre nearly impossible. Thus, by regulating enzyme dosage and choosing the type of enzyme, the catalytic action of the enzyme is confined to the surface of cotton and to the amorphous regions, leaving the fibres as a whole intact.

15.2.3 Shrinkproofing

One of the intrinsic properties of wool is its tendency to felting and shrinkage. There are different theories concerning the origin of wool felting. The hydrophobic character and the scaly structure of the wool surface are the main factors causing the differential frictional effect (DFE) that results in all fibres moving to their root end when mechanical action is applied in the wet state.[13]

Therefore, shrinkproofing processes aim at the modification of the fibre surface either by oxidative or reductive methods, and/or by the application of a polymer resin onto the surface. The most frequently used commercial process (the chlorine/Hercosett process) consists of a chlorination step followed by a dechlorination step and polymer application.[13] The chlorination results in the oxidation of cystine residues to cysteic acid residues in the surface of the fibre, and allows the cationic polymer to spread and adhere to the wool surface. Chlorination produces byproducts (AOX) which appear in the effluent and ultimately may generate toxicity in the whole food chain by being taken up by aquatic organisms. There is therefore an increasing demand for environmentally friendly alternatives.

Taking into account the problems related to the conventional antifelting process mentioned above, it becomes obvious that most of the enzymatic processes concern the development of an alternative method for shrinkproofing. The requirements for an enzymatic process were discussed by Haefely;[14] the antifelting effect should be achieved without application of a synthetic resin, only ‘soft chemistry’ should be applied and the whole process should be environmentally friendly, producing no harmful substances – a premise that is not yet fulfilled in all of the processes using enzymes as fibre-modifying agents. In some of the earliest enzyme finishing processes, wool was pretreated by gas chlorination (Chlorzym process[15]) or by H_2O_2 (Perzym process[16]) prior to incubating the fibres with papain, the plant derived protease, and bisulfite. These processes resulted in a complete removal of the cuticle cells. Because of the high prices of the enzymes used and the non-tolerable weight loss of the fibres, these early combined enzymatic processes never achieved an industrial scaling-up.

The major part of enzymatic processes published in the last few years also comprises combined processes. In 1983, a process was described for rendering wool shrink resistant, which completely descaled the fibres.[17] The treatment used potassium permanganate ($KMnO_4$) as a pre-oxidizing agent and a subsequent proteolytic treatment, and gave a certain pilling resistance for wool fabrics. Not only the early ones, like the Chlorzym process, but also current enzymatic processes still include the use of chlorinating agents. Inoue[18] described a three-step process: the first step comprises the application of a mixture of papain, monoethanolamin hydrosulfite and urea, the second step a treatment with dichloroisocyanuric acid, and the last step again an enzyme treatment resulting in a reduced area shrinkage of the fabric treated in that way. Connell et al.[19] combined a protease pretreatment either with a wet chlorination or with an oxidative treatment with sodium hypochlorite and potassium permanganate and additional polymer application to achieve a reduced area shrinkage of the fabric.

Not only chemical but also physical pretreatment processes are combined with the enzyme treatment of wool. In a process patented by Nakanishi and Iwasaki,[20] a low temperature plasma was applied to the fibres prior to a treatment with polymeric shrinkproofing agents. The enzyme was used to remove fibres protruding from the surface of the fabric, thus achieving a higher softness, too. Ciampi et al.[21] combined a protease treatment with a heat treatment in saturated steam, and Fornelli and Souren[22] described the use of high frequency (HF) radiation on enzyme-treated material.

In 1991, the Schoeller Superwash 2000 treatment of wool was reported by Schindler.[23] The treatment is a three-step process consisting of a so-called black-box pretreatment, an enzyme treatment and the application of an AOX-low polyamide resin. In the process reported by Aulbach[24] (also referred to as the Schoeller process) a 'certain minimum chemical pretreatment' was described as necessary for the enzyme process. In this process, a superwash-standard is achieved without the application of a resin. Fornelli[25,26] described the use of a resin as 'still imperative' to achieve a sufficient antifelting effect in the enzyme process reported ('BIO-LANA') because by the 'enzymatic filing' of the 'scaly epicuticle' of the wool fibre, only a certain, but insufficient, degree of antifelting was obtained. This was confirmed by Riva et al.,[27] who reported the role of an enzyme in reducing wool shrinkage. The *Streptomyces fradiae* protease used is described to be 'effective in reducing wool shrinkage' but not to 'confer the desirable shrink-resistant levels for severe machine-washed wool'. The shrinkage results were not improved by the additional use of sodium sulfite. Proteases were applied either after oxidative treatment using hydrogen peroxide or plasma treatment. In both cases, the felting resistance was improved significantly by the enzyme post-treatment.[28] The shrinkage of wool is reduced after protease treatment, but concerning the efficiency of a protease treatment alone it was stated that Basolan DC treatment, for example, was still superior.[29] In view of this, the question was raised how much shrinkproofing wool would need.[30] A practical approach was reported, showing that the degree of felting of enzyme-treated wool washed in household laundry machines is comparable to chlorinated wool.

The common characteristic of the so far reported processes is the application of proteolytic enzymes. In the following section, a survey of processes is given where other enzyme classes are applied.

The enzymatic treatment for shrinkproofing wool described by King and Brockway[31] is one of the few enzymatic processes working without the aid of a chemical or physical pre- or post-treatment. In this application, the enzyme PDI (protein disulfide isomerase), which rearranges disulfide bonds, is applied to washed material constituting wool. The PDI-treatment resulted in a non-shrinking material in contrast to the non-treated, misshaped one. Ogawa et al.[32] described the application of the enzyme transglutaminase for shrinkproofing wool. The enzyme introduces additional cross-links into the substrate, leading to an improved shrinkage resistance, anti-pilling and hydrophobicity ‘without impairing the texture’ of the material.

15.2.4 Handle modification

Softness plays an essential role in qualifying textile products. Consequently, a further goal beside the antifelting effect in the pretreatment and processing of wool fibres is the production of a ‘cashmere-like’ handle. It is the aim of the processes to modify wool fibres to reduce prickle and to enhance softness and lustre, thus improving the characteristics of wool as a basic material for high quality textiles. Prickle is caused by wool fibre endings that are stiff enough to stimulate nerve endings situated directly below the skin’s surface. Therefore, a reduction of the bending modulus is aimed at. Besides that, fibre diameter and fabric construction play decisive roles concerning handle. Thus, most of the wool treatments to improve handle attempt to reduce the fibre diameter, e.g. by the complete descaling of the wool.[33] The descaling is performed by pretreating the fibres with $KMnO_4$ and ammonium sulphate, acetic acid and bisulfite, and a subsequent treatment with a proteolytic enzyme. Descaling was also achieved by the application of a heat-resistant neutral protease resulting in a ‘cashmere-like’ feel.[34] The combined use of the chlorinating agent dichloroisocyanurate and a proteolytic enzyme was also reported to improve handle properties.[35] In contrast to the descaling of wool, some investigations follow another attempt to improve handle. Benesch[36] described the complete removal of degraded or damaged portions of wool fibres, not of the cuticle alone, by a protease treatment, followed by a rinse with formic acid and by the application of a softener. A cashmere-like handle was also achieved by treating wool with sodium dichloroisocyanurate, neutralizing, incubating with papain and steaming at 100 °C.[37] Wool/cotton blends were treated by cellulases and proteases, resulting in a soft feel of the material.[38]

By carefully controlled treatments with proteolytic enzymes, it was possible to reduce the buckling load of wool yarns. It was shown that softness is improved and the subjectively perceived prickle of fabrics is reduced.[39] The new yarn-bundle compression test discriminates between wool samples that differ by about 1 μm in mean fibre diameter.

15.2.5 Whiteness and lustre

Another important factor in wool fibre pretreatment is the enhancement of whiteness and lustre. Bleaching of wool is necessary, especially when dyeing in pastel shades is desired. Using proteolytic enzymes alone[40] or in combination with H_2O_2,[41] the degree of whiteness and the hydrophilicity of the fibres were increased compared to the sole oxidative treatment.[42] Whiteness in wool bleaching is enhanced by the presence of a protease with both peroxide bleaching and using dithionite or bisulphite.[43] The treatment is accompanied by losses in weight and strength.

15.2.6 Dyeing behaviour

The suitability of enzymes for improving the dye uptake of wool was studied by integrating the enzymatic process in a pretreatment step prior to dyeing,[28] and by using them as auxiliary agents in wool dyeing.[44] It was shown that bulky dyestuffs are taken up more equally and in higher amounts by the enzyme-treated samples.[45] The fastness of dyed wool samples to artificial light is enhanced after enzyme treatment.[44]

15.2.7 Carbonization

Beside wool itself, natural soilings like vegetable matter (grass seeds, burrs) and skin flakes can be enzymatically modified. If not completely degraded and removed from the textile goods, vegetable matter and skin residues will lead to uneven dyeing and printing. The vegetable matter is normally removed by carbonizing, a process where wool is impregnated with sulfuric acid and then baked to char the cellulosic impurities. The residuals are then crushed and extracted from the wool as carbon dust by brushing and suction. Research work has been done to replace carbonizing by the use of enzymes like cellulases and ligninases, with the aim of reducing wool fibre damage and effluent load, and to save energy.

Some patents concern the enzymatic decomposition of plant constituents in wool. Sawicka-Zukowska and Zakrzewski[46] reported the removal of plant impurities from wool by the use of hydrolases, lyases and oxidoreductases. The amount of sulfuric acid used for carbonization was reduced by the action of cellulolytic and pectinolytic enzymes.[47] After having incubated wool with cellulases, burr removal became easier by weakening the cohesion between burr and wool.[48] No chemical or physical damage to the wool was observed after mechanical removal of the enzyme-treated burrs. Brahimi-Horn et al.[49] gave a survey of the use of enzymes on a range of model compounds for wool grease and on vegetable matter. The treatment of wool by a mixture of cellulases, pectinases and ligninases did not impair wool fibres. Liebeskind et al.[50] produced commercially unavailable lignin peroxidases with the aim of degrading especially the lignin of the burrs. The process of lignin degradation is a long-term process and in the time recorded (24 h) H_2O_2 was added several times. The wool was not attacked by this procedure, but neither were the burrs markedly modified. The 'Biocarbo' process was introduced, applying pectolytic and cellulytic enzymes by padding and washing in an acidic enzyme bath.

After drying, vegetable residues are removed by carding or beating; the method is recommended for wools containing less than 3% vegetable matter.[51] In contrast to this, the removal of vegetable matter from wool by using a trash tester (USTER MDTA 3) was not enhanced after treatment with hydrolytic enzymes (pectinases, hemicellulases, cellulases).[52] There are prospects for the use of oxidative enzymes in this field.

15.2.8 Silk

The degumming process of silk as another representative of natural proteinaceous fibres is normally performed by chemical treatment using soaps, alkali, acids or water. By this process, sericine, the amorphous protein glue, is removed from the silk thread liberating two highly crystalline fibroine fibres. Besides chemical degumming, the proteolytic removal of sericine is also successfully applied.[53] It was shown that the application of ultrasound accelerates the degumming process when using the proteolytic enzyme papain, whereas in the case of Alcalase™ (NOVO Nordisk A/S) and trypsin, the beneficial effect of the physical treatment is lower.[54]

15.2.9 Summary

Of all the processes described, only a few are 'pure' enzymatic processes, i.e. enzyme processes without any pre- or post-treatment. In two processes, other enzyme classes than proteases are used: transglutaminase[32] and protein disulfide isomerase.[31] Proteases are used to cut off the damaged fibres[36] or to achieve certain texturing effects.[38,55] The combined processes using proteases include the additional application of a resin[19,20,23,25,26] where the enzyme is used as a pre- or post-treatment. Oxidative[20–22,33,35,37,56] and physical pretreatments[20–22] are also combined with the application of enzymes. Then, emphasis is put on softening or improving the handle, followed by dyeing acceleration,[57–59a,c] bleaching[40,41] and pilling resistance.

In the combined processes, the cuticle surface is modified by the respective pretreatment removing lipids and cleaving disulfide bridges and, by the proteolytic post-treatment, enhancing the number of hydrophilic binding sites in the fibres. Both pre- and post-treatment lead to electrostatic repulsion of the fibres, to an enhanced degree of fibre swelling and to an improved dye uptake. If the fibre modification is successfully performed by the use of enzymes alone, either other enzyme classes than proteases are applied[11,31,32] or proteases are used not to modify the fibre itself but to completely degrade and remove fibres having been damaged in the course of earlier processing steps.

The combined enzymatic processes, including chemical pretreatment and especially chlorination steps, are not real alternative processes because AOX is still produced, even though in reduced amounts.

By the complete descaling of the fibres on the one hand both lustre and handle are enhanced and feltability is reduced. On the other hand, the fibre cortex is being exposed, thus leading to a weakening of the fibre. Regarding the fibre damage by enzymatic, especially proteolytic action, it can be stated that in order to achieve the desired effect, either the enzymatic action has to be controlled, e.g. diffusion control by enzyme immobilization,[59b] or the enzyme has to be specially 'designed', e.g. by genetic engineering. By the latter processes, a new enzyme is created or a usual enzyme is modified in such a way that only a distinct part of the target substrate is altered. Fornelli describes enzymes suitable for wool finishing as 'intelligent' or 'magic'.[25,26,42] Actually, the user of enzymes takes advantage of the enzyme's inherent characteristics of specificity and selectivity, the enzyme under use being either native or especially designed for a distinct process.

15.3 Treatment of cotton with enzymes

15.3.1 Morphology of cotton

Cotton is built up of cellulosic and non-cellulosic material. The outermost layer of the cotton fibre is the cuticle covered by waxes and pectins, followed inwards by a primary wall built up of cellulose, pectins, waxes and proteinic material.[60] The inner part of the cotton fibre consists of the secondary wall subdivided into several layers of parallel cellulose fibrils and the lumen. The smallest unit of the fibrils is the elementary fibril, consisting of densely packed bundles of cellulose chains.[61] In longitudinal direction, highly ordered (crystalline) regions alternate with less ordered (amorphous) regions. The non-cellulosic material is composed of pectins, waxes, proteinic material, other organic compounds and minerals. Additionally, sizes and soilings are added to cotton fibres. The whole material adhering to the fibre is up to 20% of the fibre weight. The non-cellulosic material is situated in or on the primary wall, the outer layer of a cotton fibre making up 1% of the fibre diameter. The secondary wall, which amounts to 90% of the fibre weight, is mainly composed of cellulose.

The enzymatic hydrolysis of cotton is performed by cellulase, being composed of at least three enzyme systems working together synergetically.[62,63] Endo-β(1,4)-glucanases (1) hydrolyse chains of native cellulose, thus degrading structures of low crystallinity and producing free chain endings. Cellobiohydrolases (CBHs) (2) degrade cellulose from the chain end, liberating cellobiose, which is hydrolysed by β-(1,4)-glucosidase (3) to glucose units. The most important cellulase-producing organisms are fungi of the genus *Trichoderma*, *Penicillium* and *Fusarium.*

Pectin is the generic term for polysaccharides like galacturonans, rhamnogalacturonans, arabinans, galactans and arabinogalactans. The hemicelluloses, consisting of xylans, glucomannans and xyloglucans, build up the other group of non-cellulosic material. In cotton, pectins mainly consist of α-(1,4)-bound polygalacturonic acid, the carboxylic groups being esterified with methanol. Pectinolytic enzymes are polygalacturonases cleaving the α-(1,4)-glycosidic bonds of pectin.

15.3.2 Enzymatic processing of cellulosic fibres

The enzymatic treatment of cotton can be subdivided into three major topics. The first one concerns the cellulosic part of the cotton and consequently the enzymes used are mainly cellulases. The effects achieved by these enzymes are pilling reduction, increase in softness, and amelioration of handle, surface structure and fabric appearance. These effects are summarized as 'biopolishing', a term created by the Danish company NOVO Nordisk. In the second application of enzymes in cotton finishing, the stone-wash process of denim material is replaced by the use of cellulases. By the enzyme treatment, the amount of stone material required can be reduced or even completely replaced and, unlike the stone-wash process, the enzyme treatment can be prolonged without damaging the textile material. The third area of application concerns the removal of natural fibre-adhering material (pectin) as a preparatory procedure for the subsequent processing steps. Pectinases, or a combination of pectinases and cellulases, are the enzymes used for degradation of the pectin material. The influence of interfering factors like surfactants, electrolytes and dyestuff materials on the quality of biofinish processes has been monitored via weight loss determination.[64] Cellulase treatment is not just for cotton but also for synthetic cellulosic fibres like lyocell/tencel and rayon, where it improves softness, drapeability, pilling tendencies and post-laundry appearance. On cellulose acetate, it is described as giving little benefit.[65] Using enzymes for the modification of lyocell in fibre blends, the enzyme product always has to be adjusted to the needs of the accompanying fibre.[66]

15.3.3 Biopolishing

The softening effects achieved by enzymatic treatment of cotton textiles were already patented 20 years ago.[67] The treatment did not lower the tensile strength while softening the textile. In 1981, a process was patented which comprises swelling of the cellulosic fibres with sulfuric acid, followed by a treatment with cellulases to give a modified fabric with soft handle.[68] The first real cellulase treatment of cellulosic fibres was published in 1988.[69] The process led to a weight reduction of the fibres, and a weight loss of 3–5% was evaluated as the optimum to obtain a soft handle and a better surface appearance. A combined process for cotton softening was patented in 1990.[70]

A low-temperature plasma was applied prior to the cellulase treatment. The effect was measured by the determination of the tear strength. By treating cotton fabrics with cellulases, e.g. from *Trichoderma reesei*, an improved softness and fabric appearance and a high dyeing yield are achieved, the weight loss of the fibres remaining low.[71] Seko et al.[72] described the use of cellulases produced by bacteria of the genus *Bacillus* on a cotton knit, enhancing softness and hygroscopicity and preserving excellent fibre tensile strength. In 1992, Pedersen et al.[73] reported the 'biopolishing' effect. The basis of biopolishing is a partial hydrolysis of the cellulosic fibres,[74] resulting in a certain loss of tensile strength. The optimum effect was achieved, with a loss in strength of 2 to 7%. The short fibre ends emerging from the fabric surface were enzymatically hydrolysed but an additional mechanical treatment was necessary to complete the process, i.e. to remove the fibres normally leading to pilling. The surface appearance of the fabrics treated in that way was improved. The effect was permanent, i.e. even after several machine washings, the textiles remained almost entirely without pills. In contrast to the softeners applied to the fibre surface, the water regain was not decreased by the enzymatic treatment.[75a,b,c] The process parameters and the commercial name of the enzyme used were disclosed by Bazin et al.[76] In 1993, a biopolishing process was patented by Videbaek and Andersen[77] With a surface application of the enzymes instead of batch processing, the strength loss of the fibres was minimized in the softening treatment of towelling.[78] The treatment of cotton/wool blends with cellulases and proteases resulted in fabric softening.[38] Cellulase-treated cotton fabrics were compared to alkali-treated polyester fabrics with 5% weight loss each; in both cases bending rigidity was decreased.[79] Clarke introduced an enzymatic process to reduce pilling, especially from garment dyed goods made of cotton or wool.[80] In the case of wool, a reduction reagent was added. The mechanism of cellulose degradation was described by Almeida and Cavaco-Paulo[81] The enzymatic hydrolysis of the cellulose mainly occurs in the amorphous regions. Consequently, a pretreatment decreasing the degree of crystallinity of the cellulose will enhance the enzymatic hydrolysis rate, e.g. mercerized cotton will be more prone to enzymatical modification than non-pretreated cotton. The authors define the softness of a fabric: the mechanical properties of a soft fabric are characterized by low bending and shearing stiffness and a high degree of elongation. A long-term enzymatic treatment exhibits a negative effect causing fibre damage and a decline of handle properties. Koo et al.[82] reported the use of cellulases on cotton dyed with different dye classes. A fabric dyed with direct or reactive dyes seemed to inhibit the cellulase action, documented by the fact that the higher the dye concentration on the fibres, the lower the weight loss of the fibres after enzyme treatment. In contrast, the catalytic action of cellulases applied to fabrics dyed with vat dyes was not inhibited (this is an important fact concerning the biostoning of cotton referred to later in this article). The authors also confirm that the fuzziness of the garments was reduced by degradation of the fragments of cotton fibrils, and as a consequence the treated fabrics showed less colour fading after laundering. Because of its lower degree of polymerization as compared with cotton, rayon is more sensitive to losses of strength when treated with cellulases.[83]

Generally it is accepted that short treatment time and surface-sensitive mechanical impact lead to a targeted surface modification of cotton, whereas continuous installations without liquor turbulence are unsuitable for this purpose.[84] Mechanical agitation during enzyme treatment affects not only tactile and aesthetic qualities but also thermal comfort performance.[85] Considering the variety of dyeing machines and methods that involve very different modes and levels of agitation, the effect of mechanical agitation on the quality of the cellulase-treated textile goods is of high practical interest. It was elucidated that endoglucanase activity increased at high agitation levels, thus leading to a higher risk of fabric strength loss.[86] Besides mechanical agitation, fabric processing history and fabric construction are as important parameters as the choice of enzyme composition and concentration.[87]

The components of the cellulase enzyme system were purified and analysed for their impact on cotton modification. Regarding cotton samples with same weight loss levels, either due to the catalytic action of cellobiohydrolase (CBH I) or endoglucanase, more strength loss was observed in the case of the endoglucanase-treated sample, but at the same time, positive effects on bending behaviour and pilling were achieved.[88] Compared to an endoglucanase-enriched preparation, the use of whole cellulase is more effective regarding surface fuzz removal, whereas the endo-enriched enzyme is less aggressive and causes less fibre damage, thus being more suitable for delicate knits.[89] Enzymatic hydrolysis of cotton fabrics dyed with direct dyes leads to weight losses equal to that of undyed fabrics, whereas on cotton dyed with reactive dyes, enzymatic degradation seems to be inhibited.[90]

15.3.4 Biostoning

Many casual garments are treated by a washing process to give them a ‘worn appearance’. A well-known example is the stone-washing of denim jeans; the blue denim is faded by the abrasive action of pumice stones. In the ‘biostoning’ process, cellulases (neutral or acidic) are used to accelerate the abrasion by loosening the indigo dye on the denim.[91] The process is highly environmentally acceptable because of replacing or reducing the amount of stones, thus protecting the machines and avoiding the occurrence of pumice dust in the laundry environment. The process has already found broad acceptance in the denim-washing industry. Tyndall reported the use of cellulases in combination with a mechanical action for improving softness and surface appearance.[92] Enzymatic treatment led to a worn appearance of textile goods dyed with ‘indigo, sulfur, pigments, vats or other surface dyes’. In this treatment, a certain degree of weight and strength loss has to be accepted. A broad survey of the denim finishing programme was given by Ehret,[93] describing the indigo dyeing process, the stone-washing process and its substitution by the cellulase treatment. To gain the desired ‘old look’ of denim material, it is important to minimize back staining, being highest at pH 5. Ehret stated that cellulases hydrolysing cellulosic material in the neutral pH range therefore, are preferably used for jeans finishing. Zeyer et al.[94] drew up an empirical model based on the observations made during the enzymatic decolourization of cellulose fabrics. The authors conclude that fibre surface friction plays an important role in the enzymatic decolourization of cotton. They state that mechanical action opens the outermost layers of the cellulosic crystal, thus increasing the enzyme-accessible part of the cellulose and allowing the enzymatic removal of the dye.

Indigo backstaining during biostoning was studied. It was concluded that backstaining increases with treatment time and enzyme concentration. Using different enzymes, the backstaining is low in case of a neutral cellulase (pH 6–8) and high in case of an acid cellulase (pH 4.5–5.5).[95]

15.3.5 Bleach cleanup

After bleaching cotton with H_2O_2, the bleaching liquor cannot be used for the next treatment step, e.g. dyeing, because of the oxidative effect of the residual H_2O_2. The degradation of this residual H_2O_2 in the bleaching bath by the enzyme catalase makes replacement of the treatment liquor or the washing of the goods unnecessary. Thus the same liquor can be used for the next processing step, leading to a saving of time, of waste water, and of energy.[96] The process of removing residual peroxide from cotton material was evaluated not only from an ecological but also from an economical point of view, with the result that, by the application of catalase the amount of fresh water used for rinsing, cooling and heating is reduced and waste water is saved, leading to total cost savings of 6 to 8% per year.[97]

15.3.6 Bioscouring

Effective dyeing and printing of textiles require uniform adsorbency. Furthermore, no disturbing amounts of dirt, sizes or adhering natural material should remain on the fibres. Sixty percent of all the problems occurring in the dyeing and finishing of cotton originate from a wrong or uneven pretreatment.[98]

Therefore, the pretreatment is the most important step in cotton finishing. Consequently, the adhering natural material and the sizes have to be removed. Surface waxes produce a water-repellent fibre surface. Seed husks, pectins, hemicelluloses and sizes fix part of the dyestuff and therefore cause uneven dyeing. Furthermore, when using sodium hypochlorite as a bleaching agent, this material, if not removed,[99] leads to the formation of AOX in the effluent. Therefore, prior to the bleaching process an alkaline boiling off is performed to reduce the amount of cotton-adhering material.

Regarding the enzymatic removal of natural material-adhering cotton, Bach and Schollmeyer examined the degradation of the cotton pectin by pectinolytic enzymes.[100] The pectin was either extracted from the cotton and used as a substrate in homogeneous solution, or degraded directly on the cotton surface in heterogeneous reaction. The degree of degradation was determined by measuring the amount of reducing groups being released into the solution. The consequences of this degradation were published by Bach and Schollmeyer in 1993.[101] The degree of whiteness after enzymatic degradation of the pectin was lower compared to alkaline boiling-off. However, combining the enzyme treatment (a simultaneous treatment of pectinase and cellulase) or the alkaline boiling-off with an alkaline H_2O_2 bleaching, the total degree of whiteness was higher in combination with the enzyme treatment. Roessner[102] confirmed that the degree of whiteness of a cotton sample only treated with enzymes was lower by 8–10% than the degree of whiteness of an alkaline boiled-off material. The effect of the enzymatic treatment was also determined by measuring the wettability of differently pretreated fabrics. The differences were documented by the TEGEWA drop test. Desized fabrics were either enzyme or alkali treated. Differences in wettability occurring in this treatment step were removed by an additional peroxide bleaching process. The combined process, including an enzyme treatment, delivered results comparable to the alkali treatment.

Factors influencing scouring are the nature of the substrate, the kind of enzyme used, the enzyme activity, the use of surfactants and mechanical impact.[103] It was observed that, during pectinase scouring, much less wax was removed compared with the alkaline scouring. If the treatment was combined with surfactant treatment, results equivalent to alkaline scouring could be achieved.[104] A water treatment at 100 °C is reported to increase the effectiveness of the subsequent scouring of cotton fabric with a combination of pectinase, protease and lipase, whereas the use of these enzymes alone showed very little effect.[105] A new pectinase (BioPrep™, NOVO Nordisk A/S) was screened that is stable under alkaline conditions, i.e. the optimum conditions for removal of cotton-adhering substances. Pectinase action does not create full wettability alone. Surfactants, Ca-binding salts, emulsifiers and high treatment temperatures complete the removal of the Ca-pectate/wax complex.[106]

The relative colour depths of caustic soda-scoured and environmentally friendly bioprepared fabrics do not show significant differences.[107]

The effect of scouring with enzymes was compared to conventional caustic soda treatment and solvent extraction. Whereas caustic soda treatment resulted in the highest deterioration on a molecular level, but led to a high level of whiteness, the solvent-extracted samples showed superior tensile strength and the bioscoured samples the best softening effect.[108]

15.3.7 Linen

Linen is the most sensitive fibre concerning treatment with cellulases. It has been worked out that mono-component cellulases are necessary to limit the enzyme treatment to the desired effects like enhanced handle or used look on pigment-dyed or printed textiles. To improve dyeing and wrinkle recovery, a major proportion of the pectic substances has to be eliminated without damaging the cellulosic part of the fibres. It is described that the control of this reaction is difficult in practice.[109] The quality of flax fibres can be enhanced via controlled enzyme retting, thus minimizing over-retting and reduced fibre strength.[110,111]

15.3.8 Hemp

Hemp fabrics were modified by using cellulase, hemicellulase and cellulase in combination and cellulase plus β-glucosidase. The hydrolysis rate and product properties like tensile strength, crystallinity and pore structure were investigated. It was shown that mechanical agitation has the greatest impact on the fabrics when applied during the enzyme treatment. The largest total porosity and the highest number of small pores was achieved after a treatment using cellulase alone.[112]

15.3.9 Lyocell

Lyocell is a synthetic cellulosic and a high-fibrillating fibre. The high fibrillation rate leads to interesting handle and look, although dyeing and finishing are more difficult due to the higher risk of local damage.[84] During processing, a primary fibrillation occurs due to hydro-mechanical action. After that stage the cellulase treatment is performed. By the catalytic action of these enzymes, fibrillated fibres are removed. In a subsequent secondary fibrillation step, short fibrils that cannot connect to form pills are produced, thus leading to a change in handle and appearance (peach skin). Endoglucanase-enriched enzyme preparations produce superior fabric handle and minimize seam damage.[113]

15.3.10 Summary

Most of the work done in the field of enzymatic cotton processing concerns the reduction of pilling and fuzzing of cotton fabrics by the catalytic action of cellulases. Furthermore, casual wear is produced by the catalytic action of cellulases in the biostoning process, replacing stone-washing.[93,94] In some of the processes, the enzyme treatment is combined with mechanical action to enhance the accessibility of the cotton substrate.[92] Another approach is the combination of a plasma treatment with the enzyme treatment.[70] A lot of research work has been done in the field of enzymatic scouring of cotton, with the aim of replacing the alkaline boiling-off.[101,102] The kinetics of enzymatic pectin degradation was investigated to study and optimize the process.[100] Bast fibres like flax and hemp, and synthetic cellulosic fibres like lyocell are also targets for enzyme-catalysed processes and have already been successfully modified.

15.4 Enzymatic modification of synthetic fibres

Polycaprolactone fibres were modified by the catalytic action of a lipase. The fibres were not stretched because the enzyme-catalysed degradation declines with rising degrees of stretch. After enzyme hydrolysis, fibres in unstretched form show irregular structures, whereas stretched fibres show longitudinally oriented structures.[114] Lipases improve wetting and absorbency of polyester fabrics. Compared to the reduced strength and mass from alkaline hydrolysis, the enzyme-treated fabrics showed full strength retention. The wettability effect proved to be due to hydrolytic action rather than protein adsorption.[115]

15.5 Spider silk

Spider dragline silk is stronger than steel and has a tensile strength approaching that of Kevlar. It is remarkable in its extremely high elasticity.[116] This unusual combination of high strength and stretch renders this material extremely attractive for researchers. Spider's dragline silk is mainly constituted of glycine (42%) and alanine (25%), and the remainder is predominantly built up of glutamine, serine and tyrosine.[117] Poly-alanine of 5 to 10 residues builds up a β-sheet and accounts for most of the crystalline fraction (30%). The crystalline domains are bonded via glycine-rich regions (β-turns) and are embedded in amorphous regions.[118] In humid surroundings the fibres supercontract, achieving 60% of their former length. It is the aim of research work to produce spider silk proteins biotechnologically in requested quantities and process them to fibres in industrial scale.[119] There are two main tasks within this field. First, the cloning and recombinant expression of spider silk proteins and second, to elucidate fundamentals and requirements for the processing of spider silk proteins to fibres. Spider silk analogues have been expressed in bacterial cells[120] but the overexpression of larger protein segments has not been achieved up to now.[119] Model substances like degummed natural silk from the mulberry silkworm *Bombyx mori* were used for solubility studies and for testing a laboratory scale spinning device to produce filaments from polymer solutions of small volume.[119] The future will show if appropriate technological parameters, possibly including biotechnical processing, will be feasible.

15.6 'Intelligent' fibres

Textiles contributing to thermal regulation via the incorporation of 'phase change' materials are related to wear comfort, especially in sports and leisure wear. Perspectives are opening up for these materials also in the field of medical textiles[121] and protective clothing with shape memory for fire brigades and racing and petrol pump attendants is under development.[122] The latter contains shape memory materials in a layer that at certain high temperatures contribute to the formation of an insulating layer by returning to their original shape. In this way, it protects the human from being overheated. The perspectives for biotechnical processing in the field of specialty fibres ranges from the enzyme-catalysed functionalization of fibres to the inclusion and thus immobilization of enzymes in or on those fibres.

15.7 Conclusions

The use of enzymes in cotton finishing has found much broader acceptance than the use of enzymes in wool finishing. Enzymatic processes are already well established in the cotton industry. The terms biofinishing and biopolishing are not only advertising slogans but also stand for ecologically acceptable processes. Compared to cotton fibres, wool is a more complex fibre material. The composite structure and the accessibility even of the bulk part of the fibres complicate the restriction of the enzyme treatment to the fibre surface. The complete degradation of fibres or fibre ends from textiles by enzymatic treatment leads to the desired effects of lustre and softness in cotton finishing. In wool finishing, single fibres have to be modified to achieve, for example, the antifelting effect, soft handle and lustre. Therefore, reaction control plays a more important role in wool finishing due to the possibility of enzymes diffusing into and damaging the wool fibres. Wool fibres are often pretreated by chemical or physical means prior to the enzyme treatment, to enhance the accessibility of the cuticle, to shorten the treatment time and to restrict the enzyme to the fibre surface.

Hence, the design of specialized enzymes reacting with only one specific component of the fibre and/or the production of diffusion-controlled enzymes might be a solution to develop future biotechnical processes for textile finishing. Thus, not only optimization of process parameters like pH value, temperature, ionic strength and knowledge on technological items like mechanical impact due to different machine devices, but rather completely engineered enzymes will lead us to 'tailor-made' smart products and processes. There is therefore a need for close cooperation between textile and bio-chemists that will lead to new enzymes and new fibres. As one example, there are vast perspectives in the field of 'intelligent' textile materials. In view of this, it should never be forgotten that enzymes should not be used for the sake of enzymes. However, it has been shown in many fields that ecology and economy profit from intelligent enzymatic processes.

The major advantage of enzymatic processes is the possibility of using conventional technology already existing in textile plants. Enzyme formulations should be applied in solution, to avoid dust formation and to reduce the known allergizing potential of protein material when inhaled. A heat treatment is sufficient to stop the enzymatic action irreversibly. Thus the transfer of an enzymatic process developed on laboratory scale into the textile industry should be possible without great delay.

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