THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Interactive Textile Structures

Creating Multifunctional Textiles based on Smart Materials

LENA T H BERGLIN

Department of Computer Science and Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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LENA T H BERGLIN

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Chalmers University of Technology
Doctoral Program: Human – Technology – Design
Department of Computer Science and Engineering

Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone +46 (0)31 – 772 1000

The Swedish School of Textiles
University Borås
SE-501 90 Borås
Sweden
Telephone +46 (0)33 – 435 4000

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ABSTRACT

Textiles of today are materials with applications in almost all our activities. We wear clothes all the time and we are surrounded with textiles in almost all our environments. The integration of multifunctional values in such a common material has become a special area of interest in recent years. Smart Textile represents the next generation of textiles anticipated for use in several fashion, furnishing and technical textile applications. The term smart is used to refer to materials that sense and respond in a pre-defined manner to environmental stimuli. The degree of smartness varies and it is possible to enhance the intelligence further by combining these materials with a controlling unit, for example a microprocessor. As an interdisciplinary area Smart Textile includes design spaces from several areas; the textile design space, the information technology design space and the design space of material science.

This thesis addresses how Smart Textiles affect the textile design space; how the introduction of smart materials and information technology affects the creation of future textile products. The aim is to explore the convergence between textiles, smart materials and information technology and to contribute to providing a basis for future research in this area. The research method is based on a series of interlinked experiments designed through the research questions and the research objects. The experiments are separated into two different sections: interactive textile structures and health monitoring.

The result is a series of basic methods for how interactive textile structures are created and a general system for health monitoring. Furthermore the result consists of a new design space, advanced textile design. In advanced textile design the focus is set on the relation between the different natures of a textile object: its physical structure and its structure in the context of design and use.

Keywords: Smart Textile, Textile Design, Textile Engineering, Textile Sensors, Textile Actuators, Conductive Textiles.

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LIST OF APPENDED PAPERS

PAPER I

Berglin L. (2005). *Design of a flexible textile system for wireless communication*. In Proceedings of World textile Conference, AUTEX 2005, Portoroz, Slovenia 2005

PAPER II

Berglin L. (2005). *Wanted 2 – a mobile phone interface integrated in a glove.* In Proceedings of Ambiene, Tampere, Finland, 2005.

PAPER III

Berglin L. (2005). *Spookies – Combining Smart Materials and Computing Technology in an Interactive Toy*. In Proceedings of Interaction Design for Children, IDC 2005, Boulder, Colorado, USA, 2005.

PAPER IV

Berglin, L., Zetterblom, M. (2008). *Textile microphone elements*. In Proceedings of World Textile Conference, AUTEX 2008, Biella, Italy, 2008.

PAPER V

Sandsjö, L., Berglin, L., Wiklund, U., Lindecrantz., K. Karlsson, J.S. (2006). *Self-administered long-term ambulatory monitoring of electrophysiological signals based on smart textiles*. In Proceedings of IEA 2006, International Ergonomics Association Conference, Maastricht, the Netherlands, 2006.

PAPER VI

Wiklund, U., Karlsson, M., Östlund, N., Berglin, L., Lindecrantz, K., Karlsson, S., Sandsjö, L. (2007). *Adaptive spatio-temporal filtering of disturbed ECGs: a multi-channel approach to heartbeat detection in smart clothing*. Medical and Biological Engineering and Computing, Volume 45, Number 6, 2007. Springer Link.

PAPER VII

Karlsson, S. J., Wiklund, U., Berglin, L., Östlund, N., Karlsson, M., Bäcklund, T., Lindecrantz, K., Sandsjö, L. (2008). *Wireless Monitoring*

of Heart Rate and Electromyographic Signals using a Smart T-shirt. In Proceedings of pHealth 2008. International Workshop on Wearable Micro and Nanosystems for Personalised Health, Valencia, Spain, 2008.

INVOLVEMENT AND PARTICIPATION

PAPER I, II AND III
Performed the whole study and wrote the text.
PAPER IV
Performed the study setup, analysis, design the experiment, made the experiment materials, performed the measurement and participated in writing the text.
PAPER V, VI AND VII
Participated in the development of the concept. Performed the textile part of the experiments: design and manufacturing of textile electrodes, data transfer. Designed and developed the garments. Developed the general electrode system. Participated in writing the text around textiles and applications.

REFEREED PAPERS NOT INCLUDED

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Östlund, N., Karlsson, M., Karlsson, S., Berglin, L, Lindecrantz, K., Sandsjö, L., Wiklund, U. (2006). *Multichannel for heartbeat detection in noisy ECG recordings*. World congress on Medical and Biomedical Engineering. Seoul Korea, 2006.

Berglin, L. (2008). *Designing for extreme conditions*. In Proceedings of Cumulus Design Conference, Kyoto, Japan, 2008.

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All photographs and illustrations made by Lena Berglin unless stated otherwise.

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1. INTRODUCTION

Textiles have been part of human life for thousands of years. In the beginning, humans used textiles primarily as clothing or protection, but textile use has gradually broadened. Textiles of today are materials with applications in almost all our activities. We wear clothes all the time and we are surrounded by textiles in almost all our environments. The integration of multifunctional values in such a common material has become a special area of interest in recent years. Fibres yarns, fabric and other structures with added-value functionality have been developed for a range of applications [Lam Po Tang, Stylos]. Textile materials and techniques have become an important platform for high-tech innovations.

Smart Textile represents the next generation of textiles anticipated for use in several fashion, furnishing and technical textile applications. Smart material is a generic term for materials that in some sense react to their environment. These materials have been known in polymer science and electronics for a long time. In smart technology and intelligent systems, for example, smart materials such as sensors and actuators are available in a wide range of products [Singh][Worden et.al]. Smart Textile is based on research which has its foundation in different research disciplines; textile design and technology, chemistry, physics, material science , computer science and technology. Significant for this research is the interdisciplinary approach and the interaction between basic and applied research. Examples of basic research can be found in the investigations of how functionalities are built in textile fibres and structures, for example sensor [Meyer et.al][Tognetti et.al] or actuator structures [Chan Vili][Mörhing et.al]. The applied research on the other hand explore the area from an application approach where different basic research results are combined in a product. Examples of applied research are health monitoring prototypes [Weber et. al][Paradiso et.al] where expertise in textiles, computing technology and signal processing integrate textile electrode systems in garments in order to measure biomedical signals such as heart rate.

The vision of Smart Textile is to create textile products that interact by combining smart materials and integrated computing power into textile applications. The introduction of smart materials and computing technology in textile structures offers an opportunity to develop textiles with a new type of behaviour and functionality. Besides behaviour like sense, reaction and conducting electricity, the textile will be able to perform computational operations [Leitch]. Smart Textile and computing technology are introducing a shift in textile, from a passive to a dynamic behaviour, from textiles with static functionalities to products that exhibit dynamic functionalities. But the convergence between textile, smart materials and computing technology may not only affect textile products. It may also change the way we design and use computer artefacts. There will be another dimension in textile design, which is interactivity, but there will also be another dimension in computer artefacts, the textile structure. The shift of dimensions will affect the use, design and aesthetics of textile and computer products.

New dynamic forms of behaviour change the applications areas and the way we use textiles. The aesthetical processes will change accordingly since aesthetics will not only concern static visual elements like form, composition and colour. When textile products become more interactive, textile design approaches interaction design. Interaction design is the design of interactive products, so far mostly focused on different types of computer artefacts like desktop appliances in computers, PDA or mobile phone for examples. Human computer interaction is the most established discipline within interaction design concerned with the design, evaluation and implementation of computing system for human use [Carroll]. But interaction design also refers to immaterial processes and services that adapt to user needs and preferences [Thackara]. Today interaction with desktop appliances is not the only issue in interaction design. Ubiquitous computing is a desktop model in which information processing is integrated in everyday objects and activities [Weiser et.al]. Opposed to the traditional use of computers where a single user engages a single device, a user of ubiquitous computing engages many computational devices and systems simultaneously, and may not necessarily be aware of doing so. Ubiquitous computing for everyday use in the Smart Textile context includes products that we more or less interact with. Clothing for example will not be something we wear to protect and express ourselves; clothing can at the same time be used for measuring health status, facilitating communication and expressing our feelings in real time. Textiles in our environment will not just be something we use to decorate our homes and workplaces, they will at the same time communicate or bring data from our environment. Textiles have the opportunity to act as a user interface to technology that is already there and that we always bring with us, and we may use them consciously or without being aware. Design of user experience as well as physical properties will be a part of the smart textile design process.

Besides new behaviour Smart Textile introduces new principles from materials science as well as computer science and engineering. Basic investigation on how textile structures transfer different types of signals, basic foundation in sensing techniques and acoustic values are new elements in the textile design space. How different energy fields are converted due to different stimuli in smart materials is also a new type of aspect to be considered in the design process. Understanding the basic structures of materials also provides a basis for designing materials with different qualities or properties. We can describe these as the properties or values of interactive textile structures. To understand and apply these new principles, it is necessary to explore the convergence between textile, smart materials and information technology. Understanding sensors and actuators and the possibilities to control them using software has so far been an advantage in smart textile research and a majority of contributions and initiatives in smart textiles have their origin in computing science and engineering labs. But approaching smart textile as computing in textiles has shortcomings. Electronics and computing development aims to find the most effective solution according to electronic functionality with reference to hardware and software. But integrating interactivity into textiles requires a wider perspective. Textile is soft and flexible and textile use requires a material that stands wear and tear and sometimes several washing cycles. To get a maximum performance in textile, maximum performance in software and hardware will sometimes have to be reduced.

Progress in smart textile will depend on how successful we are in combining research from different disciplines like material sciences, electronics and computer science to textile technology and textile design. Applied research combined with basic research is an opportunity to relate the different projects systematically to the basic questions of what smart textile will mean for future textile products. In such speculations the notion of smart textile is a central issue: What is a smart textile? What is the motivation for smart textiles? What new methods do we need to develop? When should we define the products as textile and when is it to be considered a computing product?

As an interdisciplinary area Smart Textile includes design spaces from several areas; the textile design space, the information technology design space and the design space of materials science. This thesis addresses how Smart Textile affect the textile design space; how the introduction of smart materials and information technology affects the creation of future textile products. The convergence of technologies introduces a set of new design elements into the textile design space, based on new properties and new scientific and technological principles.

The research is based on a series of projects that are interdisciplinary carried out as design activities combined with systematic investigations. While the project-based research looks into the application field and the combination of the research fields through different prototypes, the systematic investigations expressly explore the basis of interactive textile structures.

2. RESEARCH OUTLINE

The aim of this thesis is to explore how the convergence between textiles, smart materials and information technology affect the textile design space and to contribute to providing a basis for future research in this area. The convergence between textile design and design of other types of materials affects the use, the textile structures and aesthetics of textiles and the research addresses the basic foundations of using and creating interactive textile structures. The research is based on a series of interlinked experiments in which three product concepts are explored.

Smart Textile is based on three main areas; textile design and technology, smart materials and computing science and engineering. Each of these contribute to the whole system in their own way; textile design and technology with its materials and fabric structures; smart materials with its ability to react to different stimuli; computing science and engineering for the design of dynamic functionality. A key issue is the level of integration: conventional smart technologies can be integrated in textile products, partly or completely integrated as intelligent functionality in the textile structure. These two levels set the boundaries for the research. When do we or do we not have a Smart Textile? The motivation for a pure textile solution is that electronic components, as designed today, do not acquire the properties required for textile use. Textile is a soft and flexible material designed to have certain properties for fashion interiors and technical application.

Textiles are designed to retain their physical integrity under conditions of mechanical stress. Textile has to remain in the same state after wear, use and care procedures. Finally we require certain comfort values like thermo-physiological, sensorial and movement comfort. These properties are not familiar in information technology where a rather fragile technology is packaged in materials more rigid and unresilient than textile structures. If we for example decompose the components in a photo resistor and create the components as different textile substrates like fibres or coatings and thereafter redesign the functionality into the textile structures as a textile photo resistor. Then we will have a more sustainable solution and a better manufacturing process with the respect to textile than if we just integrate a conventional photo resistor into a textile structure. However, such pure textile solutions will probably not be the only existing solutions in future smart textiles. It is still a combination of technologies and ideas that are motivated but not practicable as pure textile solutions could certainly form acceptable hybrids.

RESEARCH QUESTION

The overall questions addressed in this thesis are:

What will Smart Textile mean for future textile products?
What is a Smart Textile?
What is the advantage of developing Smart Textile?
What new methods do we need to develop?

The convergence of technologies introduces a set of new design elements into the textile design space, based on new behaviours and new scientific and technological principles. The relationship between new technologies and textile structures depends on the issue of integration. The more specifically research questions are:

In what ways is it possible to integrate electronic functionality into textile structure?
In what ways is it possible to integrate feedback in textile structures?
In what ways is it possible to integrate sensor input in textile structures?

These questions aim to deepen the knowledge about basic foundations in interactive textile structures and the combination of these with computing technology.

PRODUCT CONCEPTS

The research questions are explored through three types of products, an idea for a toy, a glove wirelessly connected to the mobile phone and a series of health monitoring prototypes. The products are used as tools for generating experiments and rendering issues and research questions experimentally precise. In addition the prototypes have been used as tools for testing and evaluating research results. The selection of the toy and glove products has mainly been made due to their accessibility concerning products and co-operation partners. As products they were already there and the integrated technology was familiar from both a computing and textile perspective. Concerning the selection of health monitoring as the next research objects it is based on both co-operation aspects and specific interest within the area. The area is motivated from a user approach and it is connected to design for extreme conditions, which was the motivation of the glove project. Besides that, there are probably several interesting projects to approach in the area of health care as a future prospect in the research area.

THE TOY

The toy concept, called Spookies, is an interactive toy that encourages free play. Spookies contain 14 different units organised in seven pairs. Each unit has one function and units in a pair are wirelessly connected. The game can be based on communication between the units but it is also possible to combine the units in order to build more complex ones.

In the toy concept all technology, hardware and software, is embedded in the product. The interaction is based on input to control the interaction and output as different kinds of feedback. In this study both input and feedback are explored through the different aspects of interaction between the user and the product. The research object has been used as a tool for generating experiments aiming to give a practical orientation in smart textiles.

THE GLOVE
The glove is wirelessly connected to the mobile-phone which makes it possible to make and receive calls through the glove. The glove is integrated with a minor part of hardware and software. The main part of technology is placed in the terminal, the mobile phone, to which the glove has a wireless access. The interaction is based on the act of communication to make and receive calls using voice and hand gestures. In this study, the use of technology and user input has been investigated. As in the toy concept, the objects have been used as tools to investigate smart textiles

HEALTH MONITORING
Health monitoring through textile products allows the recording of electrophysiological signals through different types of garments. Clothing with integrated textile sensors enables applications to be made in many areas: clinical applications, sports ergonomics and in professions exposed to dangerous outer circumstances. Unlike the former two applications this is a system which the user interacts with, without being aware of it. The challenge does not lie in interaction but in the construction of the whole system as a textile structure and the garment. In this study research, the objects have been used in an evolutionary process to refine interactive structures into general principles which can be applied in different types of textile fabric structures.

OUTLINE OF THESIS
The remaining part of this thesis describes the research background, methods, experiments, results and conclusions. ***Setting the arena*** presents the research background: smart materials, smart technologies and related Smart Textile projects. ***Textile design*** is the theoretical background for the methodology used in this thesis. ***Advanced textile design*** describes the research method used. ***Experiment and results*** is an overview of realised experiments and the result of these experiments. Experiment and results is divided in two parts: ***Interactive textile structures*** and ***Health monitoring.*** In ***Conclusions*** the overall research questions are discussed. Finally in ***Ideas for the future*** there will be a discussion on how the result contributes to future research efforts.

3. SETTING THE ARENA

Humans have used smart materials for thousands of years [Singh]: "*The footprint of a soft trail can tell a well-trained human what kind of animal recently passed and even how much it weighed. In this case the soft mud acts as the smart material*". The term smart is used to refer to materials that sense and respond in a pre-defined manner to environmental stimuli [Tao1]. The degree of smartness varies and it is possible to enhance the intelligence further by combining these materials with a controlling unit, for example a microprocessor. Such progress has become feasible due to the miniaturisation of computing technology, it possible to combine and even integrate hardware, software and textiles in an unobtrusive way [Tao2]. Wireless linking between various components in the smart textile system is another essential technology supported by the development of wireless technologies.

The basic concept of Smart Textile consists of a textile structure that senses and reacts to different stimuli from its environment. In its simplest form the textile senses and reacts automatically without a controlling unit, and in a more complex form, smart textiles sense, react and activate a specific function through a processing unit (Figure 1). The latter is an example of smart technology with the ability not only to sense the change and react to environmental changes but also to execute measures to enhance the functionality [Worden et.al]. Each application with smart technologies will have its own unique scenario – determined by the intended function.

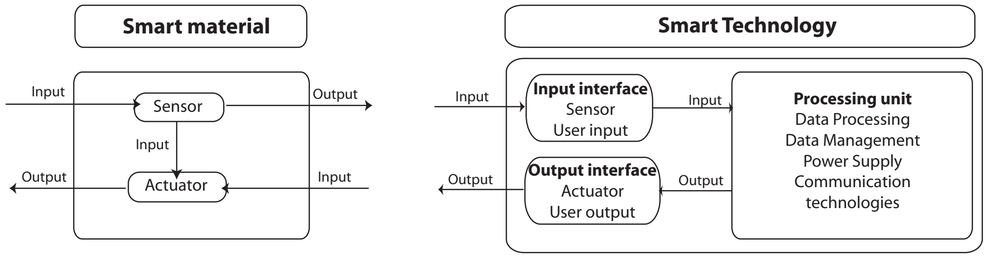


Figure 1. Smart material and smart technology

SMART MATERIALS

There are two different approaches to classify smart materials, classifications that refer to the function and a series of action they go through or classification due to the nature and fundamentals of materials that sense and react.

When smart materials are defined due to their function and behaviour they are usually divided into passive smart and active smart materials [Tao1][Langenhove, Hertleer]. Passive smart materials only sense the environmental conditions or stimuli, they are sensors. Active smart materials both sense and react to the conditions or stimuli, they are sensors and actuators.

Definitions due to the nature and fundamentals go more into the details of the ways in which each material reacts. In these definitions smart materials are divided quite differently. An example of definitions is the output thresholding behaviour in smart materials (Figure 2), which is low for a range of input and then over a small range of input it becomes high [Singh]. This is a response that can be exploited for switching applications or memory applications. The input that a device may respond to, may be an optical or a microwave signal, a poisonous gas, a pressure, an electrical voltage pulse etc. The output response also depends upon a wide range of physical phenomena that alter the state of the device. The most commonly used physical phenomena for smart devices are conductivity changes, optical properties, polarisation changes and magnetisation changes.

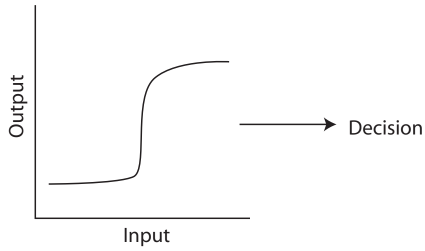


Figure 2. The physical effect of an intelligent device

Another way of explaining the nature of smart materials that could be useful in smart textiles has been made by Addington and Schoedeck [Addington, Schoedeck]. They group smart materials according to their capabilities: property change capabilities, energy exchange capabilities and reversibility. Property change materials undergo change in property/or properties – chemical, thermal, mechanical, magnetic, optical or electrical – in response to change in the conditions of the environment of the material. Energy exchange materials distinguish themselves in the ability to recover internal energy in a more usable form. For example when solar radiation strikes a photovoltaic material, the photon energy is absorbed by the atom that releases this energy via semi-conductors to electricity. Reversibility is the ability of many of the above classes of materials of being reversible or bi-directional. What this classification explains is the energy fields and the mechanics through which energy input to a material is converted.
While the definition of Singh covers both sensor and actuator the main materials that are organised in this form are active smart materials, which are both sensors and actuators.

Accordingly, smart materials can assume various forms and serve several functions which enable us to consider them in different ways. A basic way is via the energy form that is used, mechanical, thermal optical etc. This approach is useful in the creation of smart materials in textile structures since it explains what actually happens. Another way is to think about the different types due to their expected use, sensor or actuator. This kind of categorisation is useful in order to present an overview of the smart materials already developed. Here is a brief description of different types of smart materials divided in to sensors, actuators, and conductive materials that could be particularly relevant to smart textiles

SENSORS

The basis of a sensor is that it transforms one type of signal into another type of signal. There are different materials and structures that have the capacity of transforming signals.

Thermal sensors- a thermal sensor detects thermal change, for example a thermistor that changes resistance due to thermal change. Another example is stimuli-responsive hydrogels that swell in response to a thermal change [Addington,Schoedeck].

Light sensors – different types of sensors that convert light energy into voltage output, for example photoresistors.

Sound sensors – converts sound into an electrical signal, for example piezoelectric materials. [Singh][Worden et.al] [Addington, Schoedeck]

Humidity sensors – measure absolute or relative humidity. Examples that can be interesting for textile use is the capacitive device that changes dielectric properties with the absorption of moisture [Addington, Schoedeck].

Pressure sensors – Pressure sensors converts pressure to an electrical signal. A pressure sensor can be based on simple operations such as opening or closing a circuit. But they may also be based on more sophisticated forms like capacitive or piezoelectric phenomena [Addington, Schoedeck].

Strain sensors – converts strain into an electrical signal. Strain sensors may be based on semi-conducting materials, strain sensing structures or piezoelectric effects [Singh].

Chemical sensors – a series of sensors that detect presence and/or concentration of chemical/chemicals.

Biosensor – a sensing device that contains biological elements which is the primary sensing element. This element responds with a property change to an input analyte, for example the sensing of blood glucose levels.

ACTUATORS

Actuators respond to a signal and cause things to change colour, release substances, change shape and others. They are sometimes divided according to their property change or energy exchange capabilities.

Chromic materials – change their optical properties due to stimuli like temperature, light, chemical, mechanical stress etc. [Addington, Schoedeck].

Phase change materials – change from one state to another, from solid – to liquid for example. Phase change processes involve the absorbing, storing and releasing of large amounts of energy [Addington, Schoedeck] [Lam Po Tang, Stylos].

Rheological property changing materials – change their viscosity due to electric or magnetic fields, from a liquid to a solid state for example [Addington, Schoedeck].

Stimuli-responsive hydrogels – a three dimensional polymer network that responds to stimuli such as pH, electric field or temperature changes. The response is swelling and they are also able to release chemicals when required [Lam Po Tang, Stylos].

Shape memory materials – transforms energy, mostly thermal, into motion and are able to revert from one shape to a previously held shape. There are two types of shape memory materials, Shape Memory Alloys, SMA, based on metal, and Shape Memory Polymers, SMP, based on polymers [Addington, Schoedeck] [Lam Po Tang, Stylos].

Electroluminescence materials - light emitting materials where the source of excitation is an applied voltage.

Photovoltaic materials – materials that convert radiation (light) into electric potential.

Light emitting diodes – converts electrical potential to light.

Photoluminesence – converts radiation to light.

Piezoelectric materials - are based upon a reversible energy conversion between electrical and mechanical forms. Piezoelectric materials generate an electrical potential in response to mechanical pressure and the effect is reversible.

CONDUCTIVE MATERIALS

Besides sensors and actuators there is a group of materials that conducts electricity, these are the conductors. They are usually not categorised as sensors or actuators but, due to their conductive properties, they are useful in smart applications. As pathways to transferring data, they are also important components in the creation of sensors and actuators. Conductors are usually divided into super-conductors, semi-conductors and insulators, where insulators are the least conductive and super-conductor the most conductive. Metals, like silver and copper are the most conductive materials [Harlin]. Carbon has a good conductivity and is used both in its own pure form but also blended in other material to enhance theirs conductivity for example silicone. Conductive polymers are organic materials that are able to transport electricity and examples of materials that are available for commercial use are polyaniline, polypyrrole, and polytiophene. Conducive polymers are still an area under development. There are difficulties to be faced both in the processing of these materials as well as a non-sufficient conductivity for most applications.

SMART TECHNOLOGIES

In terms of intelligence, the smart system will require a central processing unit that will carry out data to the different sensors and decide action on the basis of the results [Worden et.al]. Three components may be present in such systems: sensors, actuators and a data processing unit [Tao2]. The processing unit consists of hardware and software where the software causes unique dynamic behaviour in real time. The traditional package of computing material is a computer that allows data processing as well as communication. Miniaturisation in electronics has made many electronic applications portable; like mobile phones, PDA and wearable computing in clothing. The interaction with computing technology can be quite complex since the material allows a wide range of functions, but the essence of this interaction is activation and feedback. We activate by giving an input, for example via keyboard, to the system and the system responds with some kind of feedback, for example via a display. The system basically consists of the following functions: user input interface, user output interface, communication, secondary data management, energy management and integrated circuits.

INPUT INTERFACES

Input interfaces are sensors and user input. The input from a sensor is the result of changes to which the sensor reacts. A user input interface is used to control the system, and the most common input interfaces for this purpose are buttons or keyboards. These kinds of interfaces are easy to learn, implement and use with only a few errors. The complexity and minimisation of technology requires alternative input interfaces. Example of alternative input interfaces are voice recognition, writing pads and gestures [Tao2].

OUTPUT INTERFACES

Output interfaces are actuators presenting information in different ways. The most common ones are visual interfaces like dot or segment matrix displays, liquid crystal displays (LCD), organic and polymeric light-emitting-diodes (OLEDS and PLEDS), and fibre optic displays. Alternative outputs are vibration or audio interfaces. In both cases the amount of information given is quite small.

PROCESSING UNITS

The processing unit is a control centre that converts data input to information output. The processing unit is a complex structure of electronic circuitry that executes stored program instructions. Included in this structure are; integrated circuits, secondary storages, power supply and communications technologies [Tao2][Capron, Perron]

INTEGRATED CIRCUITS

An integrated circuit is the data processing unit consisting of both hardware and software. Most integrated circuits are made of silicon because of the semiconductor properties of this substance. Another type of circuit suitable for wearable application are organic electronics. These materials are flexible, lightweight, strong and have a low production cost. The electronic properties of the conducting polymers do not match those of silicon [Tao2][Capron, Perron].

SECONDARY DATA STORAGES

Data management and storage technologies are secondary storages used to store information such as music, picture or data banks. The following three storage technologies are the most commonly used. First there are the magnetic storage systems, from music tapes to hard disk drives. Secondly there are optical storage systems which use a laser beam and optoelectronic sensors to read and store data. Thirdly there are solid-state storage systems, which make use of an EEPROM chip. They have properties well suited for wearable technologies like robustness, small size, weight and low power consumption.

POWER SUPPLY

The most common power sources are AA batteries or lithium batteries. Other forms of power supply have been considered and investigated. Photovoltaic cells harvest the energy from the sun and semiconductor thermal couples generate electricity from the difference in temperature between the human body and the environment. The greatest advantage of such an approach is that there would be a constant supply of power without the need of recharging.

COMMUNICATION TECHNOLOGIES

Communication refers to transferring information and can occur between two wearable devices on the user (short-range communication) or between two users via the Internet or a network protocol (long-range communications). Short range area includes for example infrared, Bluetooth technology, Personal area networks (PAN) and Local area networks (LAN). Infrared, as used in remote controls, requires direct lines of sight to be effective. Bluetooth technology is a new standard that allows communication between any sort of electronic equipment, for example from computers and cell phones to keyboards and headphones. Local Area network is for multiple uses and Personal area network is centred around one person and his type of network only needs low power supply [Tao2][Capron, Perron] .

SMART TEXTILE RESEARCH

Research into Smart Textile covers a wide range of approaches aiming to integrate smart behaviours with textile fibres and structures and combining these with computing technology into different kinds of. Among the related projects in Smart Textile there are two main tracks to be distinguished: ***Focus on function and technology*** in the design of new material structures and applications. ***Focus on function and artistic values*** in the design of new concepts and products with and focus on visual expression.

FUNCTION AND TECHNOLOGY

The research focused on function and technology strives to integrate as much intelligence as possible into textile in order to achieve a flexible and sustainable solution. The research shows potential in integrating smart technologies into the textile structure but it still mainly concerns sensors and actuators while dynamic processing is still mainly a computer function.

Textile sensors are developed for a wide range of use where the most common ones are stretch sensors, pressure sensors and sensors for the monitoring of physiological parameters. A stretch sensor is a structure that changes electronic properties due to stretch. Stretch sensors based on piezoresistive properties are presented in several projects. Most of them are based on knitted structures [Bickerton] [Wijesiriwardana et. al] but there are also examples of how stretch sensing materials are made of a conductive polymer coated on a stretch fabric [Tsang et. al] [Tognetti et. al]. There are also stretch sensors that are based on capacitive and piezoelectric technologies [Edmison et. al].

Pressure sensitive textile materials can be used for input devices such as textile keyboards [Leftly, Jones][Post et.al]. Press sensors have been presented in a couple of articles and there are two types of press sensors available on the market Eleksen [Eleksen] and Softswitch [Leftly, Jones][Softswitch]. Eleksen is a combination of conductive and non-conducive fabric layers laminated together to form a resistive touchpad. Softswitch is a special designed conductive composite (Quantum Tunnelling Composite), that when mechanically distorted or compresses changes resistance proportional to the force applied. The softswitch technology has been integrated in several jackets in order to control an integrated MP3 player or mobile phone. Others involve more sophisticated forms of touch measurements, they make use of changes in the electronic properties to define touch, for example capacitive switches [Meyer et.al][Sergio et.al]. The Biotex project [Biotex] aims at developing biochemical-sensing techniques for integration into textile allowing the monitoring of body fluids via sensors on a textile substrate.

The design and development of the Georgia Tech Wearable Motherboard [Park et. al], GTWM, represents the first effort to integrate textile and computing. The project has been funded by US Army and resulted in a smart shirt/vest for monitoring heart rate, temperature and pulse for example. The integration of textile-based sensors for health monitoring has been tested in several projects, Vtam [Weber et.al], Wealthy [Paradiso et.al][Taccini et. al] and research at Ghent University [Hertleer et al]. The project Wealthy [Paradiso et.al] also uses conductive and piezoresistive yarns in knitted garments that are to function as sensors and electrodes in an attempt to assist cardiac patients.

An example of integrated feedback is France Telecom's textile screen prototypes using optical fibres [Deflin et.al]. The research institute TITV in Germany has developed different type of display using electroluminescent print on conducting textiles [Möhring et.al] further developed into the Philips photonic textiles [Philips]. Maggie Orth has been exploring feedback and activation in smart textiles through different projects [Post et.al]. She is now an active part of International fashion machines [IFMachines]. One of the company's product is the electric plaid, an electronically controlled colour change weave. The company Corpo Nove [Carosio, Monero] created a smart shirt where the trained memory shape is a straight thread. When heating the shirt after it has been washed, the creases in the shirt disappear. Shape memory alloys have also been explored in woven structures were the structures are changed due to different stimuli [Chan Vili]. Textile displays should function and look like common displays though they are made of and integrated into textiles. An exception to textile displays with a traditional look and behaviour is the Electric Plaid [IFMachines] made of conductive threads and thermochromic print, which offers an abstract feedback, a pattern change.

Textile databuses where data is transferred through conductive textile lines is an opportunity to substitute traditional wires. The problem with textile databuses is the interconnection with electronic modules and components. Infineon Technologies has presented two different solutions for module packaging[Jung et. al.]. In the first one the endings of the conductive woven fabric are prepared by soldering tiny contact plates. The module is then connected by electrically isolated bonding wires. A second approach uses a thin flexible circuit board with structured electrodes which are glued or soldered to the textile structure. In both cases, the module and the interconnect areas are fully encapsulated by a flexible and isolating layer to ensure stability against mechanical and leakage problems.

Besides using sensors, actuators and data transfer some efforts have been made to replace other types of electronic components with textiles structures, for example textile antennas and transistors. Textile antennas for wireless communication is the next level in wearable computing where the interface between computing technology and smart textile structures consists of a pure textile antenna, and textile antennas have been developed in several projects [Mörhing et. al][Hertleer et.al] [Klemm, Troester]. Textile transistors integrated directly in the yarn [Bonfiglio et.al] or in stretchable electronics in Stella project [Stella] includes the integration of electronic components, energy supply, sensors and actuators on a stretchable substrate.

FUNCTION AND ARTISTIC VALUES

The research on function and artistic value focuses on the visual aspects of Smart Textile and it is presented in a numerous of projects. Research with an artistic focus is characterised by the use of different actuators visualising different kinds of information. In these projects the proof of concept often overrides the level of integration in textile structures. Joanna Berzowska [Bersowska] and Rachel Wingfield [Loop] are examples of two researchers combining artistic values and technology in the area of Smart Textiles.

Wingfield [Loop] uses electroluminescent panels to create responses to different kinds of changes in our environment. The Blumen print is a pattern that emerges and develops through responses to its environments. Digital Dawn is a surface that digitally emulates the process of photosynthesis, the darker a space becomes the brighter the digital dawn will glow. Light sleeper is another example where light panels integrated into bedding textiles are used to balance disharmonies in our body clocks through light therapy.

Berzowska uses other types of actuators like, integrated LEDs, Nitinol (shape memory alloys) and thermo-chromic print. The integrated LEDs are used together with fabric-based press sensors in the so-called memory rich clothing projects [Berzowska, Coelho1]. These electronically enhanced garments strive to promote touch, physical proximity and human-to-human interaction. The experiment is based on Nitinol metal shape memory alloy. Two animated garments that move or change shape over time using resistive heating and control electronics [Berzowska, Coelho2]. In the Animated quilt [Berzowska, Bromley] soft computation is explored though a soft, reactive, addressable and visually animated fabric display. The quilt is constructed using conductive threads and thermo-chromic print and consists of multiple swatches that are individually addressable.

4. TEXTILE DESIGN

Textile design is the creation of fabrics aimed for several applications. The term textiles is used for a wide range of products made from fibres or filaments, woven, knitted and felted fabric and finally the products constructed from fabric [Taylor]. Textile fabrics fulfil different demands and textile products are commonly divided into three categories; technical, apparel and furnishing textiles [Bang, Nissen][Horrocks, Anand]. Apparel and furnishing are textiles used in everyday life for clothing or interior decoration. Though there are certain demands on functional properties in these two categories of textiles, aesthetics like form and colour have a strong impact on the textile processes [Bang, Nissen][Wiberg][Wilson]. Technical textiles on the other hand are textiles with detailed technical and performance specifications. The definition of technical textile adopted by the Textile Institute is "*textile and products manufactured primarily for their technical and performance properties rather than their aesthetic or decorative characteristics*" [Horrocks, Anand]. The design of textile for fashion and furnishing are traditionally defined as textile design [Wiberg], while the design of technical textiles traditionally refers to textile engineering.

The diversity of application fields and textile technologies is illustrated through the different designers needed in this process. As examples there are colourists determining colours in different stages, there are yarn designers, knitted-fabric designers, woven-fabric designers and print designers [Wilson]. The aim with textile design can be quite complex, but the overall purpose can be stated as: *"to design and produce, to an agreed timetable, and agreed number of commercially viable fabric designs"* [Wilson]. The textile designer transforms functional, economical and aesthetical intentions into satisfactory products with certain properties using different systematic design methods. Some of these methods are common design methodologies [Johnes][Lawson] while other methods are specific within the textile design space.

DESIGN METHODOLOGY

Textile design is a field within design. In the middle of the 20th century literature on design methods began to appear. Introduced in these texts were several definitions of design and of what design methodology refers to:

"*Design is the human power of conceiving, planning and making products that serve human beings in the accomplishment of their individual and collective purposes*" [Buchahan].

The Danish government statement of design from 1997 points out the aesthetical values in design: "*Design is an expression of a creative process that integrates a products physical characteristics and aesthetic values. Design is both result, the product, and the process used to create the product*" [Dickson].

But design also refers to engineering design and the innovation and product development processes in engineering: "*Engineering design is the use of scientific principal, technical information and imagination in the definition of a mechanical structure, machine or system to perform pre-specified functions with the maximum economy and efficiency*" [Fielden].

Dan Whitney and Chris Magee at the centre for Innovation and product development at Massachusetts Institute of Technology define design as: "*the reshape/remodel of user requirements and technological possibilities into business line products*" [Dickson].

All these definitions indicate that design could mean a lot of things and should be seen in a broader perspective like the definitions made by Page who describes design as: "*The imaginative jump from present facts to future possibilities*" [Page]. What this definition tells us is that design is an imaginative or creative process where we try to find out how things ought to be. It does not say that design is a combination of aesthetic, engineering, user-centred or business fields. They can rather be seen as examples of parts of the design space. In design, we aim to find out how things should be, and in order to achieve our aims we focus more or less on different aspects such as user need, technology, economy and aesthetics.

The definitions of design mostly refer to the process rather than the product, and design processes and methodologies are frequently discussed and described in different forms of literature and journals concerning design. Included in all observations about the design process there is one common process upon which many authors agree, a process consisting of three essential stages; analysis, synthesis and evaluation (Figure 3). The design process is seen as an iterative process that goes on and on until a desired state has been reached [Lawson].

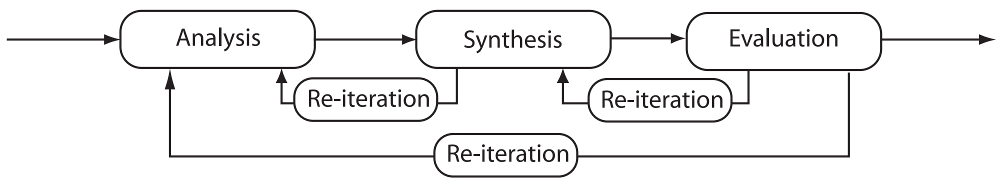


Figure 3. A simple map of the design process according to Lawson

The three stages can be described as; breaking the problem into pieces, putting the pieces together in a new way and testing and discovering the consequences of putting the new arrangement into practice. Jones [Jones] defines these three stages as divergence, transformation and convergence. Divergence refers to the act of extending the boundary of a design situation in order to have a large enough search space in which to seek a solution. This stage is characterised by a problem boundary that is unstable and undefined. Transformation refers to the stage of a creative searching of ideas. The stage aims to fix objectives, brief and problem boundaries, when critical variables are identified and judgements are made. The third stage, convergence, refers to what is traditionally seen as the whole of design. It is the stage after the problem has been identified and the objectives have been agreed. Convergence is to reduce a range of options to a single chosen design. What Jones also highlights and develops are the different methods involved in each step as the skill of the design profession (Figure 4).

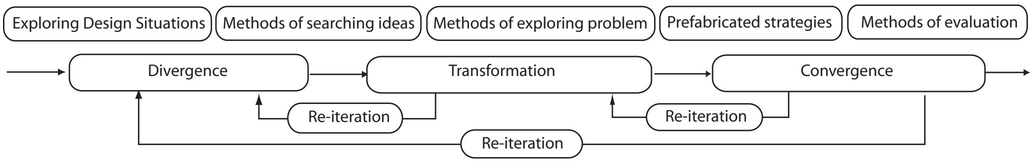


Figure 4. Design methods according to Jones

Jones' description is a well formulated general design methodology where Jones both emphasizes as well as describes the three main stages. Together with each stage, methods on how to analyse, synthesize and evaluate a design situation are collected. But a general design methodology is not a guarantee for a successful outcome. Such descriptions are easy to adopt but hard to apply, because design also includes skill and knowledge in the domain as well as knowledge about the domain processes. The insufficiency with a general methodology is obvious in the methods described in synthesizing and evaluating phases since they are directed towards main issues within industrial and product design.

THE PRODUCT AND THE DOMAIN

Though design is seen more as a process than the product the product or artefact is a prominent part of this process. There is something deeper in design than just the process, the components of the design space. Stankiewicz describes the creative synthesis process in his concept of design space, which he compares with Meccano [Stankiewicz]. Meccano is a set of simple elements which can be assembled to form a variety of structures. A person playing with Meccano gradually acquires a certain type of knowledge of the properties of the various elements as well as the relationships among them, the vocabulary and grammar. Furthermore, one develops the skills required for the manipulations of the component and discovers assemblies of components that tend to reoccur, the repertoire. Over time, one also discovers the various functions which can be performed by Meccano structures and that is what is call the application domain. The design space is dynamic and there are two dimensions that change, the addition of new components and the modification of existing components. Accordingly, the components, vocabulary and grammar that we use are important in all steps from creating the repertoire to the application domain. There are differences between design spaces, the vocabulary and grammar we have to acquire.

Rather than being a generic activity, the design process is related to the domain, the objects of these domains and knowledge connected to the domain and objects. To some extent we can see design as a generic activity, and yet there seem to be real differences between the end products created by designers in different domains [Lawson]. The objects of these domains and knowledge connected to the domain and objects. Lawson [Lawson] illustrates the three-dimensional field of design from urban design at the bottom via architecture to interior design and product design on the top (Table 1). Lawson points out that this might not indicate that architectural solutions are more complex than interior designer's solutions. What this model really illustrates is how far down in the hierarchy the designer must go. An architect may be more concerned about the design concept and form of the building while the interior designer must concentrate on more detailed solutions in the building.

Categorisation of three-dimensional design	
Product Design	↑ Small scale
Interior Design	
Architecture	
Urban Design	
Town Planning	↓ Large Scale

Table 1. Categorisation of design domains according to Lawson

Buchahan [Buchahan] categorises design in four orders, each order represents places in the sense of being topics for discovery (Table 2).

Topics of discovery	Design Domain
Symbols	Graphic Design
Things	Industrial Design
Action	Interaction Design
Thought	Environmental Design

Table 2. Categorisation design domains according to Buchahan

Neither of these categorisations includes textile design and there is no obvious position where textile design belongs. Regarding textile design in the perspective of other design areas, for example architecture or industrial design textile design concerns a different level in the product. Industrial and product design is a matter of objects and an architect or system designer has to handle an amount of objects used in a larger system or context. The components in the textile design space are fibres, yarns, textile techniques and other treatments aiming to refine these into the next level of textile product, the fabric structure. Textile design aims to create textile materials used in the next levels of design like fashion, product or industrial design. The level of product development differs between textile design and other design disciplines and, accordingly, parts of the working methods. In textile design requirements like tactility and mechanical properties for examples have to be tested in a full scale prototype before all design decisions can be cleared. In textile the design process is connected to materials and techniques and full scale prototypes. Visual concern in the aesthetic process is may be quite distinguished from the products due to computer aided design programs. But how does a designer know that the new weave set-up will fit in with required coating processes? This is what distinguishes textile design from other design disciplines like industrial design and architecture. Design concerning materials and techniques are closer to production and craft than other fields of design and the skills are based on the understanding of materials and production techniques in combination with other design aspects such as aesthetics and use. As an opposite to this there is the architect where the skill resides in imagining the result and understanding how to use a scaled sketch or prototype during the process, since it is not possible to design in full scale. In between these domains design areas are related to things and action dealing with drawings, mock-up prototypes and sometimes full-scales prototypes. These areas are however not as much concerned about materials and techniques. A new type of categorisation is presented in Table 3. To some extent this order is not distinguished from the idea that design domains are different due to the complexity it has to deal with [Lawson] or to the categorisation due to topics for discovery [Buchahan]. There is just one more thing I would like to add by illustrating design like this, that is different the design processes are in relation to the object, craft and production. Textile design is the creation of textile structures which is a different topic discovery than both things and systems and in following proposed categorisation, textile design as a design order for materials and techniques and where things and systems represent the other two.

Domain	Design space	Relation to product
Materials and Techniques	Textile Design	Synthesis in full scale product context
Object		Synthesis between full scale and scaled model context
System		Synthesis in a scaled model context

Table 3. New proposal of design domain categorisation

THE TEXTILE DESIGN SPACE

The textile design space includes components like fibres, yarns, fabrics structures and a wide range of domain specific activities. Each level, from chosen fibre to fabric processes affects the final product from different aspects such as technical performances, aesthetics, comfort, sustainability, wash ability etc. The specific textile design methodology is characterised by an interaction between product requirement – required properties and design methods as follows (Figure 5).

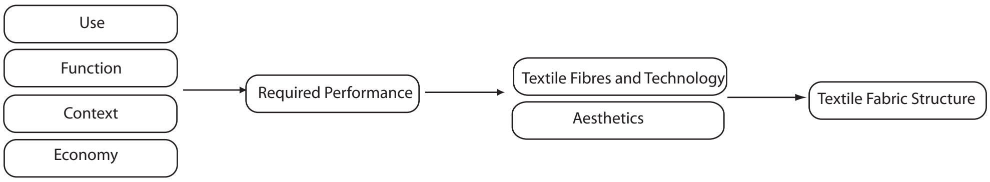


Figure 5. Textile design process

In order to achieve the desired properties the textile designer uses both aesthetics and textile technology. The textile technology, materials and techniques, are the methods used in the production of textiles and refers more to textile engineering. The aesthetic processes aims to create the expression that is required and traditionally the aesthetic processes had a strong impact when the textile design method is described [Wiberg].The relation between aesthetic and technical performances differs due to the final product's requirements. Figure 6 shows two different pieces of designed textiles, a printed textile and a three dimensional woven fabric used in a composite.

Figure 6. Textile designed for decoration versus technical use

These are both examples of a designed textile product where the design has focused on different aspects. These two products present themselves to the user in different ways. The printed fabric presents itself visually to the user and though the decisions to some extent concerns technical performances the main issue and motivation is the visual expression. The woven fabric on the other presents itself with its technical performance and ability to create a composite. The form and visual expression of this sample is mainly a result of required properties and the weaving technology. Designing the three dimensional fabric makes great demands on skills in materials and weaving technology while the design of the printed fabric demands more of aesthetic and artistic skills.

In interior and apparel sector the decoration of fabrics has traditionally played an important role and so has the process of aesthetics. Still today, aesthetical processes are described as major textile design processes [Bang, Nissen], while those of textile technology are described as processes in literature concerning textile engineering [Hatch][Taylor].

TEXTILE PERFORMANCE

Textile products are made for a variety of applications. The demands made on a fabric, hence the performance, is determined by the use and also the requirements of satisfactory behaviour. Certain requirements are common to most fabrics, aesthetics, adequate strength and durability for example, while other properties such as waterproofness or resistance to acids are demanded for fabrics with special purposes [Hatch][Taylor]. Textile performance can be divided into aesthetic, mechanical, durability, comfort, environmental and special performances. While performances like strength and durability are quite well-defined concerning evaluation, the values of aesthetics do not have systematic criteria for measurement and evaluation. Aesthetics properties are more vague and dependent on its context of use than other required properties.

AESTHETIC PROPERTIES

Aesthetic requirements involve a broad range of mechanisms that decides how pleasant we find the textile. These requirements may concerns visual qualities like colour, patterns, texture, luster, translucense and drapability. But aesthetics of textiles also concerns other sensory mechanisms like tactility, sound and smell. Touch or tactility refers to the characteristics we perceive when we feel the fabric; lightness/heaviness, firm/loose, smooth/rough for example.

MECHANICAL PROPERTIES

Mechanical properties tell the ability of a textile to retain its physical integrity under conditions of mechanical stress for a reasonable period of time.

DURABILITY PROPERTIES

Durability property is the ability of a textile to remain in the same state, concerning, size, drape colour etc, after wear, use and care procedures.

COMFORT PROPERTIES

Comfort is freedom from discomfort or pain. Thermo-physiological comfort concerns transport of heat and moisture through a fabric. Sensorial comfort is the elicitation of neural sensations when a piece of textile comes in contact with the skin. Another example of comfort is the body movement comfort of textile to allow freedom of movement, reduced burden and body

ENVIRONMENT PROPERTIES

Environmental properties are aspects of textile that make them potentially dangerous substances for the human body or the environment.

SPECIAL DEMANDS

Special demands include requirements for special applications, for example flame retardant, waterproof, resistance to wind and acid.

AESTHETICS

Traditionally aesthetics play an important role in textile design, used both as an artistic inspiration in briefing and in the shaping and colouring of the object when designing the product. Aesthetic processes support the aesthetical performances but are also tools to communicate or explain the design idea. The textile designer therefore needs to have skill in sketching as well as skills in regards to form and colour. Aesthetics in textile design does not differ much from aesthetic processes in regards to other design fields though they are more concentrated on two-dimensional form and the interaction between sketching and craft processes. Art and creative processes are often seen as highly personal activities and besides that different cultures, time and styles also affect our ability to analyse these processes objectively. Visual expression can happen spontaneously, we may pour our feelings and emotions during the creative process; the intuitive approach to visual creation [Wong]. But we can also create through prior recognition of particular problems. In this case, the goals and limits are identified, all available solutions considered while choosing the elements for synthesis and trying to find the most appropriate solution; the intellectual approach [Wong].

INSPIRATION

In the initial phase, most aesthetics processes take off using inspiration processes [Wilson]. In textile as well as other design fields these can come from a variety of sources, like sketches, photos, things, phenomena or moodboards [Wilson][Bang, Nissen]. An inspirational process may be an unprejudiced process aiming to find any expression using for example sketches and photos. But it may also be a more directed process towards a certain expression. Moodboard is one of the tools in the more directed process, a collection of ideas around a certain expression.

DESIGN ELEMENTS AND PRINCIPLES

There are certain basic design features that appear to be common to all art; the design element and the principles for putting these elements together. The elements and principles of visual design are what we can call the language of art and design [Wilson][Wong]. Visual design can be defined as relating and arranging elements to create effect. The design elements are space, line, shape, form, colour, value and texture [Wilson][Wong]. The design principles are what designers do with the elements to make the design, using principles like balance, movement, contrast, repetition, concentration to achieve a certain expression (Figure 7).

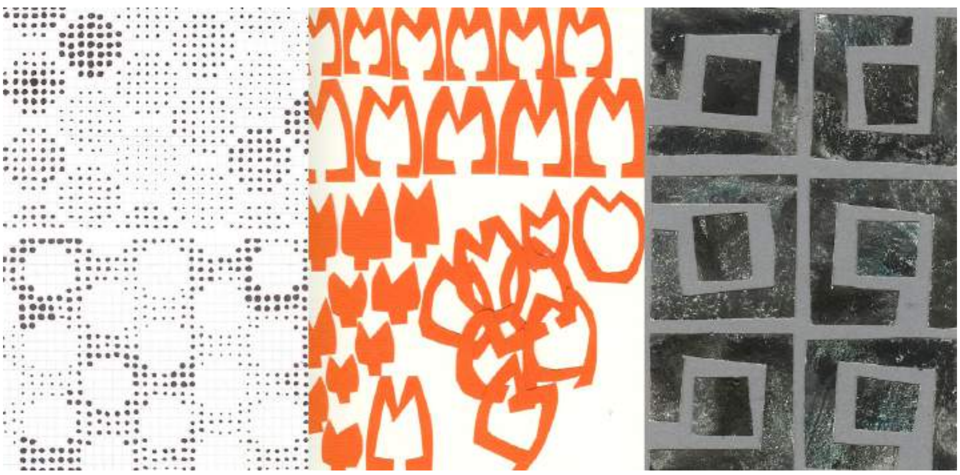


Figure 7. Design elements and compositions

COLOUR

Besides shape colour has a strong impact on how we visually perceive a textile product. The knowledge of colour includes the chemistry and physics of colour, the sense and perseverance of colour. In order to use colour effectively it is necessary to both apply mechanical knowledge about the colour as well as recognition of the interaction of colour through experience of colour [Albers][Nilsson].

PROTOTYPING

In textile design the aesthetic process made on paper or in a computer often needs assistance since that only takes care of visual effects. Tactile and other properties have to be practiced in reality. Also some visual effects, such as colour effects in a weave need to be tested in a prototype sample. Sample prototyping can be made directly in full scale manufacturing but also in smaller scale labs or in man-made craft procedures (Figure 8).

Figure 8. Prototyping new type of materials combinations

TEXTILE FIBRES AND TECHNOLOGY

Textile fibres and textile technology, include a wide range of processes that are used in order to produce fabric structures. These processes distinguish textile design from other areas of design and they affect aesthetics as well as abstract design values such as technical performances of the fabric. Fibres are manufactured or processed into yarns, and yarns are made into fabrics. Fabrics may be manufactured by a variety of processes such as knitting, weaving, lacemaking, felt-making, knotting and stitch bonding. There are processes to create compound fabrics such as coating and lamination. The fabrics may be coloured by dyeing or printing, or be finished to enhance their appearance or performance. The research and engineering field of textile is becoming more and more connected to other scientific fields like polymer and chemistry science in the case of fibre materials and chemical treatments. And mechanical engineering when new processes are introduced and new types of machines have to be developed. The textile technology is characterised as a layered technology where a set of processes may be used to affect the final product (Table 4).

Textile Layers	Techniques
Fibre	
Yarn	
Fabric Structure	Woven
	Knitted
	Twisted/Knotted
	NonWoven
	Coat
Compund Structure	Laminate
	Embroidery
	Quilt
	Fushion-bonded
	Tufted
Composite	
Finishing	
Dye	
Print	

Table 4. Textile as Layered technology

TEXTILE FIBRES

A textile fibre is a unit which forms the basis elements of fabrics and other textile structures. The general classification of textile fibres is the division into natural and manufactured fibres. Natural fibres are those obtained from nature, cellulose fibres and protein fibres (Table 5). Manufactures or man-made fibres are artificial materials such as natural and synthetic polymers, carbon- and glass fibres (Table 6).

Natural fibres		
Protein	**Cellulosic**	**Mineral**
Ex: Sheep's wool, Cashmere, Mohair, Camel hair, Alpaca	Ex: Cotton, Flax, Ramie, Jute, Hemp, SIsal	Asbestos

Table 5. Natural fibres

Manufactured fibres		
Cellulosic	**Synthetic**	**Inorganic**
Ex: Rayon, Acetate	Ex: Nylon, Polyester, Acrylic, Spandex, Rubber, Aramid	Ex: Glass, Metal-lic, Silicon, Carbon, Alumina

Table 6. Manufactured fibres

YARN

Yarn is a generic term for continuous strands of textile fibres, filaments or materials suitable for weaving, knitting or otherwise intertwining to form textile fabric [Hatch] are long continuous strands with different characteristics for different purposes. Spun yarns (Figure 9) are made from short fibre twisted together. Continuous filament yarns (Figure 10) are composed of filaments that run continuously the full length of the yarn. A compound yarn is composed of one strand that forms the centre or core and one that forms the covering or wrap. Fancy Yarns are produced with presence of irregularities during their formation and therefore differ from the others.

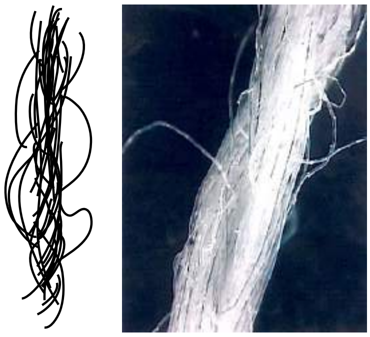


Figure 9. Spun Yarns

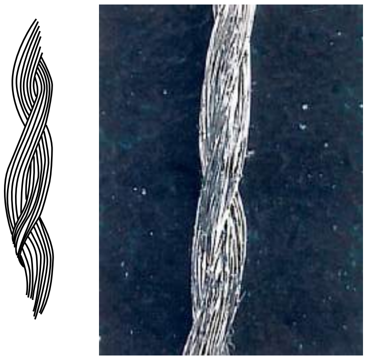


Figure 10. Continuous filament yarns

FABRIC STRUCTURES

Fabric structures are fibres and/or yarns assembled to a surface area. There are four major types of fabrics structures. Three types that are based on yarn; woven fabric, twisted and knotted fabrics and knit fabrics and one that is comprised of webs or batts of fibres, non-woven fabrics.

Woven fabrics consist of two sets of yarns, warp and weft, at right angles to each other [Hatch]. Weave is a type of matrix between the warp and weft and depending on how the two sets of thread interlace with each other the fabric will have different properties. The most common weave is the plain weave with the maximum of binding points (Figure 11).

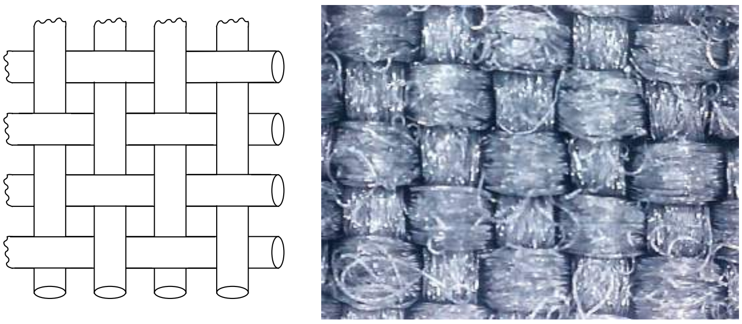


Figure 11. Woven matrix

Knitted fabrics are composed of intermeshing loops of yarns [Hatch]. There are two main industrial categories of machine knitting, weft knitting and warp knitting [Taylor]. The fabric in both these categories consists of a series of interlinked loops of yarns.

Each horizontal row of loops is known as a course and each vertical line of loops is known as a wale. In weft knitting (Figure 12), these loops are formed in successions one loop at a time, and each new row of loops is drawn through the previous row of loops in the fabric. Warp knitting (Figure 13) is produced from a set of warp yarns, normally one yarn per wale, knitted parallel to each other down the length of the fabric. The chain of loops in the wale direction is interconnected.

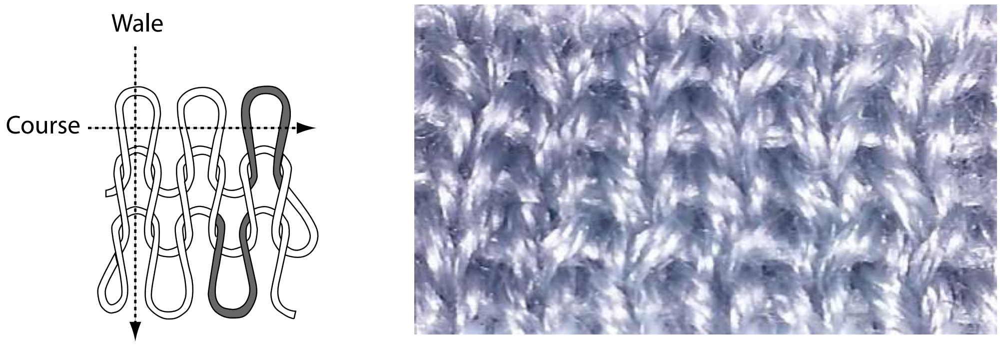


Figure 12. Weft knitting

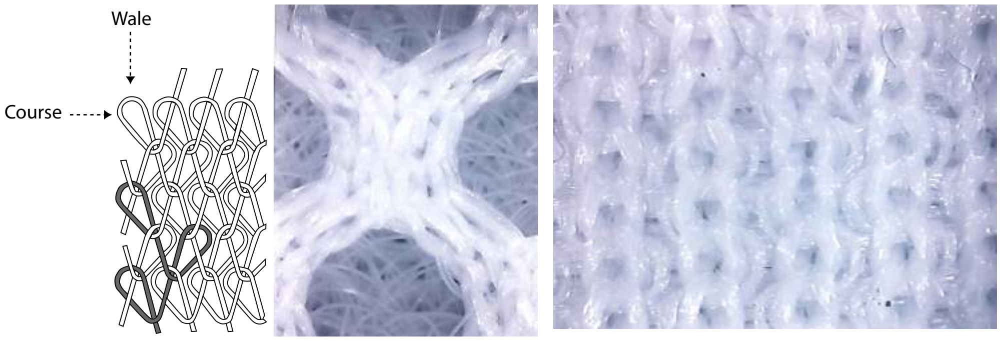


Figure 13. Warp knitting

Twisted and knotted fabrics are made of a number of techniques where threads are caused to intertwine with each other at right or other angles to each other. These techniques are used to produce constructions limited to very specific purposes.

Non-woven fabrics are fabrics made from “webs” or “batts” of fibres that are directionally or randomly directed [Taylor]. The fibres are bonded by friction, cohesion or adhesion. The properties are determined by the way the batts of fibres are prepared, the type of fineness of the fibres used, the thickness and the methods used in bonding the structure.

COMPOUND FABRICS

Compound fabrics are composed of two or more layers of fabric or of a fabric and another component (yarn, fibre, vinyl, film etc) held together by stitching, fusing, adhesive bonding and other means [Hatch]. Examples are quilted, embroidery, tufted, flocked, coated, laminated, fusion-bonded and foam-and-fibre fabrics. Coated (Figure 14) and laminated (Figure 15) fabrics are made in a very wide and diverse range of applications. These include clothing for which a coated fabric may be chosen mainly for aesthetic appeal, as for example simulated leather, or clothing on which coated fabric is chosen for its ability to keep the wearer dry in a storm while still permitting water vapour released from the body as perspiration to escape. Coating is the process of applying a layer or layers of a polymer film to the surface of a woven, warp- or weft-knitted, or nonwoven base fabric. Lamination is the process of combining two or more layers of fabrics with an intermediate layer of polymer adhering to both.

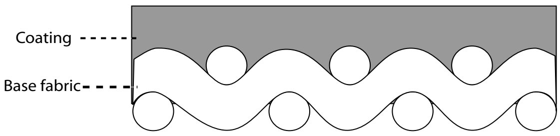


Figure 14. Coated fabrics

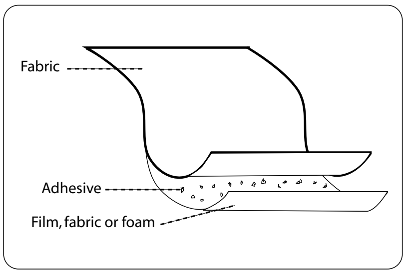


Figure 15. Laminated fabric

COMPOSITE

The term composite refers to a combination of two or more materials, differing in form and composition, into a new material with enhanced characteristics [Braddock, O'Mahony1]. Composite materials contain a base reinforcement, a fibre, along with a matrix, a binder, to improve dimension stability. Common reinforcements are glass, aramide or carbon fibres, while cross-linked polyester and epoxis is a common resin or binder.

FINISHING

Finished textiles are those textiles that have been converted from greige into merchandise state [Hatch]. Greige fabrics are fabrics just off the loom or knitting machine. The major finishing processes are chemical, mechanical and thermal finishing. Chemically finished textiles have been subjected to chemical compounds. Mechanically and thermally finished textiles are textiles in which the geometry of the fabric or the polymer arrangement within fibres has been altered.

Finishing can be used in order to prepare a fabric or to apply comfort, protection and aesthetic appeal.

DYE

Dyed textile are textiles in which colorant is distributed within or on the surface [Hatch]. Colorants are the components of which the textiles derive their colour. There are two types of colorants, dyes and pigments. Dyes are organic chemicals that diffuses into the fibre. Pigments are water insoluble colour particles that are usually held on the surface of a fibre by a resin. Dye processes are available for fibres, yarn, pieces as well as garments.

PRINT

Printed textile is a process where colorants, pigments or dye are applied on certain areas (patterns) of the fabric. The main processes are roller printing, flatbed screen printing, rotary screen printing and heat transfer. Roller printing is a process where engraving copper rolls from where the pigment is transferred to the fabric. In a flatbed and rotary screen the pigment is applied through pre-defined wholes in a screen. In heat transfer the pigment is transferred from pre-printed paper.

5. ADVANCED TEXTILE DESIGN

Research is a systematic inquiry with the goal to achieve knowledge that is repeatable and unambiguous (stable in interpretation) [Cross][Glanville]. Textile research is a broad area of research; research within mechanical engineering aimed to develop production processes and chemistry related research to develop new textile materials. These are examples of established research fields in textiles, textile engineering, which are well represented in textile research journals [Autex][Textile Research Journal]. Textile design research seems to be more of a new field in the process of formulating definitions and frameworks [Bang, Nissen]. Conceptually, design of textile products is a subject of both textile design and textile engineering, but so far the areas have had a different focus. While engineering is concerned with technical performance, textile design is more concerned with visual performance. Textile design is directed towards aesthetics, and textile engineering towards technology in the creation of textile products. Since an increasing number of textile products are a combination of equal measures of aesthetics and function, these categorisations need to be reconsidered. An example of this is the use of advanced high-tech material in contemporary textile and fashion [Braddock, O'Mahony1] and the development of materials and product in sports applications [Braddock, O'Mahony2]. Another example is sound design where the foundation is based not only on textile structures, but also on principles that affect sounds like for example acoustic principles [Zetterblom].

In the dynamic and broad area of modern textiles, things like materials, processes, products and applications change and textile design space also need to undergo changes. Distinctions between textile design and engineering become more blurred and the involvement of new application fields based on other technologies has to be included in the design process. In the future there will be distinctions between being a designer using already developed and well-defined technologies, and a designer involved in creating new foundations and the use of new technologies or technologies that are not so developed. Textile design of today refers to the former description, while the latter is a new field in textile design, advanced textile design. Instead of including these two areas in the same design space, they should be divided into two types of textile design spaces, artistic- and advanced textile design (Figure 16).

Artistic Textile Design: the textile design space towards artistic processes
Advanced Textile Design: the textile design space towards textile fibres and technology

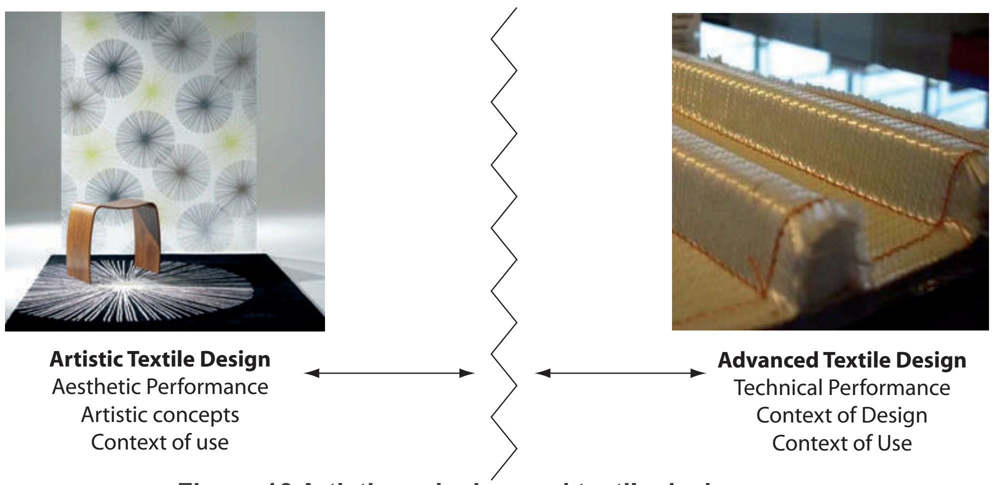


Figure 16 Artistic and advanced textile design space

The following proposal applies to advanced textile design, a design engineering research based on textile materials and techniques. Advanced in this case refers to the focus and concentration on the textile materials and technology in combination with aspects like use and function. In the interaction between textile technology and user aspects, the aesthetical issues are used with an intellectual rather than an intuitive approache [Wong]. This proposal should be perceived as a first attempt to form a research foundation for advanced textile design based on practice-based research aiming to develop interdisciplinary processes for the creation of new type of materials structures and solutions in the field of textiles.

DESIGN RESEARCH

The different ways of defining design is reflected in the varied opinions about design research. Though humans have designed things from time immemorial and the design of things is an important activity in the evolution of our society [Ziman], design as academic activity is quite new and there are still discussions about how it should proceed. The main questions discussed concerning design research is whether it is research at all and what design research can be said to be.

If we analyse something, for example a natural phenomenon, systematically according to an accepted scientific research method and out of that achieve new knowledge, then there is no doubt that such a process is research. But if we go the other way around by exploring phenomena and putting components together to achieve knowledge out of that synthesis, such a process could often be judged as product development and not research. The status of design research in academia is described in the instruction of the research at the School of Design at Carnegie Mellon University: "*Unlike research in the natural and social science, design research always explores the relationship among theories, practice and production. This kind of "making" is seldom recognised in academic culture as an area of expertise and a domain of special problems requiring investigation*" [Dickson].

One of the first to explain the role of design and engineering as academic research was Herbert Simon who distinguished analysis from synthesis [Simon]. According to Simon design research is more concerned with synthesis than analysis. Natural science is knowledge about natural objects and phenomena and Simon asks whether there cannot also be "artificial" science – knowledge about artificial objects and phenomena. The artificial as produced by art rather than by nature [Simon]. Synthesis and artifice introduce engineering, which is concerned with synthesis while science is concerned with analysis. An engineer or a designer is concerned with how things ought to be in order to attain goal, and to function. Natural science concerns present facts while the artificial relates to facts of the future.

What then is research concerned about the artificial? Is it research through design, synthesis, or about design, analyses [Dickson][Cross]? Research about design is considered to increase our knowledge about design processes and practice while research through design aims to create new solutions in social, environmental or material issues[Cross][Dickson]. But research through design has the potential to develop the design process. *"Design research can also mean, systematic experiments, theoretical reflections etc aimed at developing design practice itself. To develop practice we must first understand practice"* [Hallnäs, Redström]. In research through design we use design practice itself as a way to design experiments and out of that acquire knowledge about how things, new solutions and practice ought to be. Today, research through design has become an important method in research areas that traditionally have not used design. The design process, the interaction between analyses, synthesis and evaluation, is used in for example material science and medicine in order to create more advanced materials and medicaments [Vetenskapsrådet].

Design research and engineering science concern the development of methods, techniques, materials and programs for the construction of new ”things” and systems. The experimental constructions and guiding examples play a central role in both areas. It is in a certain sense rational constructive research which makes it rather different from analytical empirical research (Cf. [Simon]). It is clear that the interlinking of analysis and synthesis in practice based design rather than clear-cut analysis can connect the different disciplines in order to clarify the relation between them. Buchanan suggests and distinguishes three types of research in which are all important for a complete view of design research; clinical, applied and basic research. Clinical research is what most designers today mean by research and as a form of research its cut off from the others. Clinical research in design practice means the initial search for information involved in a current topic [Wilson][Buchahan]. In order to advance the understanding, the more fundamental methods, applied and basic research, have to enter the arena of designer search [Buchahan]. Applied research is directed towards problems in a general class of products or situations. The goal is not to find the first principles but to discover some principles that account for a class of phenomena. Basic research on the other hand is directed towards fundamental problems in understanding the principles, sometimes even the first principle.

In practice-based design we can combine different aspects, integrate them and express them through a product. The design object, the product, plays a central role in formulating research issues and questions and in providing results through guiding examples [Seago, Dunne]. Simon [Simon] analyses the function and goals with the artefact as the relation between three terms, the goal, the character of the artefact and the environment in which the artefact performs. Simon considers the artefact to be an interface between an inner and an outer environment, the substance and character of the artefact itself and the surroundings in which it operates. Such a dual nature sets the research space for the research of artificial things since we should consider both its structure and its performance in its context. This can be termed the dual nature of an artefact and similar distinction between the construction and use of the artefact is described and discussed by several authors [Borgmann][Kroes][Hallnäs]. The relation between what things are doing when we use them and what we are doing when we use the things positions the dual nature of the artefact in the context of interaction design [Hallnäs]. Kroes develops Simon's dual nature, extending the context of human action by at least two significant contexts, the context of design and the context of use [Kroes]. In these two contexts the artefact manifests itself in different ways. In the design context the emphasis lies in how to construct an object in order to realise a certain function. In the context of use, the object presents itself and the function of the object in relation to its use. Kroes asks for a rational explanation between these structures developed through research in design methodology in order to improve design practice.

ADVANCED TEXTILE DESIGN

In research through design the objects play an important role and in comparison with design methodology design research is not just a general research field since it approaches the domain. The dual nature of an artefact [Simon][Hallnäs][Kroes] points to the fact that there is a structure that realises a certain function, technical performance, and another structure that realises that function in its context or use, design and user performance. This dual nature is what traditionally separates textile design and engineering, preventing them from interacting with each other. Advanced textile design concerns the relation between these natures and accordingly the advanced textile design space combines the design spaces of design and engineering. Advanced textile design as research aims to explore and achieve knowledge about the relationship between this physical structure and the context of design and use in textile products.

METHOD

Advanced textile design space consists of textile structures; how we combine textile materials and techniques into fabrics, how we learn a higher level of assemblies and functionalities using materials and techniques. Finally we are able to combine these components into structures for an intended use considering the textile objects from its dual nature. So what are the search activities for new structures and performances? Referring to Buchahans' clinical, applied and basic research it is the effect produced by the combination of these three methods. Clinical research is the theoretical and practice-based background investigation that we need to orientate within our space and other spaces. Basic foundations and structures are explored in basic research. In applied research, we are able to explore how basic structures are combined in more complex structures but also how the artefact presents itself in human action. The following proposal is based on the research structure used in this thesis and the basis of the method is to combine systematic investigation (Buchahan basic research) with design activities (Buchahan applied research).

The research approach in this project has been to make discoveries through search activities based on processes from textile design and engineering practice. The process can be described combining design activities with a series of experiments exploring basic foundations interlinked through given product applications (Figure 17). The research approach is based on how the difference in nature of textile structures and objects relate to each other, to use, to technology and aesthetics. The relation between these phenomena is explored through the physical structure, the context of design and use.

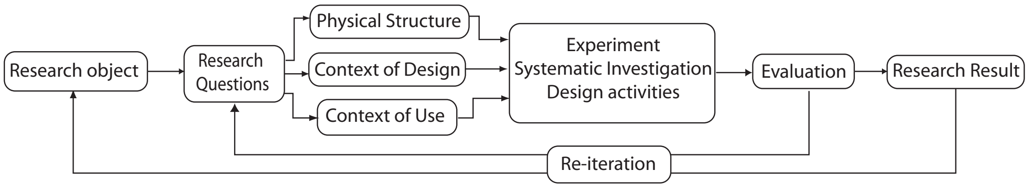


Figure 17. Research method

Research question

The research question is the frame for the research: we formulate our experiments in accordance with the questions and we can use several objects and projects and explore the same phenomenon through the research questions.

Research object

The research object is a tool in formulating research issues and questions and in providing results through guiding examples. In interdisciplinary research the object also plays a central role as a tool when results from different disciplines are combined. In this project there are several research objects involved. The first two objects "Wanted" and "Spookies", were used in a combination of theoretical as well as practise-based orientation in smart textiles. The result of that turned the research into a new type of objects, health monitoring objects in which certain conductive phenomena has been explored. The final objects serve as a guiding example on the relation between the dual natures of a smart textile object.

Physical structure

The physical structure of a product realises a certain function apart from how it in the end should be constructed or its interface to the user. The physical structure is based on basic phenomena put together in order in order to attain a certain function. Exploring the physical structure includes both putting basic phenomena together in order to break certain functions into pieces and explore basic functional phenomena.

Context of design

The context of design concerns how to construct an object in order to realise a certain function. This structure refines the physical structure into a construction that realises the function according to construction principles in textile materials and technology.

Context of use

In the context of use we consider what the product presents itself and its function in the realisation of goals towards the user. This structure refines the physical structure into a construction that realises the function in its context of use according to performances like comfort, aesthetics, durability etc.

Experiment

Based on the research question, the object and research approach, we design an experiment. It is through the experiments that we expand the design spaces. In order to do that we need to direct the experiments through different search activities; systematic investigations and design activities. In systematic investigation we investigate certain basic phenomena, like electronic and sound properties in conductive textile structures. In the applied research we combine basic foundations into more complex systems exploring the dual nature of structures and objects.The result of each experiment may emanate in a research result or a continuation of the research through a new research object and new types of experiments

Evaluation

In evaluation we evaluate the result of the experiments and decide how we can proceed or if we actually have found some kind of research result. Evaluation can be done using precise measurements in more systematic investigations. Evaluating the physical structure is an example where there already exists a set of established methods. Evaluation of design activities has more of a character of subjective evaluation and the methods are not so established. In design activities subjective judgements are used in order to evaluate how close we are to our goals. The evaluation refers to the research question; is the result an answer to what we are looking for? Or, how can we proceed in order to explore the questions further?

Research result

The research result is what we discover during research that we can use to expand our design space such as new components, solutions and methods.

6. EXPERIMENTS AND RESULTS

The research method is based on a series of interlinked experiments designed through the research questions and the research objects. The experiments are separated into two different sections: interactive textile structures and health monitoring. The experiments are based on both systematic investigations and design activities. In systematic investigations certain basic phenomena are explored, for example sound properties in piezoelectric structures. In the design activities smart textiles are explored through an application, for example the extended concept of communication and the health monitoring prototypes. These prototypes are investigated from their dual structures, the physical structure and the structure within the context of design and use.

INTERACTIVE TEXTILE STRUCTURES

This section explores interactive textile structures through two product concepts and the specific research questions (Figure 18). The experiments investigating Interactive Textile Structures are described in Papers I, II, III, IV. The aim is to get a practice-based orientation in interactive textiles structures in order to refine basic foundations for design and future research.

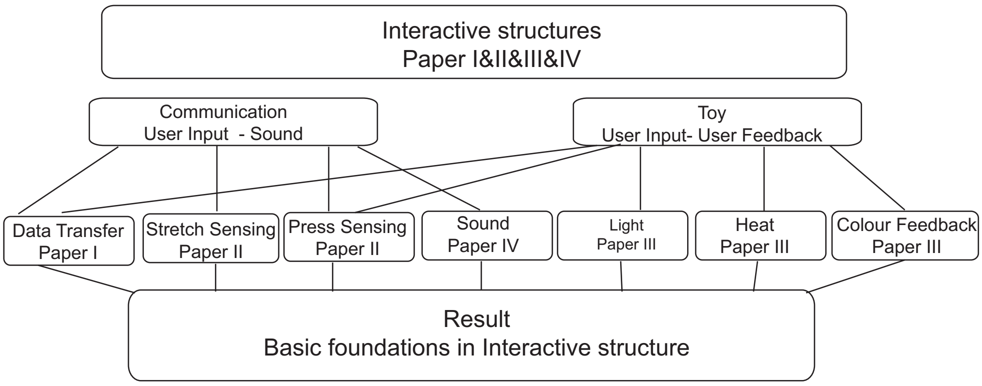


Figure 18 Structure of Interactive textile structures experiments, papers and result

HEALTH MONITORING

The second part goes deeper into a specific design case, health monitoring (Figure 19). The design activities are described in this thesis and the evaluations of the prototypes are described in Papers V, VI, VII. Health monitoring aims to get deeper into how interactive structures are integrated within a system/product from two perspectives: the physical structure and the structure of use and design.

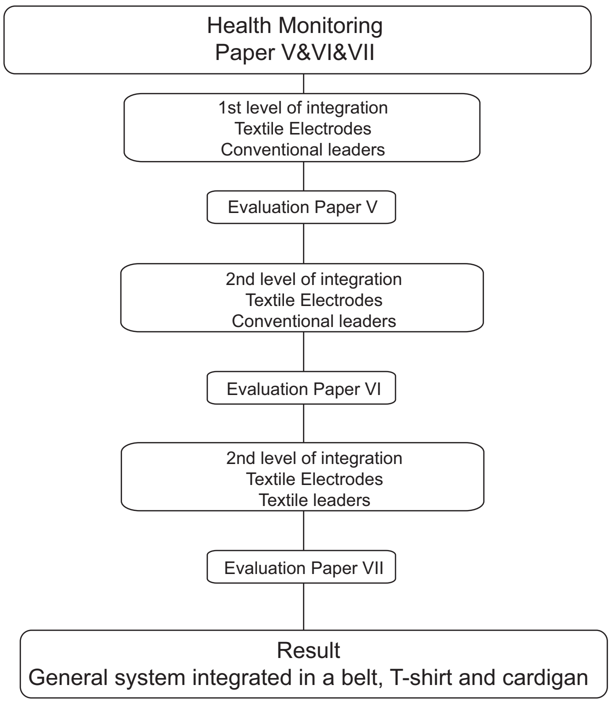


Figure 19 Structure of Health Monitoring experiments, papers and result

7. INTERACTIVE TEXTILE STRUCTURES

Interactive textile structures are structures that can be controlled by using computer technology. This section explores the basis of interactive textiles structures through two product concepts and with reference to specific research questions.

In what ways is it possible to integrate electronic functionality into textile structure?
In what ways is it possible to integrate feedback in textile structures?
In what ways is it possible to integrate sensor input in textile structures?

These questions are explored in familiar contexts concerning both textile and computing technology, as in the two products. Such an approach delimits the search area and enhances the understanding of the relationship between textile, computing, smart material and use. The result is a series of basic methods for how interactive textile structures are created and how they relate to constructions in textile consisting of up to three-layers.

Experiments concerning interactive textile structures are described in Papers I-IV. Paper I and II include experiments in the communication project. Subjects for investigation are user aspects, interaction design and integration of interactive textiles. Paper III describes different textile structures aiming to enhance the interaction as well as integrating textile structure with the computing technology system in the toy concept. Structures described in these papers are mainly based on conductive capabilities. The last paper, Paper IV, on interactive textile structures, presents a piezoelectric sound structure which is a result and a continuation of the earlier papers. This is the first step towards exploring a new type of material with built in energy exchanging properties.

PAPER I

Paper I describes the product concept "Wanted" and the first step to go from embedded technology to a more flexible integration of technology (Figure 20). The implementation of technology in the glove introduces new types of use but also a more complicated product due to the integrated technology. Electronic components are less sustainable than textiles and not washable. The integration of technology into a single textile product also limits the use of the technology to that product.

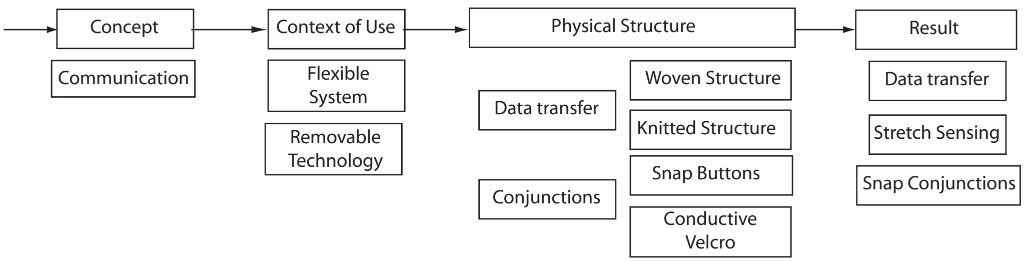


Figure 20 Paper I overview

Aim: This experiment addresses the following issues: Is it possible to prepare a conjunction system of conductive textile surfaces that allows the user to remove the communication system from the conductive textile surfaces? How should the surfaces be constructed? How should the conjunctions between the system and the components be made?

Method: Four types of textile data buses were constructed: the textiles were made in 1.1 rib and plain weave. Two types of yarn were used, 100% stainless steel and stainless steel blended with polyester. The electronics were connected to the conductive surfaces in three different ways: traditional electronic conjunctions, snap buttons and conductive Velcro fastening. The transmission of signals is acceptable in all structures and yarns, but the performance differs. Solid yarns with high conductivity and a structure that makes the conductive thread to run as straight as possible led to a better performance. A knitted structure with a blended yarn caused disturbances in sound when stretching the material and therefore worked better as a sensor. The choice of conjunctions created very little difference between traditional conjunctions and snap buttons while the Velcro fastening performs worse and is also more clumsy and hard to handle.

Contribution: This paper describes how the first set of textile data transfer, knitted and woven structures, are developed. In these two types of structures two types of yarns are tested for signal transmission of sound. Both structures and yarn affect the transmission of sound. There are signal disturbance in knitted structures and this disturbance is enhanced in structures made of a staple fibre yarn made of both conducing and non-conducting fibres. This combination of structures and yarns may on the other hand be useful as stretch sensors. The paper also shows a flexible integration, textile as infrastructure to different technical solutions where the user decides functions and products.

PAPER II

Paper II deals with the development of a wider concept and use of the Wanted glove in order to extend the textile structures that could be used (Figure 21). The user aspects and interaction design provides a basis for the direction of the chosen textile structures.

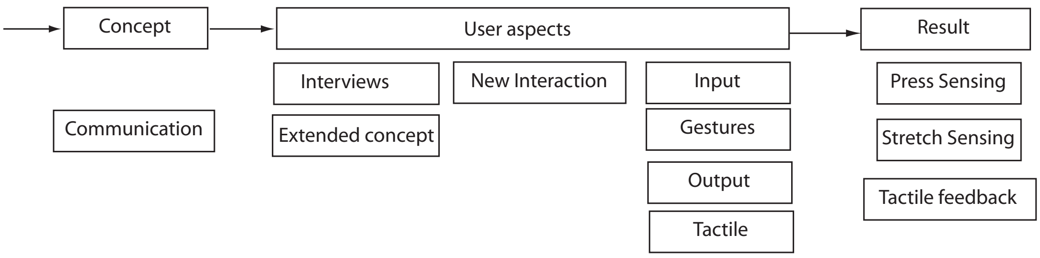


Figure 21. Paper II overview

Aim: The aim with this paper is to create an alternative interaction when mobile technology is connected to a textile product.
Method: The tool for this project is a glove that is wirelessly connected to the mobile phone. The concept is eleborated with the aid

of interviews. The interviewees are professionals who are exposed to hard weather and whose tasks are physically demanding. An overall impression from the interviews is that the use of technology as well as other equipment is functional to the fulfilment of some important needs. Ease of use is highly important due to the exposed context. The result from the interviews shows that the mobile-phone or a communication radio is an important tool when handling different tasks and keeping the situation secure. The extended concept consists of three types of functions, communication, information and an open function that identifies the user in order to allow access to different systems. The extended concept opens up for further questions like: How should the interaction between the extended concept and the user be designed? How could the textile structure be used in order to improve the interaction?

Contribution: This paper contributes with a design concept for a glove wirelessly connected to a mobile phone. The concept is a general design proposal where a glove is an alternative user interface to the mobile phone. A glove introduces a set of possibilities for the use of gestures in the interaction. The potential of textile sensor structures, such as stretch and pressure sensors, are of interest in such interaction. Tactile feedback offers alternative to visual feedback and is suitable in more extreme conditions. What this paper also contributes with is further insights into how future improvements in both textile and computing technology affect the possibility of realising the design concepts.

PAPER III

Paper III describes the use of textile material as a user interface for interactive toys called Spookies (Figure 22). Both traditional textiles and smart textiles are used in order to communicate the function and the interaction. In this concept there are several opportunities for interaction both by activating the function and also by getting feedback, where feedback is of major interest.

Aim: This paper addresses the following questions: How can textiles be used as a user interface to an interactive toy? What are the possible smart materials to use in order to communicate the interaction? How can smart materials be applied to the toy? How will the use of smart materials affect the product?

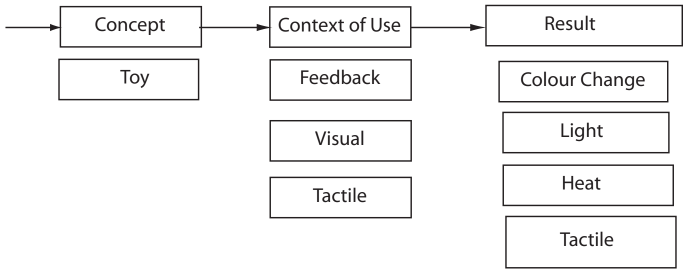


Figure 22. Paper III overview

Method: The project shows how dynamic feedback can be applied in textiles at different levels; colour change, light, heat and tactile feedback. Feedback has shortcomings due to rather large power consumption. An exception from that is the tactile feedback and LED but they are integrated technology and not pure textile solutions. Light feedback is of interest but there has to be more work done in order to develop light emitting structures. Colour feedback and heating are easy to integrate in different configuration as pure textile solutions. They are however quite power consuming.

Contribution: The contribution of this paper is colour change material and principles of applying and activating such materials in a textile structure. Other feedbacks that have been explored are heating, tactile and light feedback.

PAPER IV

Paper IV describes the first step in substituting an electronic component, the microphone (Figure 23).

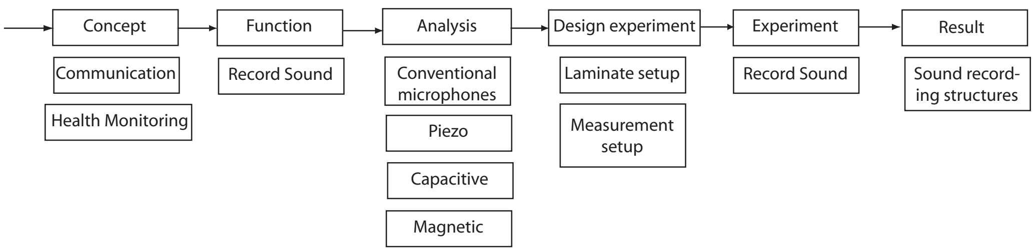


Figure 23. Paper IV overview

Aim: The focus of this project is the development of textile microphone elements, like textile surfaces able to sense and transfer sound. An interesting aspect of a microphone element is its function both as an active sensor and actuator. The project aims to promote the development of these abilities.

Method: This project uses piezoelectric PVDF films laminated between different textile fabric structures. In order to explore whether the textile structures affect the recording of sound signals, textiles of different thicknesses, densities and manufacture techniques are used. The textile samples were joined up with a measurement set-up. Different sounds are recorded via the textile sample into the computer for further analysis. The only signal filtration is a 45-55 Hz filter to eliminate the most common noise emanating from other electrical devices in the measurement environment. Besides this filter we decided to keep the raw format of the signal in order to make necessary adjustments in view of future applications. The initial results show that the laminated piezoelectric film registers sound. The signal quality depends of the laminate set-up.

Contribution: This paper contributes with a presentation of a set of piezoelectric structures able to record sound.

RESULT

The result consists of a series of methods for the creation of a set of interactive textile structures and a concept of interactive textiles as layered structure. The presented examples of interactive textile are based on conductivity, thermochromic pigments, electroluminescent coating and piezoelectric materials. The contribution of the basic methods is not the functionality itself, since most of them can be referred to related projects. Related projects are, however, more focused on certain applications and specific textile solutions rather than highlighting fundamental aspects of how these structures are created. By presenting them as general design elements it is possible to create an interactive textile structure in yarns, in any textile technique or combinations of techniques. The basic structures are examples of new design elements and assemblies in the expansion of the design space. The explored projects show that both input and feedback is of interest but a majority of the results found have been sensors. So far an actuator has shown to be a more complicated structure to integrate and a structure that requires a higher power supply compared to sensors. Transforming electronics into structure is also a process for long-term of research efforts. The microphone element experiments are examples of such attempt.

The interactive textile structures are categorised as conductive, colour change, light and piezoelectric structures (Table 7). Each structure is described in general layers that can be transferred into several textile techniques for example weave, knit, warp-knit, coating and lamination. All structures are presented as fundamental constructions that are necessary in order to achieve a certain function. Besides the knowledge of how each of the functionalities is created, the basic methods also form a foundation for further research on textile structures. The conductive structures for example, have already been an important input to the luminescent and piezoelectric structures.

RESULT INTERACTIVE TEXTILE STRUCTURES	
CONDUCTIVE	Data transfer Press Sensing Stretch Sensing
COLOUR CHANGE	
LIGHT	
PIEZOELECTRIC	Stretch Sound

Table 7. Organisation of interactive textile structures

CONDUCTIVE STRUCTURES

Conductive structures are frequently presented in Smart Textile research. Since these structures conducts current they are useful from two aspects: The first is that conductive materials may be used in the creation of conductive interactive structures. The second is that conductive materials form an important basis to other smart materials.

CONDUCTIVE MATERIALS

Conductive materials for textile use are available as yarns, coatings and films for lamination (Table 8). The conductivity is based on metals or carbon where the metal-based are the most conductive materials. There are different methods for applying the conductivity into the textile material. In coatings, carbon particles are blended into a coating like silicon. Films are pure and thin metal sheets. Conductive yarns are created in different ways; staple metal fibres, filaments of metals, metal-coated conventional yarns or thin metal filaments twisted around conventional yarn. The conductivity of the yarn is based on the conductivity of the conducting part of the yarns.

Examples of conductive yarn, film and coating

A. Metal filament twisted around Nylon/Lycra Yarn

Thin conductor, elastic yarns, easy to process. Thin conductor, therefore easy to break and less conductive. Non continuous surface conductivity. Pleasant touch.

B. Silver coated nylon

Rather elastic and easy to process. High conductive. Continuous surface conductivity. Not so robust to strain, washing and wear and tear. Acceptable touch.

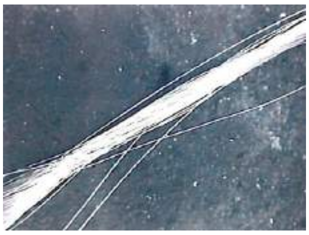
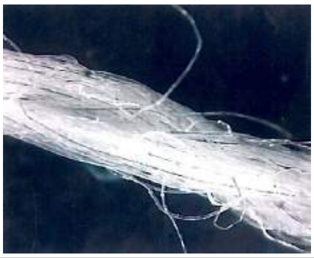
C, 100% Stainless steel. Monofilament	
	Not elastic, hard to process. High conductivity. Continuous surface conductivity. Robust and resistive to ear and tear. Unpleasant touch.
D. 80% Polyester 20% Stainless steel. Staple fibres	
	Rather elastic and easy to process. Low conductivity. Non continuous surface conductivity. Piezoresistive properties.
E. 100% Aluminium foil	
	High conductive material for laminate processing. Offers a variable integration. Brittle material
F. Silicon/Carbon coating	
	Semi-conductive material for coating on textile. Piezoresistive properties.

Table 8. Examples of conductive materials

Besides the conductivity of the material itself it is also possible to adjust conductivity by using the difference in width or thickness of the conductor. One (a-conductor), two (b-conductor) or four (c-conductor) yarns integrated into a conductor affect the conductivity (Figure 24).

Another factor that affects the conductivity is the textile structure itself when conductive yarns are used (Figure 25).

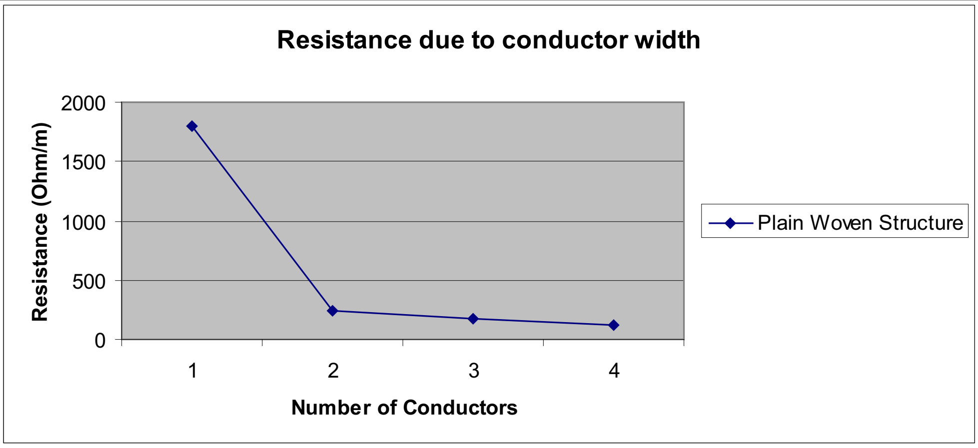


Figure 24. Conductivity in a one, two and four- row conductors in a knitted fabric

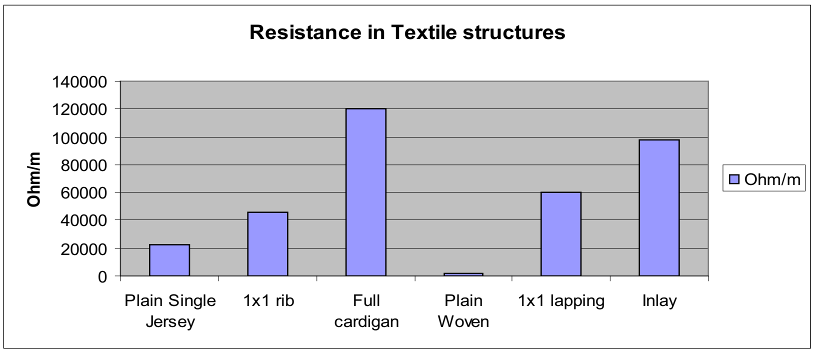


Figure 25. Conductivity in different structures, using the same type of yarn

DATA TRANSFERRING STRUCTURES

Data transferring structures shift data from one point to another, like a common wire or a series databus. A data transferring structure is one of the most basic principles and the first structures that showed proof of a smart textile concept [Jung et. al]. Today, such structures are used in several applications and though they seem basic they should not be overlooked. Data transferring structures are not just the interface between electronics and textiles, but also a system between different sensors and actuators. The basic principle is simple but the more complex system should be included the more one has to take the construction into consideration. The structure can be constructed in several ways and in different textile techniques (Figure 26) but there are three basic principles that affect the function and use of the data transferring structure (Figure 27). The first basic principle is a single layer construction, where the leader is unprotected and available on both sides. The second is a two-layer construction where the conductivity is available from one side and protected from the other. The third is a three-layer construction where the conductivity is placed between two layers and totally protected.

Figure 26. Data transfer made in two different qualitites

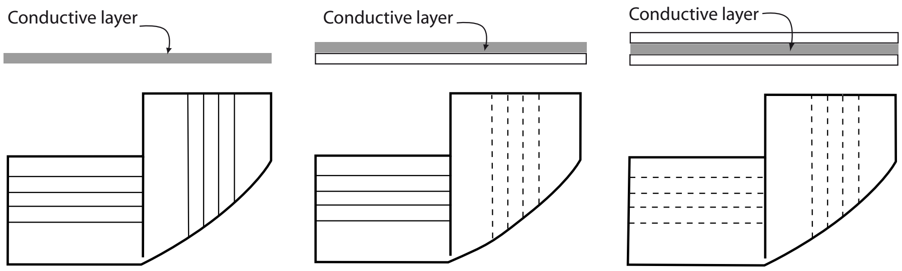


Figure 27. Data transfer principles

The basic structures can be combined into a complex of structures depending on the required use. Sometimes it is necessary to protect the conductor from both sides in certain areas, while the conductor has to be available for conduction in other parts. To solve that, a three-layer construction is combined with either the single or double layer principle (Figure 28). A two and three layer construction can be achieved directly in a weaving or knitting procedure. It is also possible to create a two or three-layered databus by coating or laminating a single-layer construction. It is a technique that offers extremely thin multi-layers fabrics and. Another way of achieving several levels in a single level is to use isolated yarns.

The electrical performance of a data transfer structure is dependent on the following three aspects: the conductivity of the yarn, the number of threads integrated in the leader and the textile structure used.

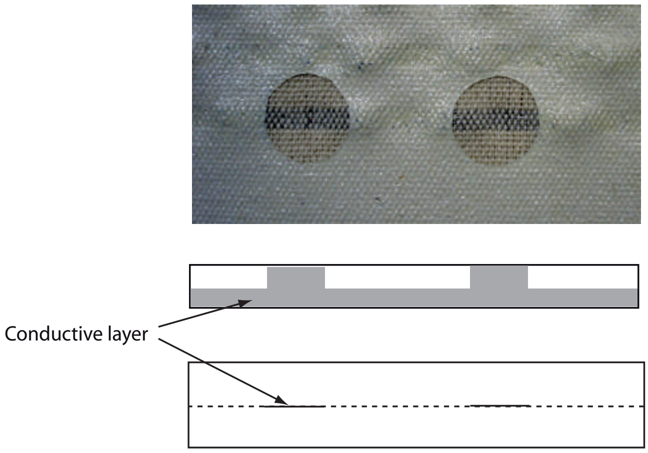


Figure 28. Combination of layers

PRESS SENSING STRUCTURES

The principle of a press sensor is a structure that is touch or pressure sensitive. When such materials are mechanically distorted they will change their electronic properties. There are many different types of touch sensors and they can be based on a variety of materials. Some are based on simple mechanical operations, for example a switch that closes or opens circuits. Others involve more sophisticated forms of touch measurements, they use changes in the electronic properties to define touch, for example capacitive switches [Meyer et.al] [Sergio et. al]. There are two types of press sensors available on the market Eleksen [Eleksen] and Softswitch[Leflty, Jones]. Eleksen is a combination of conductive and non-conducive fabric layers laminated together forming a resistive touchpad. Softswitch is a specially designed conductive composite (Quantum Tunnelling Composite), that when mechanically distorted or compresses changes resistance proportional to the force applied. In our prototypes we have done experiments with basic and position switches.

A simple touch switch opens or closes electrical circuits (Figure 29). It is at least a three layer structure where the outer layers are conductive and the middle layer is a meshed layer.

The design of the mesh decides the quality of the switch. A sparse mesh allows a light touch while a closer mesh requires a harder touch.

It is also possible to alter the thickness of the mesh in order to get different types of touch properties. As often with basic solutions, this is a robust construction and easy to control since it is a matter of absolute values. A basic switch is not dependent on high conductive materials. The most important aspect of the conductive materials is that the conductivity applies all over the touch surface.

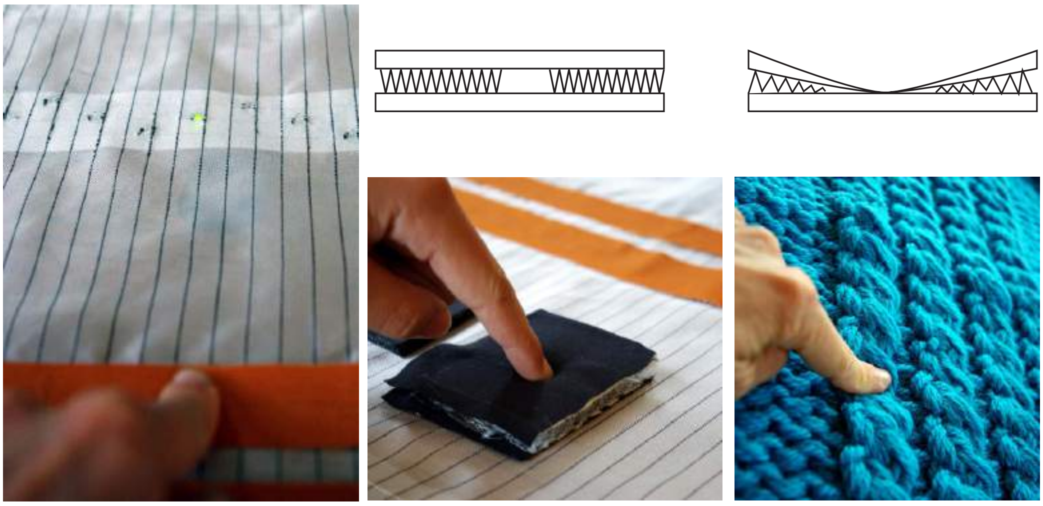


Figure 29. Basic touch switch

Position switches determine the location of pressure. A matrix defines position based on rows and columns. The basic touch principle can be developed into a matrix switch system. It is also possible to use a high resistance material in the switch and define position in a row of switches (Figure 30) or within a matrix (Figure 31).

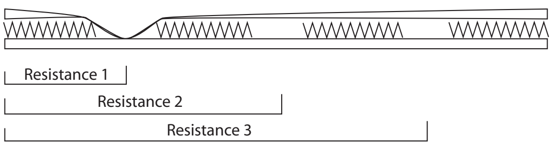


Figure 30. Position based on resistance

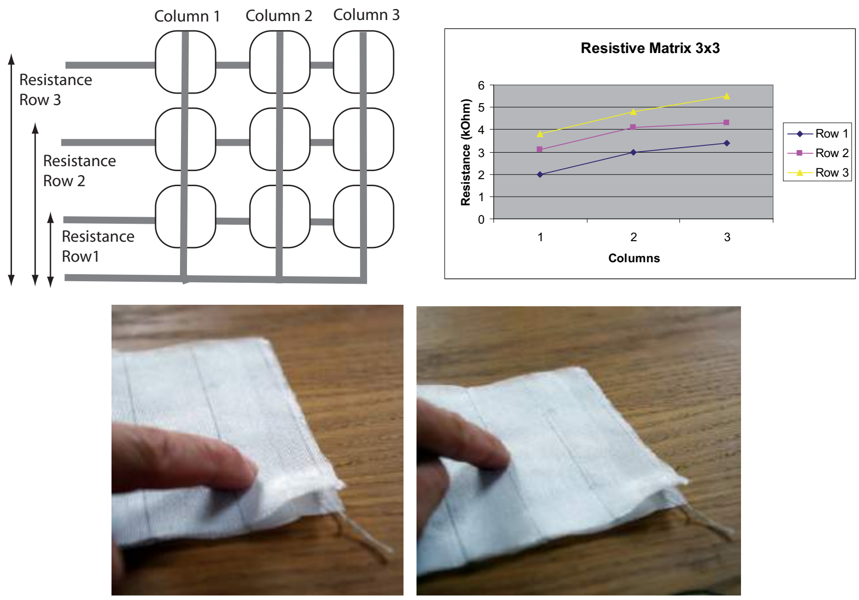


Figure 31. Matrix based on resistive structure

STRETCH SENSING STRUCTURES

A stretch sensor is a structure that changes electronic properties due to stretch. This could mean for example that the conductivity will increase or decrease due to structural changes in the sensor, which is an example of a piezoresistive sensor. But there are also stretch sensors that are based on capacitive and piezoelectric technologies [Edmison et. al]. Stretch sensors based on piezoresistive properties are presented in several projects. Most of them are based on knitted structures[Bickerton] [Wijesiriwardana et. al] but there are also examples of how stretch sensing materials are made of a conductive polymer that is coated on a stretch fabric [Tsang et. al] [Tognetti et. al].

A stretch sensor changes conductivity due to stretch, which in turn is due to the construction of the material (Figure 32). An example of that is a staple fibre containing a minor part of metal fibre, if the yarn is stretched the metal filaments are brought closer together and the resistance will decrease. Another example is to use a conductive polymer coating on a stretch fabric where the conducting part will be pulled away from each other resulting in a increased resistance.

Although a stretch sensor can be made through any textile technique, it is important to note that different techniques and materials affect the character of the sensor. The diagrams below shows how the output voltage is affected by applied strain in three different types of stretch sensors; a knitted structures integrated with a stainless steel/polyester staple fibre yarn (Figure 33) an elastic weave integrated with a stainless steel/polyester staple fibre yarn (Figure 34) and a conductive coating applied on an elastic weave (Figure 35). While the woven sample only indicates stretch or no stretch, it is possible to register each stretch in the other two samples.

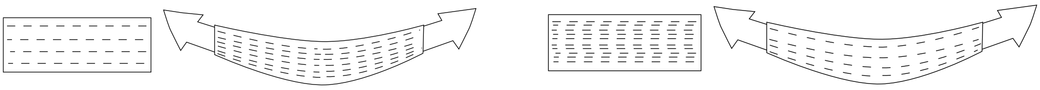


Figure 32. Conductive elements approaching each other respectively separating from each other

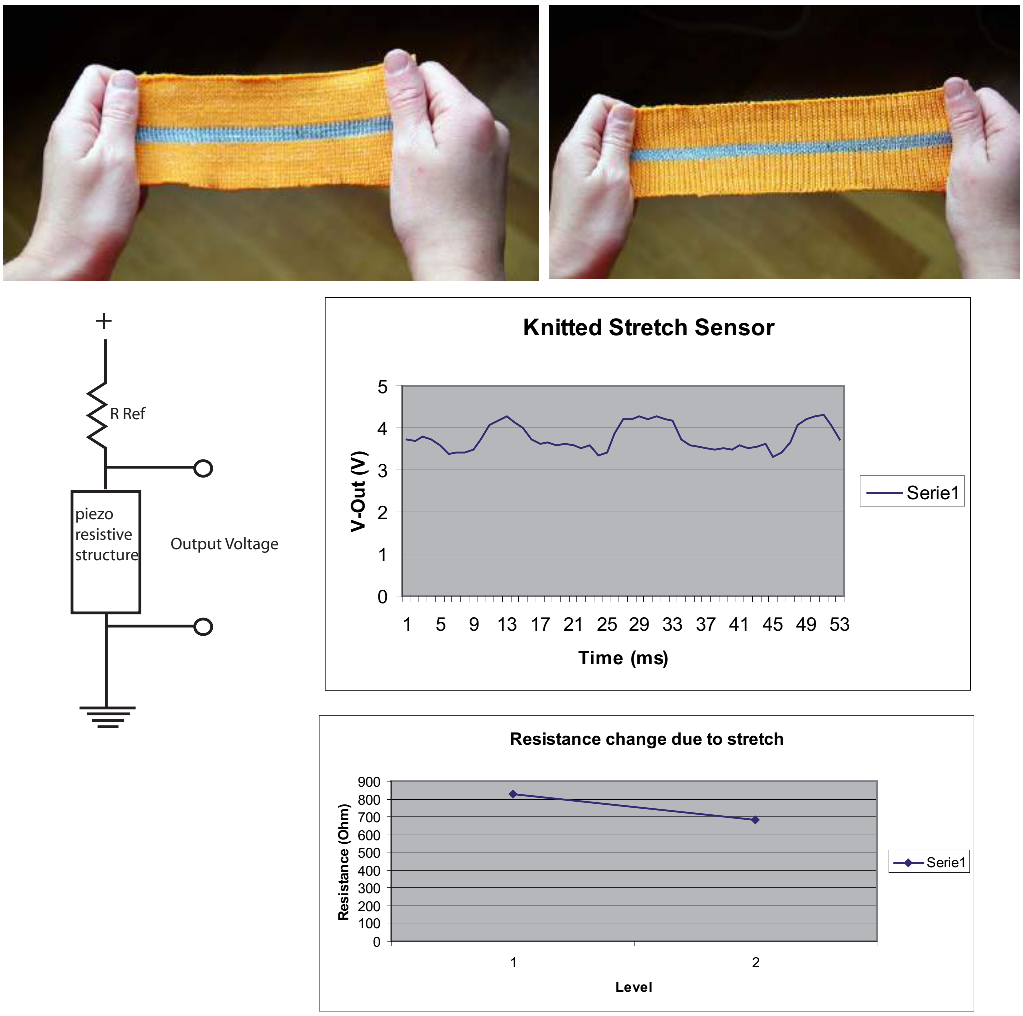


Figure 33. Characteristics of a knitted stretch sensor

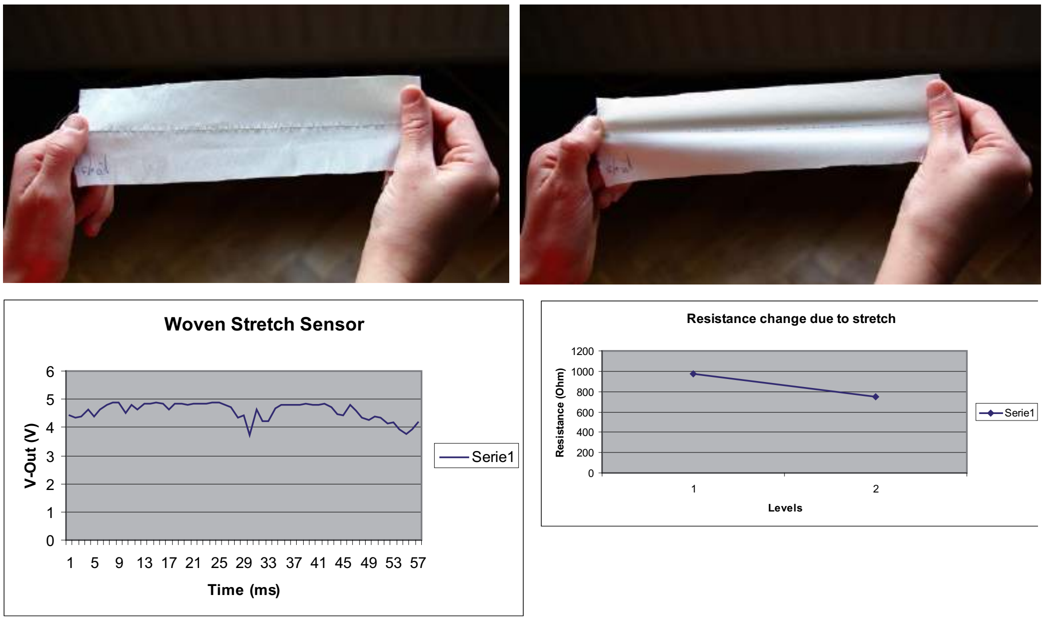


Figure 34. Characteristics of a woven stretch sensor

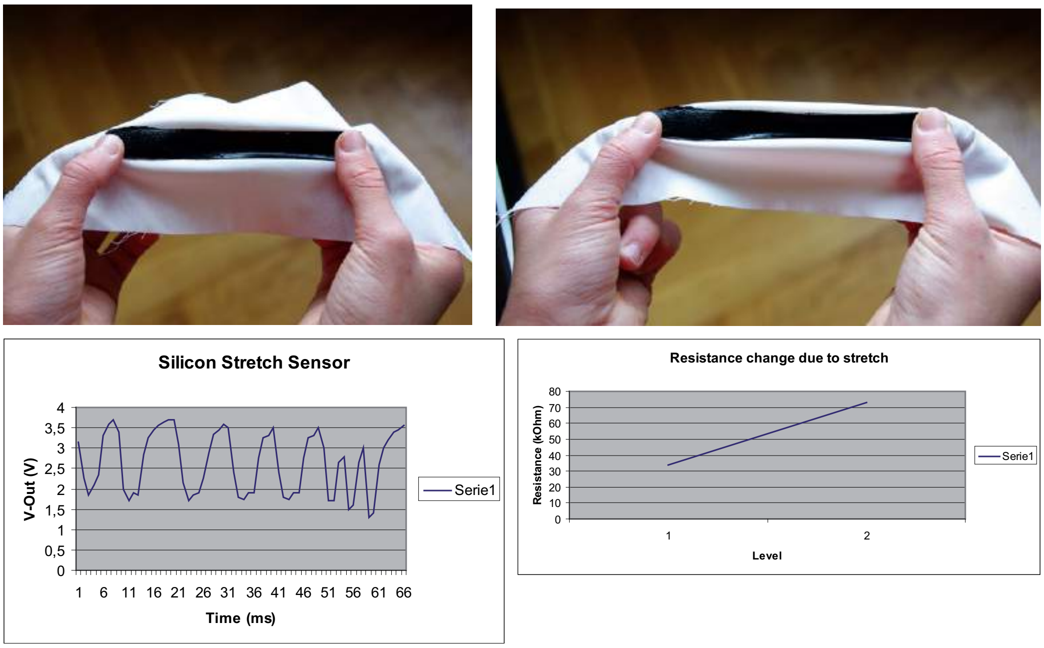


Figure 35. Characteristics of a coated stretch sensor

COLOUR CHANGE

Colour change materials are a group of materials in which external stimuli change their optical properties, often perceived as a colour change. Thermochromics materials absorb heat which leads to a thermally induced chemical reaction. Blending thermochromic with traditional colour or printing thermochromic colour on a coloured surface, gives an illusion of change from one colour to another. In these experiments the colour changes have been integrated on both woven and knitted surfaces. The heating can be applied in different ways (Figure 36); print on a heating fabric, print on fabric laminated to a heated fabric or print on a three-layer construction where the heating fabric is placed in the middle layer. In Figure 37 and 38 a thermochromic print is applied on a woven heating fabric and a three-layer knitted fabric.

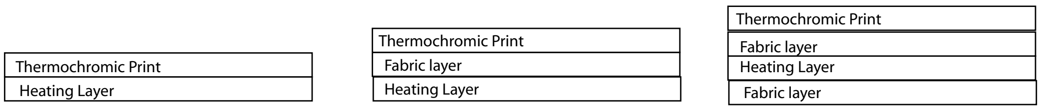


Figure 36. Colour change principle

Figure 37. Thermochromic print on a woven heating fabric

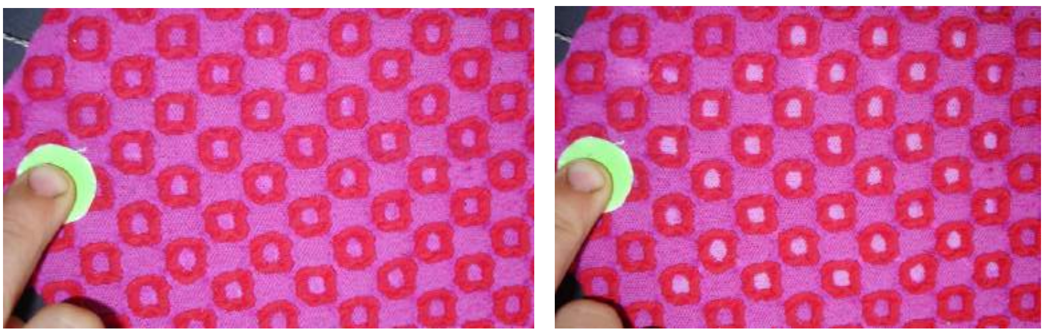


Figure 38 Thermochromic print on a three-layer knit.

LIGHT STRUCTURES

Light absorption and emission can occur through various processes, depending on which material system is used; conventional semiconductors, organic semiconductors and pyroelectric sensors [Singh]. As in the piezoelectric structures these structures can be used as both sensors and actuators by their capacity to absorb and emit light. Photonic textile based on electroluminescence has been developed by TITV in Germany together with Philips into a variety of textile displays [Möhring et.al]. The interesting aspect of these textile structures is maybe not just that they introduce a new design element such as light in textile. They also introduce the knowledge of semi-conductor principles which opens up for photovaltic structures.

Conventional semi-conductor light particles, or photons, create electrons and holes through the absorption of light. These electrons and holes create an electrical signal that can be used to detect the absorption. Conversely, electrons and holes can emit photons, light emission. In organic semiconductors there is a transition between molecular orbitals. Pyroelectric structure uses thermal energy produced by radiation to detect or create light. Electroluminescent structure is a light-emitting materials based on luminescence, which generally refers to the emission of light due to incident energy [Addington, Schoedeck]. Luminescence is emitted light that is not caused by incandescence, but by other means such as chemical reactions. The sources of excitation can be electric, chemical or even attributable to friction.

In the electroluminescence material the source of excitation is an applied voltage or electric field. There are two different ways in which electroluminescence occurs. The first condition occurs when there are impurities scattered through phosphor. An electric field causes electrons to move through the phosphor and hit the impurities which cause light emission (Figure 39). The second condition is more complex and based on semi-conductor materials and it occurs due to general movements of electrons and holes. Figure 40 shows the first principle applied on a conductive woven fabric.

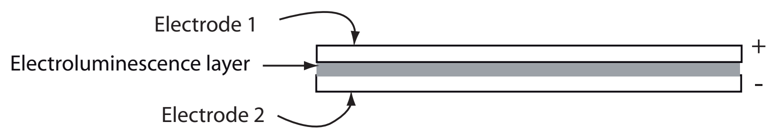


Figure 39. Electrolumicence based on phosphor and conductive layers

Figure 40. Electrolumiescence applied on textile structure

PIEZOELECTRIC STRUCTURES

A piezoelectric structure is a sensor that generates an electrical potential in response to mechanical distortion in all directions, for example stretch or pressure. The effect is reversible which means that an electric signal causes a deformation of the material. This effect appears in certain materials containing crystals where a polarisation of the crystals occurs when the material is exposed to mechanical stress. One side of the crystal will obtain a positive charge while the other side of the crystal will obtain a negative charge [Tzou et. al].

Many materials, both natural and man-made exhibit piezoelectric effects and for textile use there is a polymer, PVDF (Polyvinylidene Diflouride). In piezoelectric PVDF the intertwined long-chain molecules attract and repel each other when an electrical field is applied or the material is mechanically distorted (Figure 41) [Singh][Worden].

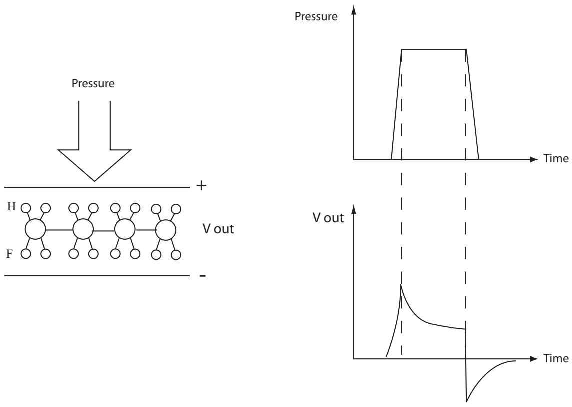


Figure 41 PVDF structure and its behaviour due to pressure

PVDF are available as films, in optional sizes and thicknesses, laminated between two conductive layers as the electrodes (Figure 42). PVDF films are easily laminated between layers of textile fabrics and a required signal is achieved from the two electrodes. Such structures can be used as stretch sensing structure [Edmison et. al] as well as a press sensing structure. The potential in Piezoelectric structures as press sensors is the ability to sense extremely small changes like for example sound waves [Yu et.al][Berglin, Zetterblom]. Another feature is that the output voltage from the material is in direct proportion to the applied force.

Figure 42. Piezoelectric structure

The stretch sensing effects are achieved by laminating a PVDF film between two stretch fabrics using a stretch web laminate. The response from this set-up is high and reliable (Figure 43).

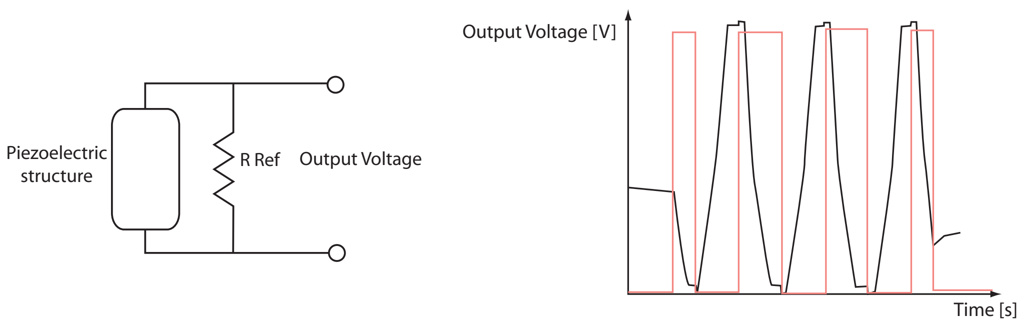


Figure 43 Piezoelectric structure exposed to stretch

Piezoelectric structures are also sensitive to pressure as small as sound waves. Depending on the laminate set-up, mainly due to the qualities of the fabrics, these structures are able to record sound (Figure44).

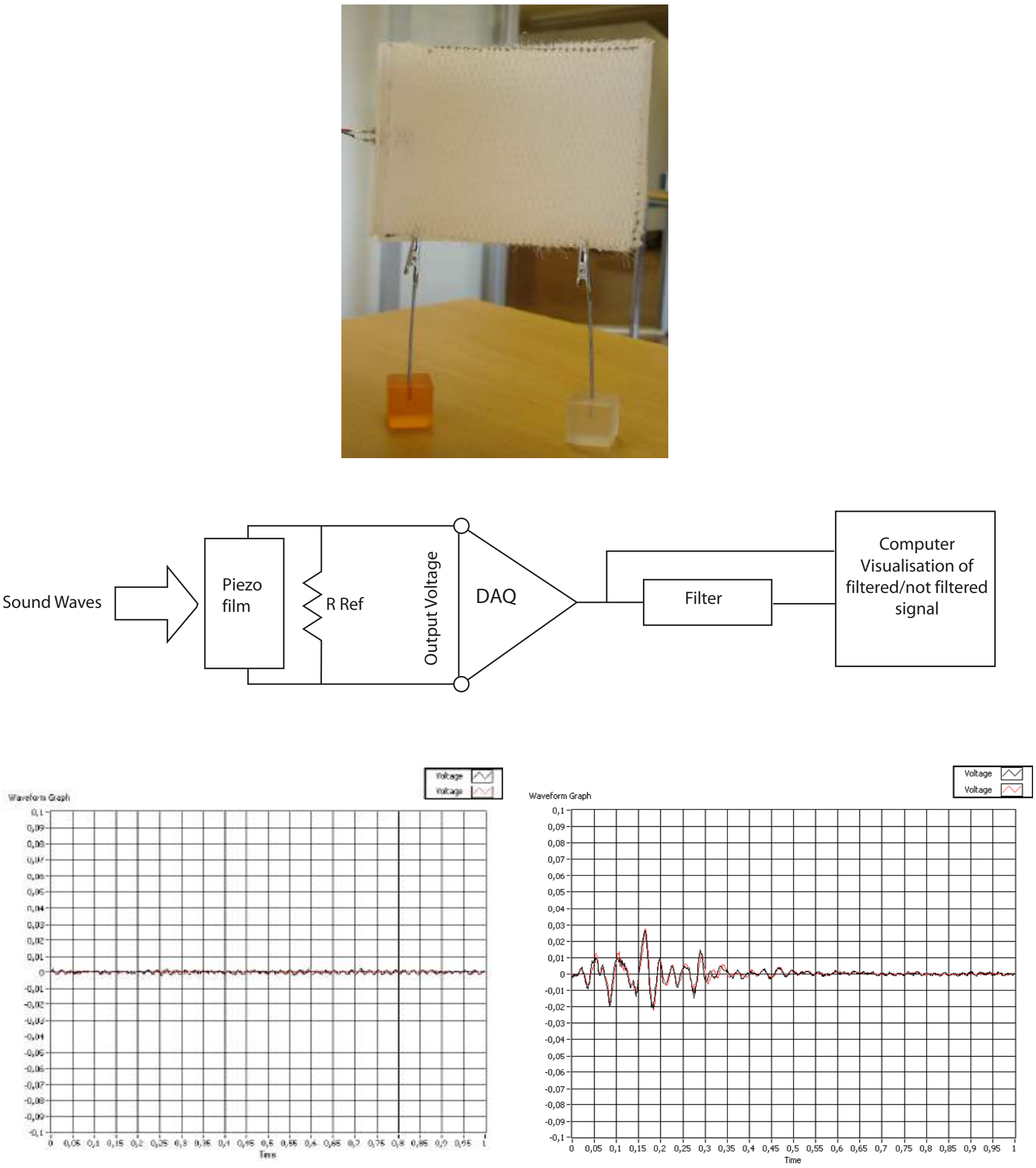


Figure 44 Piezoelectric structures recording sound

8. HEALTH MONITORING

This section describes a deeper study of a specific design case, of health monitoring aiming to explore how interactive structures are integrated into a product. An overall goal in the health monitoring concept has been to create a heart-rate measuring system (ECG) and muscle activity (EMG) through a pure textile solution consisting of textile electrodes and leaders. The vision has so far been realised concerning heart rate, while muscle activity is still being measured through the use of conventional electrodes. The design activities are described in this thesis and the evaluations of the prototypes are described in paper V, VI and VII. The research is based on a concept where a textile garment is able to measure different, vital signs and transmit them via a wireless link to any computing unit (Figure 45).

Advances in novel textile materials and structures, as well as in communication technology have opened up for a new generation of health care systems. Health monitoring through clothing is an example of an area where research and development in textile design and technology as well as wearable technology is performed. The Georgia Tech Wearable Motherboard [Park et.al], was one of the first health applications to be integrated into a garment. The demands on textile products with respect to sustainability, flexibility and washability have influenced research towards the integration of electronic functionality in textile structures since textile electrodes are flexible and easily integrated with garments. Integration of textile-based sensors for ECG recording has been demonstrated in several projects such as MyHeart [MyHeart], Proetex [Proetex] and Context [Context]. Such systems, offer mobile and flexible surveillance of different user groups within health care, extreme working conditions, sports, etc. Besides actual performance, the system should offer a flexible and comfortable solution to the different kind of users in various situations. It should fit several types of body figures and be easy to design and manufacture in a variety of garments. This is an example of the dual nature of an artefact's physical structure and the context of design and use [Kroes]. There is a physical structure focused on functional performance, but there are also contexts of use and design, which so far, have rarely been mentioned in research of these types of products.

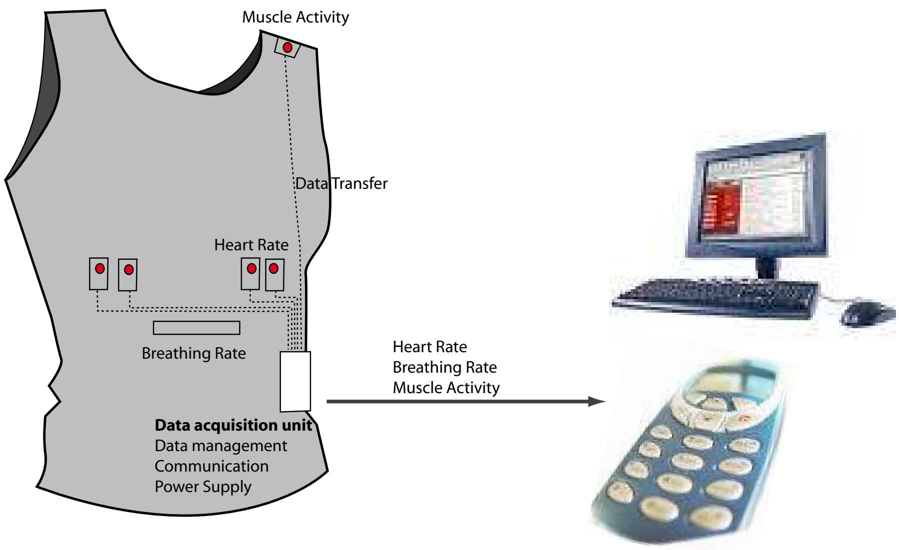


Figure 45. Wireless health monitoring system

This study has been divided into two processes exploring the dual nature of health monitoring artefacts: its physical structure and its structure within the context of human action and use. The evaluation of the prototypes from an ECG measurement perspective is described in papers V , VI, VII.

PHYSICAL STRUCTURE

The physical structure of the health monitoring prototype realises a certain function, in this case it measures heart rate and/or muscular activity. Such structures consist of textile electrodes, textile leaders, data management and power supply (Figure 46). The system is developed through a series of prototypes where textile electrodes and leaders are integrated through a step by step procedure. Textile electrodes offer a flexible and soft solution that could easily be integrated into for example garments. Intermittent disturbances are common in bio-medical signals recorded with textiles. A combination of signal processing using multi-channel methods and careful electrode design, and the design of the whole system will compensate for the shortcomings. Besides the electrodes, the health monitoring system consists of a data transfer system placed in a separate layer from the electrode

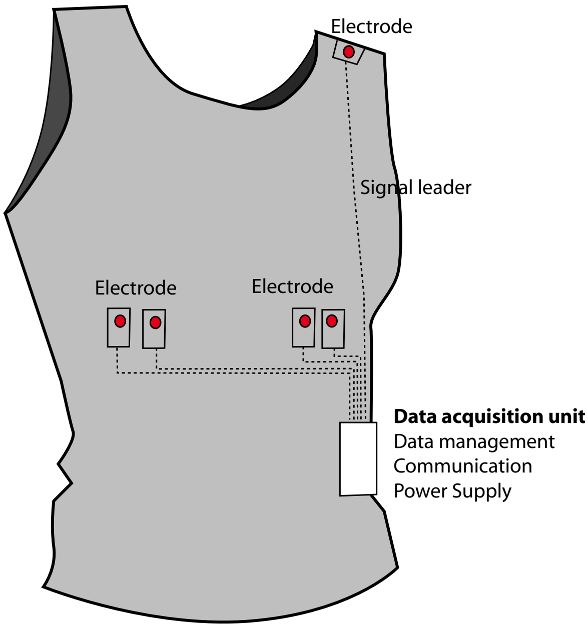


Figure 46. Physical structure of health monitoring prototypes

The physical structure of both heart rate and muscular activity measurement are conceptually the same; a conductive surface in contact with the skin and connected to a textile leader system isolated from the skin, transferring the signals to an acquisition unit. There are different problems to consider since the measuring of muscular activity is more dependent on a well-defined position of the electrode. So far the integration of a pure textile solution has been carried out in ECG measurements while EMG measurements have been carried out using conventional electrodes integrated into a padded structure. The integration of a textile system for ECG measurements has been integrated step by step (Figure 47).

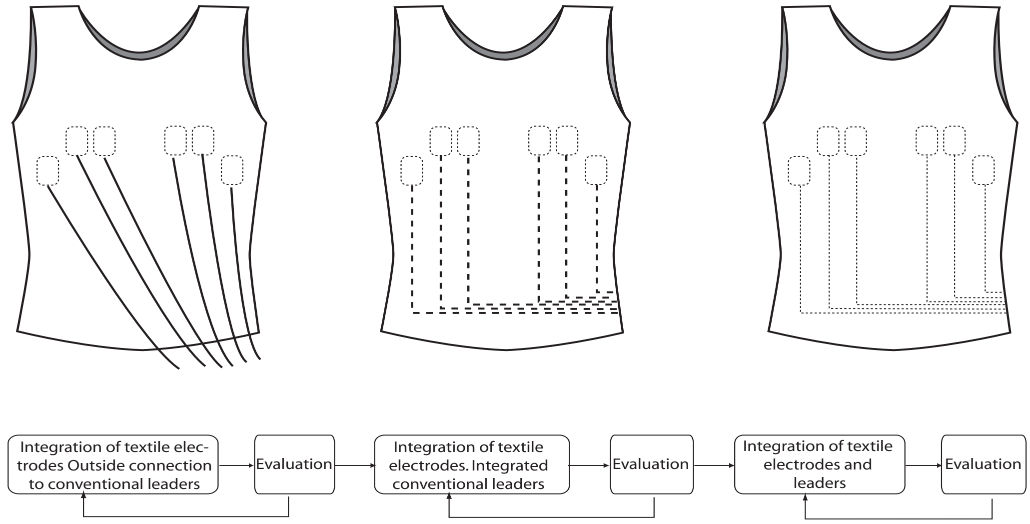


Figure 47. Process of creating the physical structure for heart rate measurement

The integration of EMG measurement has been planned into another type of step by step integration (FIgure 48).

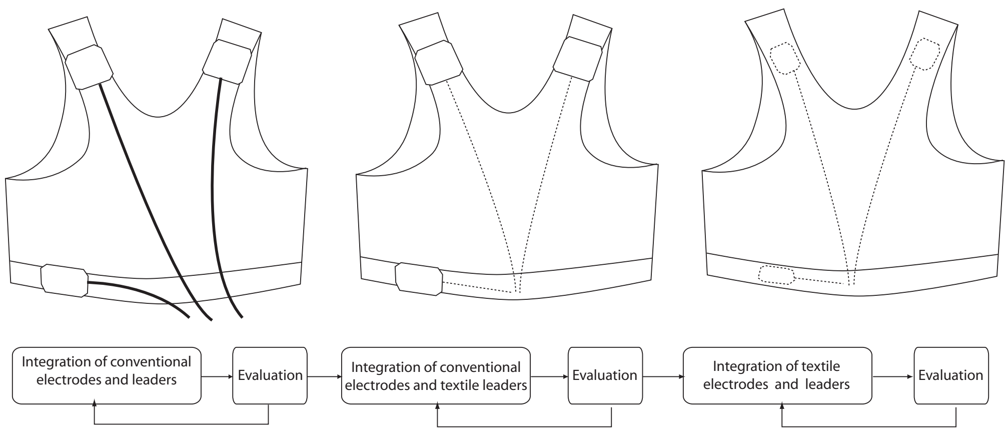


Figure 48. Process of creating the physical structure for muscle activity measurement

TEXTILE ELECTRODES

Textile electrode structures have the ability to pick data from our body, such as heart rate and muscle activity. Conventional electrodes consist of an Ag/AgCl electrode coupled with gel in order to achieve the best skin electrode impedance. A textile electrode is made of a textile conductive surface that substitutes a traditional electrode. The electrode picks up body signals and the signal is further transferred into a data transferring structure. Textile bio-electrode can be made of any conductive material but the most common ones are some kind of metal-based solution, silver or stainless steel. A yarn that is conductive all over the surface is also preferable. A 100% stainless steel or silver coated yarns are for example more suitable than a thin wire twisted around a thread or metal staple fibres twisted into a yarn since the conductive contact surface on the two latter types of yarns is too small (Table 9).

In electrode design there are three main problems to consider. The motion artefacts in textile structures add noise to the bio-signal. Since textile electrodes are preferably used in dry conditions and without using gel, the impedance in textile electrodes is relatively high which also affects the signal quality. A third aspect is the disturbances generated by loss of signals from individual electrodes. Motion artefacts from the textile structure are decreased by using a stable textile structure either in the electrode itself or in the environmental fabrics. A padded structure reduces high impedance due to the acquired pressure between the electrode and the skin (Table 9) [Zimmermann]. Sticky coating around the electrode prevents loss of electrodes from the skin.

Material	**Impedance at 1 kHz**	**Impedance in padded structure**
A. Metal filament twisted around Nylon/Lycra yarn	> 200k	> 200k. The metal contact surface is too small
B. Silver-plated nylon	>200k	Reduced to measurable value
C. 100% Stainless Steel, filament	>200k	Reduced to measurable value
D. Staple fibre, 80% Polyester 20%Stainless steel	>200k	Reduced to measurable value

Table 9. Examples of electrode effects due to materials and pressure

INTEGRATING TEXTILE ELECTRODES

In the first prototype a ready-made T-shirt is integrated with 12 textile padded electrodes measured via conventional leaders reached from the outside (Figure 49). The electrodes are knitted in a staple fibre yarn based on polyester and stainless steel.

Figure 49. Prototype 1, principle of measurement setup and garment

The second prototype (Figure 50) is made from a special designed garment construction using knitted 100% stainless steel electrodes measured via conventional leaders. The pressure is achieved from tight-fitting bands around the torso.

Figure 50. Prototype 2, detailed sketch and garment

INTEGRATING TEXTILE DATA TRANSFER

Besides electrodes, an electrode system consists of data transfer between the electrodes and the acquisition unit. While sensors should be in contact with the skin the data transfer has to be isolated from the skin. The textile leader goes from each electrode and converges at the data acquisition unit. The front side of the T-shirt was partly constructed in four dimensions consisting of electrode layer, insulating layer, data transfer layer and an outer layer (Figure 51).

Figure 51. Prototype 3

THE CONTEXT OF DESIGN AND USE

The final prototype above illustrates a typical gap between the physical structure and the context of design and use. Even though this prototype has sufficient performance concerning ECG-measurements, the construction is far from an idea of a ready made product from a construction and design perspective as well as a user perspective. The electrodes are distributed through a rather large area of the front part of the garment. From each electrode there is a textile leader that in a separate layer goes from the electrode to an acquisition unit. From a construction and production point of view the construction is more of a craft procedure. It would be possible to integrate the system directly when knitting the front side of the shirt but such a solution would have its drawbacks when it comes to isolation between the layer and a padded electrode structure. From a user perspective, a tight T-shirt may not always be suitable. Lighter garments like belts and garments that do not have to fit tight around the torso are examples of solutions directed towards a user perspective. In this process, the health monitoring devices are developed according design and user perspectives (Figure 52).

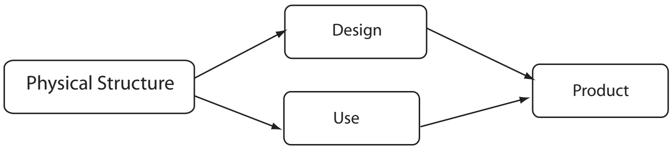


Figure 52. The context of design and use

THE CONTEXT OF DESIGN

The physical structure consists of all necessary parts for the specific performance requirements: a padded electrode structure, a data transfer structure in contact with the electrode, but protected from the skin, a specific requirement for garment fit. From a design perspective, the physical structure construction is more of a patchwork and the manufacturing process is a time-consuming craft procedure. In order to rationalise the design and manufacturing of the prototype the integral parts of the system were generalised according to the layered technology described in the section on interactive textile structures (Figure 53).

The electrode as a padded conductive structure placed on the inside of the garment.
The data transfer as a three-layer data transfer in combination with a two-layer structure in order to protect from the skin and at the same time achieve contacts wilth the electrodes.
Combining these structures as a general health monitoring structure.

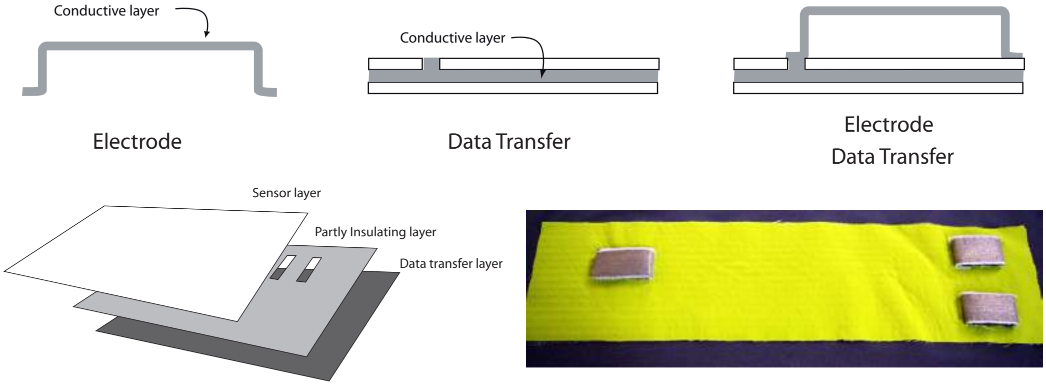


Figure 53. Electrode and data transfer combined as a health monitoring system

A general structure embedded with electrodes and leaders in a three layer construction rationalises the design and manufacture processes (Figure 54). It is possible to either integrate or separate the design and construction of the system itself from the design and construction of the garment.

Figure 54. General health monitoring system integrated in a garment

THE CONTEXT OF USE

From a user perspective the physical structure prototype is limited for certain forms of use and users. A slim fit T-shirt performs well since the tight fit guarantees good contact between the skin and the electrode. This, however, works on certain body types, those who are thin and in good shape. In a more heavy body types or with elderly people achieving the same fit may cause problems. In order to widen the use of health monitoring systems, the concept has been extended by two additional garments.

So far the project had been focused on electrodes placed on the torso. There are however several part connected to the upper part of the body that can be used for measurements (Figure 55).

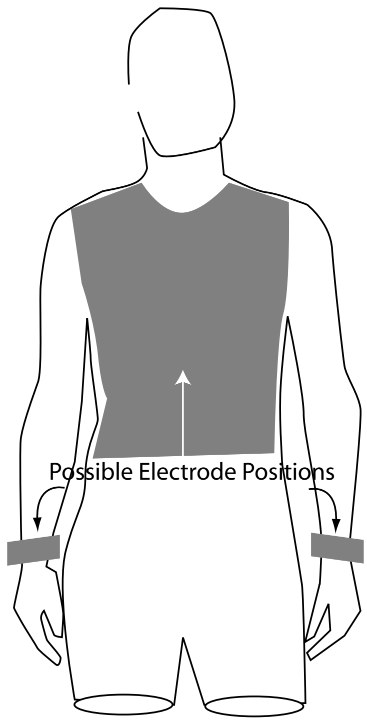


Figure 55. Possible electrode positions

The general health monitoring system was integrated within two types of additional garments Firstly, a solution that is simpler than a garment: a belt. Secondly, a solution using the wrists to measure heart rate: a cardigan (Figure 56).

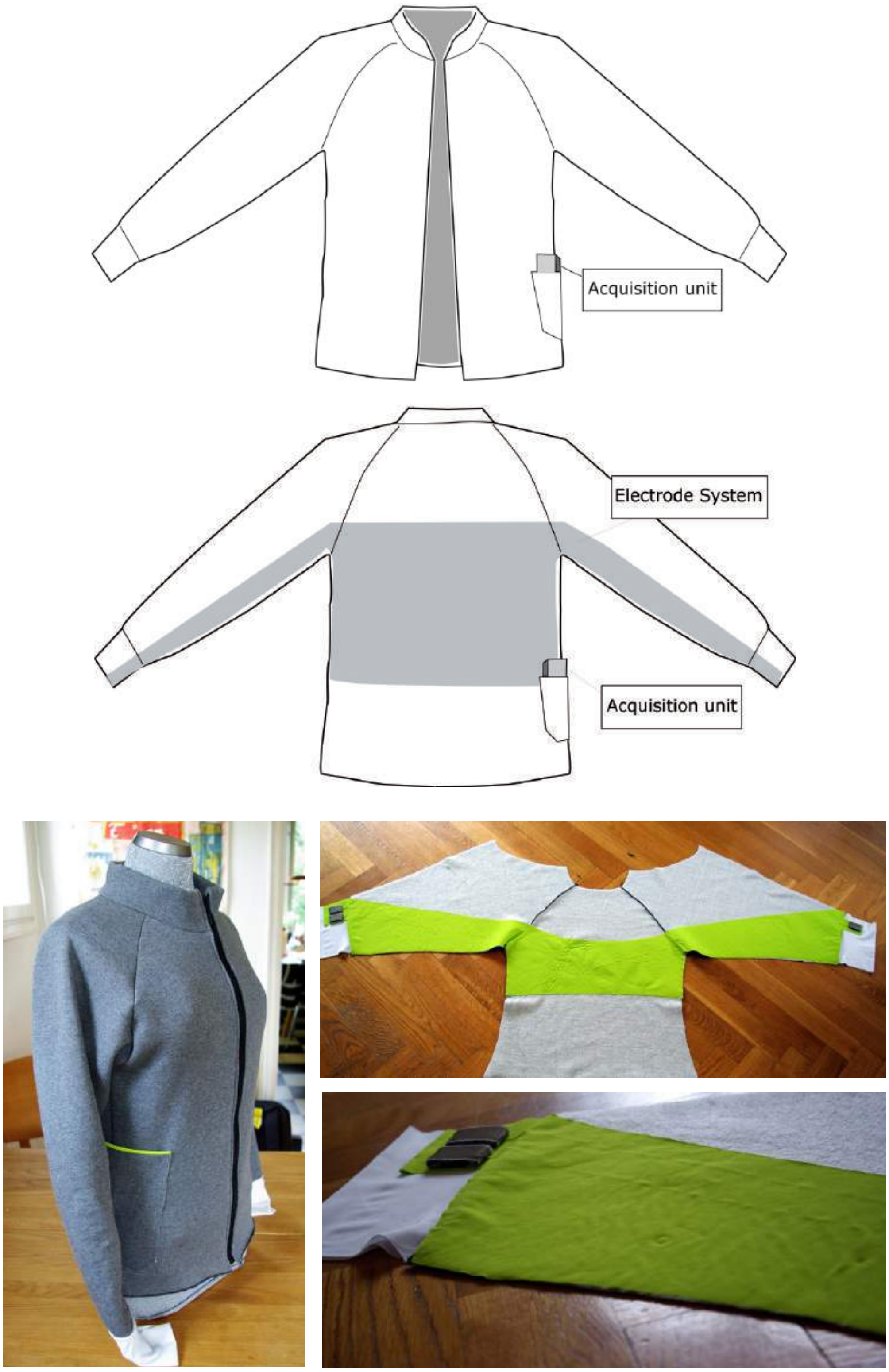


Figure 56. Construction of cardigan

PAPER V

In this study we have focused on the recording of electrophysiological signals using smart textiles integrated in a T-shirt to acquire heart activity (ECG) and in the future myoelectric signal (EMG) from the trapezius muscle.

Aim: The aim is to achieve ECG signalling of such a standard that it will be possible to perform heart rate variability analyses.
Method: A T-shirt with integrated electrodes made of 20% stainless steel and 80% polyester connected to conventional leaders was evaluated using a signal processing technique allowing the monitoring of both heart rate and heart rate variability. The method allows multi-channel recording where signal in some channels may be disturbed or even missing.
Contribution: A first step towards making a physical structure of a health monitoring system. The experiment highlights the importance of using a pressure on the electrode as the pressure acquired from a padded structure and a tight fitting garment. This multi-channel approach addresses difficulties in using textile electrodes in health monitoring. Although further improvements are needed our current experiences indicate that a smart textile T-shirt allowing long term recordings of heart and shoulder activity may be available to the research community in the near future. This would extend the possibilities currently available for use with simultaneous long-term monitoring of e.g. trapezius muscle activity and heart rate and heart - rate variability and indicators of psychological stress. This can lead to highly interesting in studies of musculoskeletal disorders of the neck and shoulder.

PAPER VI

In this study we evaluated a new prototype and a novel adaptive method for spatio-temporal filtering using multi-channel database recordings (12-channel ECGs from 10 healthy subjects).

Aim: This study aims to evaluate the next generation of health monitoring prototype and a multi-channel method for the recording of heart rate.
Method: The next generation of health-monitoring garments was

developed using prototype electrodes made of 100% stainless steel, and the pressure on the electrode was achieved through improved garment construction, through choice of garment material and tight fitting bands around the torso.
Contribution: A step forward in the development of in a physical structure for health monitoring systems. The results showed that multi-channel spatio-temporal filtering superseded both "traditional" independent component analysis. We also recorded seven channels of ECG using a T-shirt with textile electrodes. Three healthy individuals performed different sequences during a 10-minute recording: resting, standing, flexing breast muscles, walking and doing pushups. Using adaptive multi-channel filtering, the results showed a sensitivity of 99.6% and precision of 99.5%. Adaptive multi-channel spatio-temporal filtering could be used to detect heartbeats in ECGs with high noise levels, for example, when textile electrodes are used in smart clothes.

PAPER VII

This paper describes a prototype T-shirt with integrated electrodes for wireless monitoring of heart rate and muscular activity.

Aim: An evaluation of the general system and the first prototype combining measurement of both heart rate and muscle activity.
Method: The monitoring of heart rate is insensitive to the actual placement of the textile sensors by recording ECG from many positions of the trunk of the body. For recording of electromyographic signals, our current solution is to use a padded structure above the trapezius muscle housing commercially available dry electrodes. By extra padding over the electrode site, the positions of the electrode are more defined and sweat production is stimulated which enhances the recording conditions. Further we have designed a general electrode system for flexible integration in clothing. The system has been integrated in three types of prototypes, a t-shirt, a belt and a cardigan.
Contribution: The study evaluates the final idea of a general system for heart rate measurement. Also, the general system is combined with muscle activity measurements.

RESULT

This project addresses health monitoring from a functional perspective covering more than just performance. The added design perspective takes health monitoring one step further by both facilitating the construction and the use of these products. The result consists of a general sensor and data transfer system including textile electrodes for heart rate measurements. But it is also possible to integrate stretch sensing structures in order to monitor the breathing rate in the sensor layer.

THE SYSTEM

The system is based on a three-layer construction where layer one includes the different sensors, layer two is an insulating layer and the third layer is the data transfer layer (Figure 57). The contact between the sensors and data transfer layers is made through parts of layer two that are not insulated. The system is general and thereby possible to integrate in a range of textile products.

FIgure 57. General electrode system

THE GARMENTS

The system has been integrated into three types of garments: a shirt, a belt and a cardigan.The shirt and the belt consist of up to seventeen electrodes for heart rate measure (Figure 58). The cardigan consists of three electrodes for ECG measurements placed on the wrist and it is easy to put on and off compared to the other solutions (Figure59).

Figure 58. Shirt and belt for heart rate monitoring

Figure 59. Cardigan for heart rate monitoring

The signals are transferred to an acquisition unit that is wirelessly connected to a computer or a mobile phone. The unit is possible to connect to the garment. In the cardigan the connection is placed in the pocket (Figure 60).

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Figure 60. The acquisition unit and its placement in the cardigan

RELATED PROJECTS

Most of the related projects as well as this project have so far focused on textile conductive surfaces in contact with the skin for measurement of heart rate combined with textile or conventional leaders. Exceptions from these are the Context [Context] and Ofseth [Ofseth] projects. In the Context project the focus is set on muscle activity using capacitive contact-less sensors and in the Ofseth project using optical fibres to measure the breathing rate. In many projects the electrodes and leaders are integrated directly in the manufacturing of the garment for example in knitting procedures [Wealthy][Sensatex]. In order to acquire the right fit, the garments are made of elastic knitted fabrics. The most common model is a tight vest to be worn next to the body. Furthermore the descriptions of the prototypes are quite scanty from a design and construction perspective. The only actual information are photos and some information about used materials.

WEALTHY /MYHEART PROJECT

One of the most extensive projects is the Wealthy project [Paradiso et.al] and the continuation in My heart [My Heart]. It is one of the big pioneering projects mostly focused on heart rate measurement and stretch sensing structures. The result of prototypes is a tight fitting vest made in knitting material integrated with electrodes and leaders in the same process. Figure 61 shows how the whole front part of the vest is integrated with the whole system.

Figure 61. Wealthy prototypes

PROETEX

The prototypes in the Proetex project aim to rescue fire-fighters using the wireless monitoring of heart rate and temperature measurement. The heart rate is measured via textile electrodes while the temperature is measured via integrated conventional temperature sensors. The electrodes and leaders seem to be integrated directly in the knitting procedure of the garment while the connection between sensors and leaders seem to be made later in a manual procedure. The garment concept consists of a belt and a tight fitting t-shirt (Figure 62).

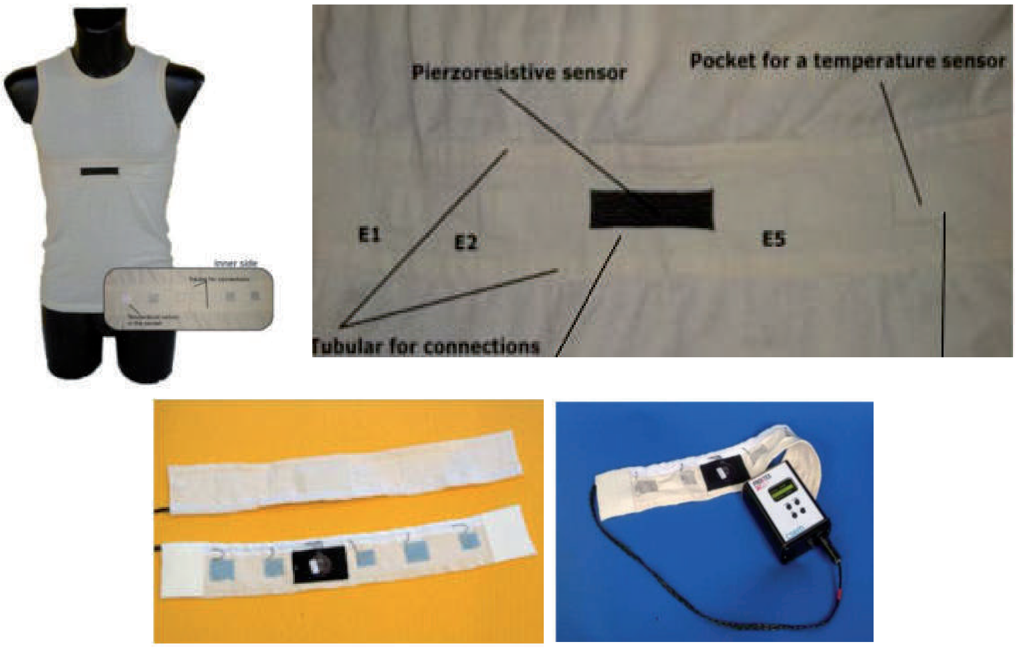

Figure 62. Proetex prototypes

OFSETH

Ofseth is an Eu-project exploring the possibilities of using integrated optical fibres to measure the breathing rate. The prototypes made in this project are compared to presented prototypes on a very basic level (Figure 63).

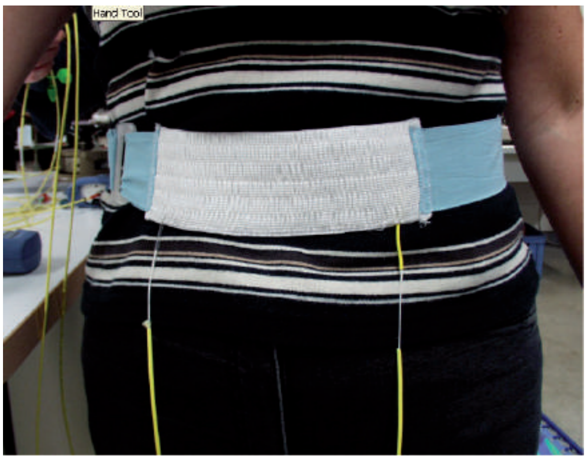

Figure 63. Ofseth prototype

CONTEXT

The context project aims to measure muscular activity using a non-patch technology based on capacitive textile sensors (Figure 64). Furthermore this project does not only focus on knitted electrodes, since the electrodes are made on embroidery and woven technology. A disadvantage with capacitive measurements is that each electrode has to be connected to an electronic circuit for measurement which decreases the motivation for using textile electrodes.

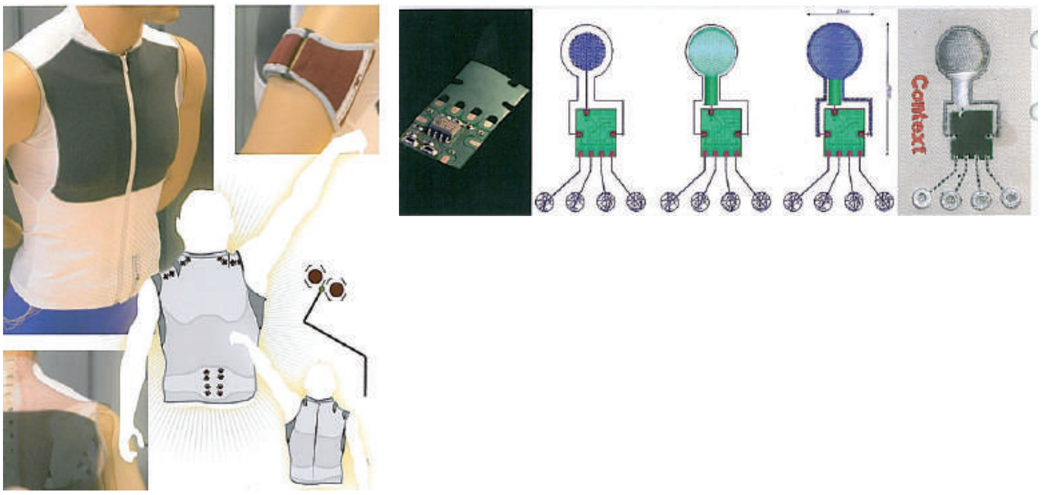

Figure 64. Context prototypes and models of sensors

REFLECTION

In many projects the electrodes and leaders are integrated directly in the manufacturing of the garment for example in knitting procedure [Wealthy][Sensatex]. In order to acquire the right fit the garments are made of elastic knitted fabrics. The most common model is a tight vest to be worn next to the body. Such a solution requires a garment with a tight and stable fit to the body in order to prevent a loss of signals. A comparison between this project and the ongoing EU-projects concerning the physical structure, the context of design and use is presented in Table 10.

THESIS PROJECT

Physical structure

The thesis prototypes measure ECG through textile electrodes transfer via textile leaders in a general electrode system. The electrode system uses a combination of different textile technologies.

Context of Design

Integration of electrodes, leaders and connection between electrodes and leaders are made in industrial processes

Context of use

General system offers a wide range of garments to use and an optimal choice of materials and production techniques. Padded electrode structure enhances the contact surface

WEALTHY

Physical structure

The prototypes in the wealthy project measure ECG through textile electrodes and transfer via textile leaders. The whole system is made in knitting technology.

Context of Design

Integration of electrodes, leaders and connection between electrodes and leaders are made in industrial processes

Context of use

The construction is made for two types of garment, a knitted t-shirts or belts with tight fit. No padded electrode structure reduces the contact surface.

PROETEX

Physical structure

The Proetex prototypes measures ECG through textile electrodes and temperature through conventional sensors. The signals are transferred via textile leaders. The prototypes are med using knitted technology.

Context of Design

Integration of electrodes and leaders in industrial process. Integration of temperature sensors manually. Connection between sensors and leaders are made manually

Context of use

The solution is made for two types of garments, a tight t-shirt and a belt. Non padded electrode structure reduced the contact surface.

OFSETH
Physical structure Measurement of breathing rate via optical fibres, transfer via conventional leaders. Knitted technology ***Context of Design*** Integration of sensors are made industrially ***Context of use*** Not defined

CONTEXT
Physical structure Measurement of muscle activity through capacitive textile electrodes and microelectronic units, transfer via textile leaders. Embroidered and woven technology. Padded structure in textile electrode ***Context of Design*** Manufacturing of electrodes are made industrially. The connection between electronic unit to each electrodes are made manually. ***Context of use*** The context solution offers a wide range of products since it uses a non-patch technology. The prototypes are integrated with several electronic components instead of one as in the other projects. Since every electrode is connected to electronic units the motivation for textile transfer is stronger than the motivation of textile electrodes in this project.

Table 10. Physical structure and the context of design and use in the different projects

9. CONCLUSIONS

The research domain of smart textiles is untried and quite complex, since the field is based on research into the areas of textile technology, material science, computer science and engineering, signal processing and various design activities. Nevertheless as the results indicate, there are several conceptual similarities between smart textiles and other types of textiles with a double function. The focus on an intended use and on the technological impact on the design process appears to be the same. It is true that smart textiles introduce computational technology and a more dynamic behaviour but as textile structures they have a lot in common with other high technological textiles. For this reason, this thesis is subtitled "Creating Multifunctional Textiles", because any textile with a double function is in a way a smart textile, thus, it is also a smart solution for textile use. We may add smart materials and computing technology to achieve a double function or a smart use. But likewise we can add flame retardant treatments in textiles and have a product with a double function: At the same time as we use it for its intended purpose, furnishing or clothing, it also reduces the danger of fire. Or, we can create a smart solution, find applications where the properties achieved from textile, flexible, soft, strong, sustainable, may be used more widely than perceived. For example textiles as degradable implants that regenerate body functions [Artimplant]. It is within the context of multifunctional textiles that Smart Textile should be placed in order to share common processes and methods focused on the performance and the use of such structures.

There are, however, certain aspects about smart textiles that distinguish them from other textiles in a so-called multifunctional field. The ability to conduct electric current could be used in heating applications as well as when performing computational operations. The connection to computing technology invites the textile structure to be a part of a real time dynamic event, and that is the most unique feature of smart textile.

WHAT IS A SMART TEXTILE?

A smart product is a product with the ability to sense changes in their circumstances and execute measures to enhance their functionality under the new circumstances [Worden]. As we recognised both in this thesis as well as in other projects, the textile part is the output and input and data transfer in this system, and, on the other side there is an electronic package including hardware and software to control and execute an intended scenario (Figure 65).

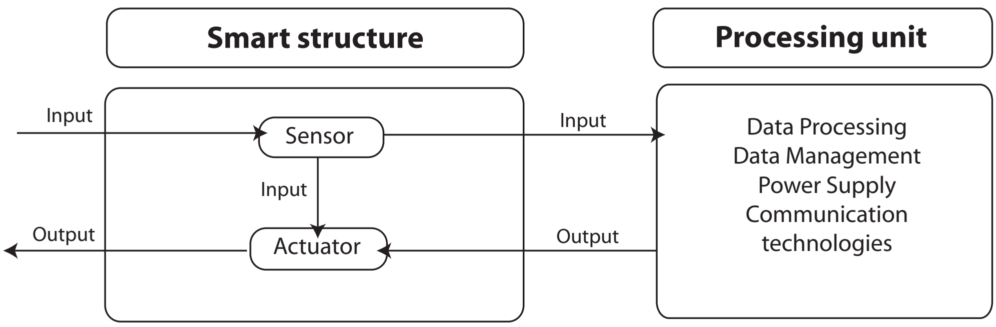

Figure 65. Smart Textile as developed so far

Converted into textile conditions, smart textile may be divided into three stages like those of smart materials; passive smart, active smart and very smart textiles. In this case the passive and active smart are the structures themselves, while the very smart category are structures combined with a controlling unit. The connection to computer hardware and software invites textile to be a part of a dynamic event, directed by the computing technology and software – a unique behaviour determined by the intended function. What Smart Textile is, will then depend on in what direction we intend and manage to develop the textile materials and structures; conventional smart technologies integrated into textile products or smart textiles as pure textile solutions. These two levels set the boundaries. Smart Textile can be categorised according to its integration in the textile structures as: ***the Hybrid level, the Network level, the Interactive level, the Computational level***

THE HYBRID LEVEL

At the hybrid level conventional smart technology is integrated into the textiles, for example by means of computing technology sewn into the textile product. The definitions of this solution as a Smart Textile is not obvious since the textile is a passive wearer of technology, almost like putting the mobile phone in the pocket of the jacket. The reason to include this level is that it creates a textile structure with smart technology features, even though there is no actual convergence between the technologies. Imagine a tent as a wearer of certain smart technology, as a textile product that reacts to its environment and make changes according to the stimuli. Such a product requires new knowledge in design, constructions and production similar to the next level of solutions in smart textiles.

THE NETWORK LEVEL

The network level goes one step further from the hybrid level by creating a data network where conventional technologies may be connected, permanently or momentarily. The system allows the user to move technology from one textile product to another. In this case the textile distributes a data and power supply as a wearer of conventional sensors and actuators combined with controlling units.

THE INTERACTIVE LEVEL

At the interactive level Smart Textile extends structure as a data network. This level is an alternative way of creating materials such as sensors and actuators that are combined with controlling units. As sensors and actuators smart textile has the ability to be controlled by computing technology.

THE COMPUTATIONAL LEVEL

The computational the level where actuators, processing units, communication and power supply are fully integrated in textile substrates and structures. This levels require that electronics is transformed into textile materials and structures which is a subject a more long-term research efforts. Such areas may become possible as a result of convergence between textiles, materials science, nanotechnology and organic electronics.

Smart Textile is not only a textile activity also at the pure textile level. The contribution from the textile field is the creation of alternative materials, material structures and products for the conventional smart technologies. Whatever level this creation is carried out at, the development is tied to the ingoing technologies. Without competence in chemistry and physics there will be no new materials. Without competence in computing science and engineering there will be no function or scenario.

WHAT IS THE ADVANTAGE OF DEVELOPING SMART TEXTILE?

Combining smart textiles and computing technology opens up an arena for new types of textile and computing products. Technology can be integrated into our environment in products we use for other purposes; the curtains may act as loudspeakers for my stereo and it is possible to make a telephone call from my armchair. Communication technology can be achieved via clothing or by clothing picking up data from the body. The possibilities with smart textiles seem to be endless but nevertheless the actual need for smart textile products is an issue to really consider for future research and commercial ambitions. There are many contexts and situations where textiles are used. Accordingly, there are several applications where the use of Smart Textile is motivated from a purely functional or aesthetic perspective. When these functional and aesthetical desires are integrated ina product with all it needs in forms of electronic components, the motivation of using these products will in many cases be reduced.

The objective for using smart textiles can be located somewhere between the outline of: Why textiles - Why interactivity? Within this outline we on the one hand ask ourselves why an already established field like smart technology should be transferred into textile structures and products. On the other hand, what is it that spurs conventional textile fields to interact through integration of computing technology into textile structure and products?

The advantage of transferring smartness into textile structures and using the textile structure as a wearer of smart technologies is that textile offers a rather unique richness of use and presence in our environment. Such a broad range of applications is based on a technology able to produce a number of different combinations of qualities; thin, thick, flexible, strong, light etc. The textile manufacturing processes are flexible and can be rearranged into different applications; the thin quality may be manufactured in the same weaving machine as the thick and strong one, for example. The performance of the fabric may be enhanced through further processes all with the same flexibility.

The motivation for creating interactive textiles is that smart materials and computing technology introduce a behaviour that to some extent will extend our use of textile products. Examples of this is facilitation of communication as in the glove project, playful interaction as in the toy project, or the control of more unconsciousness interaction such as sensor structures.

All in all, there seems to be a very successful convergence between two technologies. Nevertheless, the promises with new technological developments should not be over-emphasised. The basic needs and interest in promoting smart textile products will depend on different aspects; the level of integration, the context and environmental issues.

LEVEL OF INTEGRATION

The interests in Smart Textile will to some extend depend on how successfully we will be able to integrate the smart structures into its smart technology system according to its intended use and context. The level of integration affects how we can use textile structures, how textile structures are designed and the aesthetics features of the textiles. Functionality and successful design are important issues, since good functionality that is unobtrusive will not be motivated and vice versa. The motivation for using Smart Textile is dependent on a strong relation between use, science and technology. If we just explore this area from a material science perspective then we will end up with an amount of solutions looking for a problem. On the other hand, if we explore Smart Textile from just a conceptual point of view we will end up solving a problem without having an adequate solution to it, which in turn will demotivate the researcher from developing the concept.

CONTEXT

Another aspect that affects the motivation for smart textile is the context; in a more static context like interior and industrial use we are not as sensitive to the integrated technology as in a wearable application where everything has to be light and small and rely on wearable power supply. Besides that, textiles in our environment may be adequately motivated, a curtain or a wall textile that is already in our environment for decorative or for its comfort values could at the same time be fulfilling another purpose. Sense and reaction to pollution, sound and tensions could be a viable functions also when the required equipment for such use has been connected.

ENVIRONMENTAL ISSUES

The environmental aspect is another issue to consider since smart textiles consist of a rather complex structure of materials which could be hard to justify. Is it reasonable to have lightning in our clothing for fun when the recycling of this garment will be obstructed or even rendered impossible? It is also a question whether the increased power consumption could encourage such use since, especially actuators, require energy to move from one level to another. How our health status is affected by electrical fields is another environmental issue. On the other hand, environmental aspects may also be enhanced by Smart Textile. Techniques for one time use could be made for repeated use and in situations exposing our health, it would be possible to use smart textile as a surveillance tool.

WHAT NEW METHODS DO WE NEED TO DEVELOP?

The challenge of creating smart textiles is the need to understand rather different fields of science and technologies and at the same time explore the relationships between them. Knowing this and what textile design of today might include, it is obvious that there is a need to take textile design one step further to a new kind of design practice as well as research discipline concerning both smart and multifunctional textiles. In order to manage imagination with such scientific and technological demands, the conventional textile design space must undergo such changes that make a new design space necessary. The general focus in this space is the relationships between textile design and engineering, between the textile field and other product fields and finally between textile structures and the product.

TEXTILE DESIGN AND ENGINEERING

What we need in the future is a design discipline within textiles that fills the gap between technical textiles and traditional design. We need textile engineers focusing on creative processes and prediction of future facts and we need designers who are familiar with technology in another way than today. The technology processes will be part of the briefing processes. Similar to the way aesthetical processes have been used in textile design so far. In advanced textile design we also form technological possibilities into new products by exploring technology. By emphasizing textile science and technology in the textile design processes, we need to develop methods and gain knowledge towards such approaches, for example briefing and the way we learn and understand about materials and technology.

TEXTILES AND OTHER RESEARCH FIELDS

Textile expertise is a convergence between textiles and other fields of engineering, science and design. By introducing Smart Textile, the limits of textiles will be extended into new areas. The integration of new smart materials and technologies requires more fundamental understanding of these materials and technologies. New behaviours will change the way we use textiles and the textile applications. There will be a need to understand how to apply new principles from material sciences and computing technologies in the textile design processes. This will change the way we work and we will then need other skills and knowledge. Does that mean that a person dealing with textile needs to learn electronics and programming or should we form another type of project teams? Perhaps the answer to that question is a bit of both. Textile experts cannot learn everything about programming and electronics. We have also to form new types of working groups together with other fields like electronics, physics, chemistry, signal processing, computer science and engineering.

TEXTILE STRUCTURE AND THE FINAL PRODUCT

When designing a textile structure it is necessary to be specifically concerned about the end product. There are two reasons. The first is to go from product and product concepts to run the development of new structures and materials. Instead of developing textile structures intended for already known purposes we need to go the other way around to find new uses for textile in order to force the material and structure development. This is quite obvious in an area like Smart Textile where the use of the textile product will change into areas textiles areas not so common. The second reason is that smart material, computing science and engineering will affect the physical structure as well as the behaviour of textile structures. As a consequence of that the physical structure and the behaviour will change in the final product through the use of this textile structure. If today we design a textile fabric for general furniture applications, in the future the textile designer will be an important participant in the product design process of specific furniture.

CHANGE OF THE TEXTILE DESIGN SPACE

The introduction of Smart Textile will change the notion of a textile product and as we extend the notion by developing new materials and techniques and by integrating smart materials and technologies into textile structure, we will change the approach in the design, manufacturing and marketing of textile products. An obvious reflection during this thesis work is that there is a difference between being a designer using already developed and well-defined technologies and a designer involved in creating new foundations and uses for new technologies as well as for a convergence between technologies. The conventional textile design method operates in well a well defined field concerning technology. Materials and technologies are recognised due to their specified features rather than the understanding their features. But when new materials and technologies will become part of the process it is necessary to go directly to the understanding of structures of materials and technology in order to understand their attributes and behaviour. Understanding materials basic structures also provides a basis for designing materials with different qualities or properties.

Through the introduction of new technologies Smart Textile is changing the textile design space. Smart Textile is launching a set of new components in the design space derived from smart materials and technologies, the interactive textile structures. These structures exhibit other properties like stretch sensing, pressure sensing and conductivity. Smart Textiles present itself differently to the user differently than conventional textile. The role of the aesthetic processes will also change. The performance of textile will change and accordingly the main tool is the design process: aesthetics and textile technology will change.

GENERAL METHODOLOGY

In exploring the design situation we need more of practice-based orientation, like the collection of samples in my Licenthiate thesis [Berglin]. Another example of practice-based orientation is when we explore a new type of yarn by just weaving samples without an intended application or use in mind. These samples as well as theoretical information could form a base in the search for new ideas. In methods of searching ideas we need to focus more on the use of the product. In Smart Textile there is an interaction between the user and the textile structure and there is the same circumstance in interaction design from where we could adopt briefing ideas. As in briefing we will have an impact from interaction design and aesthetic issues viewed from such a perspective. In exploring the design problem we need to explore the relationship between the physical structure and the structure of design and use and combine them in the best way. As a consequence of this the methods of evaluation have to be reconsidered. There are hardly any doubts of how to evaluate the performance of an object's physical structure. But how do we evaluate its performance in design and use? And how do we evaluate the performance of the relationship between the different structures? This is the weak point of the presented experiments and of design in general; how such a complex structure should be judged and evaluated.

PERFORMANCE

Smart textile introduces a new set of properties into the textile field like for example stretch sensing properties, press sensing properties and conductivity. In order to verify and evaluate these properties we will need new test methods in our labs and in our production. These methods will to some extent derive from other areas. Electronic properties are for example a big issue in conductive structures and there are several established methods that the textile field has to acquire in order to design, produce and evaluate these structures. The established methods are though focusing on other types of materials than textiles and what we can see from the result these properties are affected by the textile structures. It is not always possible to use materials exhibiting the best conductivity, and textile is a kind of “live” material affecting the electronic properties.

AESTHETICS

Smart textile will change the aesthetics processes for two main reasons. The first is that a smart textile does not only present itself to the user as a product with certain visual and tactile properties. The visual expression and tactility have to be combined with dynamic behaviour. The second reason is the ever continuing process of converging the integral technologies. A key issue as to how we will perceive Smart Textile is how well the integration between different technologies will be managed; to some extent, this is an aesthetic issue.

Dynamic behaviours create a new kind of use of textile products where the design refers to interaction design and its immaterial processes that can be adapted to user needs. Compared to communicating a visual expression through a moodboard , ideas of dynamic behaviour are communicated through story-boards or videos. The aesthetics of interaction are a rarely explored area but there are some examples that show directions like “Designing for extreme characters” [Djajadiningrat et.al].

Convergence between technologies is to some extent an aesthetic issue. An example of that is the interactive textile structures described as a basic foundation for the context of design and use. Aesthetics is there as a tool for solving the convergence between for example computing technology and textile. These structures are created with a prior recognition of particular problem. The intellectual approach to aesthetics [Wong] will have greater impact in the advanced textile design space opposed to the artistic or spontaneous approach [Wong].

TEXTILE FIBRES AND TECHNOLOGY

Smart textiles introduce a new set of materials and new type of assemblies. Most of them can be managed through conventional production, but there are some indications that new production procedures have to be available in the future. A problems that needs to be solved at a second or third level is also the connection between textile and conventional electronics.

The integration of smart behaviours into fibres and yarns will to some extent simplify the process assuming that interactive functionality is made use of in the form of fibre and yarns. One of the future challenges is conductivity. Today, this is solved in many different ways, the most conductive yarns consisting of metals in all forms. The disadvantage with metals is their rather bad processability in fabric structures and their comfort properties. Conductive polymers have been predicted as the future solutions to this but so far their conductivity is too low for the most applications in smart textile. Besides that their processability still has its drawbacks.

The interactive textile structures are mainly built on layered structures which will challenge the fabric structures processes. So far the usage involves of a mixture of fabrics compositions and an industrial process including features of craftmanship. These solutions may be transformed into new processes for woven, knitted and compound fabrics. The layered principles also highlight for example coating substrates and the possibility of applying conductivity or other features in order to build smart structures.

10. IDEAS FOR THE FUTURE

The progress which is to be anticipated within Smart Textile will depend on how successful we are in creating additional interactive structures and how we manage to combine different disciplines, theories and practices in future design activities. This thesis has a wide approach and the experiments have included a series of processes to handle: use, aesthetics, textile technology as a whole, materials, the process of bringing computing and textiles together, and finally, the design and assemblies of textile products. Our future ambition (Figure 66) is to divide the research between interactive textile structure and design activities and to choose one of these in future research. Besides these two research activities, the methods in advanced textile design have to be developed through the research, and through integration of advanced textile design in higher education.

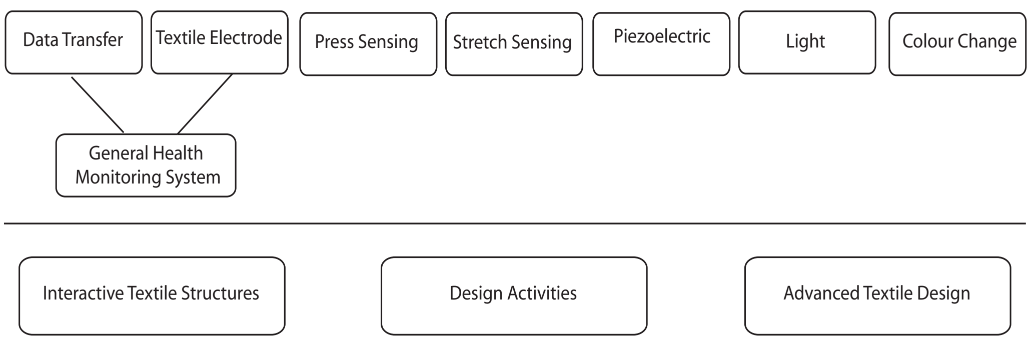

Figure 66. Research result and future ambition

INTERACTIVE STRUCTURES

The research on interactive textile structures aims to continue the integration of smart abilities with textile structures and to characterise different sensors more deeply (Figure 67).

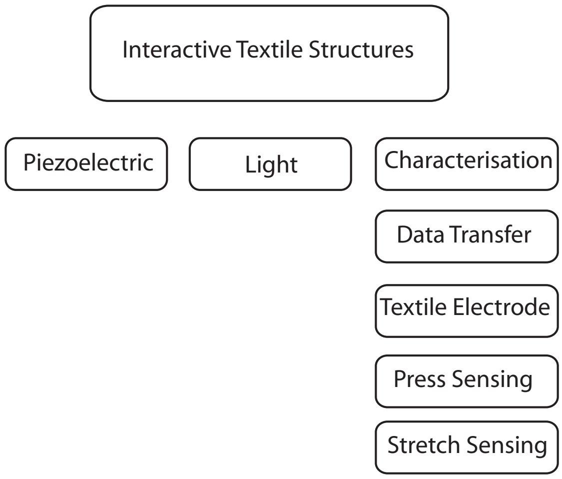

Figure 67. Future ambition within interactive textile strcutures

The continuation is based on the result so far with a special interest in sound and light structures. They are interesting from a functional perspective and they also introduce a new type of structures i e energy exchanging. The initial results on sound structures show that laminated piezoelectric film registers sound. The next step is to find new ways of integrating piezoelectric properties into textile. The light structure so far is based on electroluminescent phenomena but this structure is an entrance to semi-conducting and photovaltic structures. Light structures open up for a third area of motivated functions for textile, energy sources and power supply. Future work on interactive textile structures should investigate the techniques in organic and printed electronics.

The characterisation of interactive structures aims to prepare use of the structures in different systems. For example the characterisation of different stretch sensors could include stretch as a function of applied force, hysteresis, a characterisation of different types of sensors.

DESIGN ACTIVITIES

The design activities could concern several areas but the prospect is based on health monitoring since there are several techniques applied to that area (Figure 68).

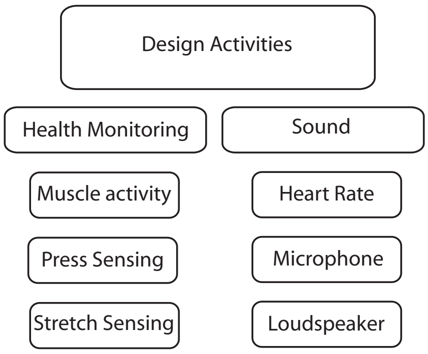

Figure 68. Future ambition within design activities

The next step is to include additional sensors in the existing health monitoring prototypes like breathing sensors and textile-based muscle activity sensors. Press sensor technique in bedsore application is also a possible future design activity.

Another sensor of interest is the piezoelectric sensor and to explore if the signals are good enough to use in a sound application, for example a microphone or in heart rate monitoring. A successful result from such application would then open up for the reverse function, to generate sound through textile.

ADVANCED TEXTILE DESIGN

Despite the fact that the research method has been efficient it should be perceived as an initial try requiring further development. Preferably this should be carried out during the progress in interactive textile structures and design activities. Research through design is an opportunity to develop practice together with materials structures and other solutions. A complement to developing advanced textile design as research area is to include it within design and engineering education. The advancement should proceed in the whole design process, analysis, synthesis and evaluation (Figure 69). One issue is to consider is how to explain the relation between the different natures of the textile product (Analysis). The next aspect is to improve the process of developing the product at its different natures (Synthesis). Finally we have to improve our evaluation processes within the context of design and use (Evaluation).

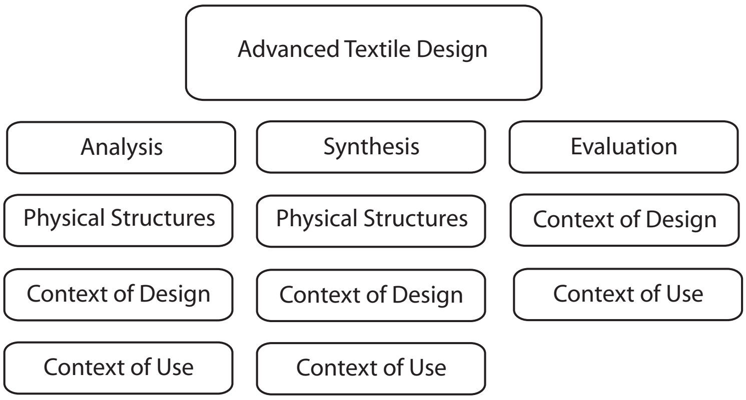

Figure 69. Development of advanced textile design

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Paper I

DESIGN OF A FLEXIBLE TEXTILE SYSTEM FOR WIRELESS COMMUNICATION

Lena Berglin
The Swedish School of Textiles, university College of Borås, Borås Sweden
Department of Computing Science and Engineering Chalmers University of Technology, Gothenburg, Sweden

Abstract

This paper describes a textile system that allows the user to move technology from one textile product to another. In this example a communication set connected to the mobile phone is integrated in the system. The system consists of a knitted and weaved system in two different types of yarn. The signal transmission has been measured for sound frequencies.

Key Words

Smart textiles, conducive fibres, weave, knit, glove

1. INTRODUCTION

Development in wearable computing and smart textiles gives opportunities to develop new interactive products in textile and fashion with new types of behaviour and use. Several projects show the potential of combining computing technology and so-called smart materials (van Langenhove, Heertler, 2004). Some projects, like for example new Nomads (Eves et al., 2001), show different concepts that could be realised by merging these two areas. Other projects like Smart Clothing for the artic Environment (Rantanen et al., 2000) go one step further showing the potential by integrating technology into clothing more like embedded technology. In this case it is possible to test the idea and use of product. The third and last category of projects merges the computing technology and smart textiles. One of the first attempts in this category was the wearable motherboard at Georgia Tech institute (Park et al., 1999). The motherboard is a woven and knitted information infrastructure that supports health monitoring through textile. The Wealthy project (Taccini et al., 2004) explores how electrodes can be knitted in a textile structure in order to support health monitoring. The reason for merging the technologies is to achieve a product that s more sustainable, flexible and washable. Just putting electronics into clothing is not good enough and several projects show the possibilities of merging textile and computing technology.
The projects in the area of Smart textiles show that several rather different disciplines are involved: from material sciences, electronics and computer science to textile technology and textile and fashion design. There is a challenge in this interdisciplinary area to combine experimental and theoretical work in order to progress and to find appropriate applications.
Wanted is a project where experimental product design has been used in order to find out how computing technology could be combined with a textile product in order to support an environmentally extreme context. This project addresses questions like: What kind of computer related functions are of interest to implement in order to achieve an interesting concept? How should the interaction be designed? How does that affect the design of the product? In this case the product is a glove that is wirelessly connected to the mobile phone. The technology has been integrated in the construction of the glove allowing the user to receive and make calls, change number by shaking hands. The interaction model is focused on one hand use. See figure 1.

Figure 1. The first prototype and interaction model.

Creating prototypes with embedded technology gives the opportunity to test and analyse concepts and product design ideas. When testing and exhibiting the glove it was clear that the idea is easy to communicate as well as easy to use. It is a concept that can be developed in Future work must though continue on merging electronics and textile technology in order to make the product washable and durable over prolonged use. The project described in this paper aims to explore how conductive fibres and textile structures can be used in order to substitute the conjunctions in the glove. The method used is experimental product design where certain product ideas are used as tools for generating experiments and questions. In this case the tool is the “smart glove” and the goal is to answer the questions the design process brings forth.

2. ISSUE

Implementing communication technology in a glove introduces a new type of use that adds qualities to the product. But the use also gets more complicated because of the implemented technology. Components are less sustainable than textile and in a glove the technology is very exposed. Textiles are washable, electronics are not. Usually you wear different gloves for different occasions. Implementing technology into one pair limits the use of communication to that pair, or demands that technology is integrated into several pairs of gloves.
Several research projects show the possibilities of solving the problem with wash and sustainability of smart wear products. These problems are solved by using new smart materials in order to substitute electronics and by package the electronics into for example silicon (Möring et al., 2003) (Infineon, 2003). In other projects the technology system is made in a separate part that can be removed from the product when washing it. (Infineon, 2003) (Rantanen et al., 2000).
The questions addressed in this project are: Is it possible to prepare a conjunction system of conductive textile surfaces that allows the user to remove the communication technology before wash, to substitute broken components or to put the technology into other products? How should the surfaces be made? How should the conjunctions between the system and the components be made? How could a textile system be used in textile and fashion design.

3. EXPERIMENT

In order to find out a solution different textiles were made, each textile had four parallel surfaces isolated from each other. In the ends a microphone (m), a headphone (h) and a connection to the mobile phone was connected, see figure 2.

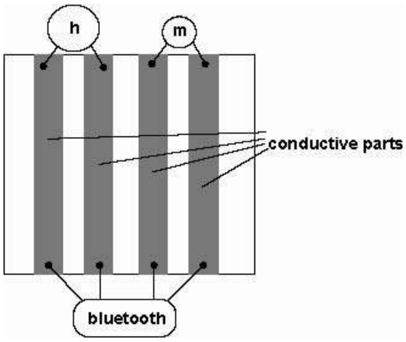

Figure 2 Principal scheme of the textiles

The surfaces were made in 1.1 rib knit and plain weave. In order to use snap buttons as conjunction a yarn that is conductive on whole surface had to be chosen. Two types of yarns were tested, 100% stainless steel and Stainless steel blended with polyester. The electronics were connected to the conductive surfaces in three different ways: traditional electronic conjunctions, snap buttons and a conductive Velcro fastening. In order to conduct properly in the snap buttons, conductive paste and a thin conductive film was applied. Figure 2 shows a knitted system where the components are connected with snap buttons

Figure 3 Components connected on knitted surface

The signal transmission in the system where tested for sound frequencies and the result is presented in table 1.

Table 1 Result of Sound Transmission

Yarn	Technique	Sound Transmission	Comments
Stainless Steel	1.1 rib	Yes	No disturbances on stretching
Stainless Steel/Polyester	1.1 rib	Yes	Some disturbance in sound, when stretching the material
Stainless Steel	Plain weave	Yes	No disturbances on stretching
Stainless Steel/Polyester	Plain weave	Yes	No disturbances on stretching

The transmission of signals works in all structures and yarns, but the performance differs. Samples in 100% stainless steel had the best performance. A structure that makes the conductive thread to go as straight as possible also gives a better performance. A knitted structure with a blended yarn caused disturbances in sound when stretching the material.

The choice of conjunctions gives a very little difference between traditional conjunctions and snap buttons while the Velcro fastening performs worse and is also more clumsy and hard to handle.

4. RESULT AND FUTURE WORK

The project resulted in both a knitted and weaved system of conductive fibres that allows the user to snap on and off the technology. The system was integrated in two different products where the communication technology could be used in either of them, see figure 4.

Figure 4. System integrated in two gloves

The system works properly but the conjunctions could cause problems if they are not tight enough. The conductive paste and the thin film improve the conjunction a lot. Since the lines are not isolated there could be some disturbances when using the system. For example moisture reduces the performance. When using blended yarn it is important to reduce the stretch in the material.

As an overall impression the system opens up for a more flexible use of the required technology, the microphone, the headphone and the Bluetooth set. The components, except for the Bluetooth set, are as exposed as before but are at least replaceable. By disconnecting the components it is possible to wash the glove, to replace a broken component and it is also possible to put them into another glove or in another product.

In future work each line has to be isolated in order to avoid moisture disturbances in use. The snap button idea has to be developed into a neater solution with an even safer performance. The measure of signal transmission shows that there is a great potential in measure electrical properties in yarns and different techniques like knit and weave. Some techniques are better for a good transmission for example. But in case of disturbance in signal transmission that could be used as a sensor when material is stretched.

The project shows that wearable computing could be integrated in a way so that the technology can be used in different products. It is the knitted or weaved system that decides how it could be used. Instead of a connection to the mobile phone it is in this case possible to use the four line system in order to connect a music player to the garment. This opens up for a lot of possibilities with smart textiles and computing technology. Instead of integrating the technology it could be of interest to create a textile infrastructure for different technical solutions where the user decides functions and product. The idea is not only applicable in clothing. Interiors and furniture could be of interest as well.
The project also shows that experimental product design could be used in order to explore the area of new material. The project has not only resulted in better performance for the glove project. New ideas and new learning for other products has also been generated.

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ADITIONAL DATA ABOUT AUTHORS

PhD Student Lena Berglin, The Swedish School of Textiles, University College of Borås. S-50190 Borås Sweden, E-mail lena.berglin@hb.se; Phone +46 33 435 5939, Fax +46 435 4009, www.hb.se/ths

Paper II

Wanted 2 – a mobile phone interface integrated in a glove

L. Berglin
The Swedish School of Textiles, University College of Borås, Borås Sweden
Chalmers University of Technology, Department of Computing Science and Engineering, Gothenburg, Sweden

ABSTRACT
This paper deals with the development of a glove wirelessly connected to a mobile-phone. The idea has been developed with the aid of interviews and experimental product design. Interviewees were professions that are exposed to hard weather and whose tasks are physically demanding. The concept is developed along three types of functions, communication, information and an open function that identifies the user in order to allow access to different systems. The concept is designed in a three finger glove where the interaction takes place mainly by voice and hand gestures. The basis for hand gesture is a textile structure sensitive to stretch.

1 INTRODUCTION

Development in computing technology into smaller units has made it possible to integrate technology into a range of product for example clothing [6][11]. At the same time textile material science has developed dynamic textile materials, so-called smart or intelligent textiles. Smart materials are able to sense stimuli from their environment and to adapt their behaviour due to the stimuli [7]. Combining electronic devices and new textile materials could give an opportunity to develop new interactive products in textile and fashion with a new type of behaviour and use. Several projects [5][10] show that it is possible and that the dynamic properties of Smart materials corresponds well to computing technology. However, not much focus has been set on how the interaction between the user and the product should be designed. Usually, a computer user interface consists of a display and a keyboard and in smart clothing it is common to use this kind of interface also in clothing. This has resulted in a variety of textile keyboards and soft displays integrated in different parts of a garment. But when integrating technology into products that we already have in our environment such as clothes, interaction design must consider the functional and aesthetical aspects connected to the product. That may result in other types of user interfaces where activation and feedback is something else than a keyboard or a display.
The aim with this project has been to explore the possibilities to create an alternative interaction when mobile technology is wirelessly connected in a textile product. The tool for this research is a glove, called Wanted [2][3]. Wanted is wirelessly connected to the mobile phone which makes it possible to make and receive calls through the glove. In this project the first prototype was focused on the act of communication, receiving and making calls through the glove and the interaction was designed using hand gestures and voice. The potential of using hand gestures as a tool for interaction has been showed in several research projects. Gestures enhance communication, like feelings or if there is a lack of understanding in language. For deaf people the gestures are the whole of communication which shows that hand gestures allows richness in interaction. Some projects explore hand gestures in human behaviour and as data input and communication [9]. Other projects explore hand tracking by integrating different type of technologies and materials in gloves. The technology in these projects consists of different sensors that measures movements of the hand [8]. Also accelerometers are used in order to define position of different part of the hand. Edmisson et al [3] uses the textiles structure by integrating a piezoelectric film in a woven structure in order to track hand movements.

This paper describes a design proposal focused an extended concept to Wanted and how hand gestures and dynamic textile structure cold be used in order to interact with the product.. The basis of the idea is a set of interviews with persons in professions that are exposed to hard weather and with physically demanding tasks. A concept was developed along three types of functions communication, information and an open function that identifies the user in order to allow access to different systems. All functions are activated by voice and different hand gestures.

2 BACKGROUND

The first prototype of Wanted [3] was focused on the act of communication. Receiving and making calls through the glove. An interesting challenge in this prototype was to avoid the interaction model from the mobile phone. Instead of using buttons and display Wanted uses hand gestures and voice. A phone call is made by activation, phoning by voice recognition, speaking and ending the call by deactivating the function, figure 1. The headphone and microphone are placed inside the hand and the activation part on the thumb.

Figure 1 Wanted first prototype

The first prototype was tested and the response was positive. It was easy for users to understand the product and to understand its purpose. In prototype number two [2] a knitted textile system was integrated. The system transmits signals between the components and allows the user to move the technology from one glove to another. When developing the textile system for signal transmission some structures and materials were avoided because of some disturbances in signal [2][13]. A common property of these materials and structure is a high resistance and a big decrease/increase of resistance when stretching the material, fig 2.

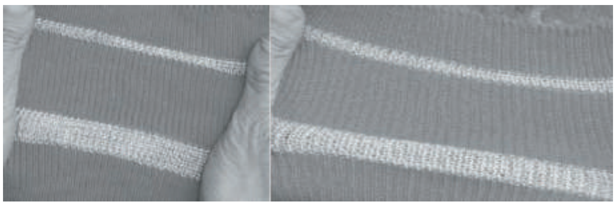


Figure 2 Stretch sensing fabric

Wanted was introduced and tested on several people. The idea appeared useful to them. Managing a mobile phone or other communication devices is difficult both in terms of picking it up and managing the dial buttons. It is also often necessary to remove the gloves, which exposes the hands to coldness. A positive thing with the prototype was the use of only one hand and the easy interaction with the product.

By using the glove as a tool for research has so far raised some questions for further work of which two are in focus in this project. Could the mobile phone be used as an intelligent terminal handling communication, information and other functions with the glove as a user interface to it? Is there an advantage to use a dynamic textile structure, like a stretch sensing fabric in order to develop the interface? This project started by defining added function and thereafter creating a design proposal for the interaction and product design.

3. CONCEPT DEVELOPMENT

The first thing to define in the design concept was the functions that should be used in the glove. The basis of concept was interviews made in connection with the first prototype [3]. The interviews were made towards four different professions with special working conditions and use of technology: An overall impression from the interviews was that the use of technology as well as other equipment is very functional to fulfil a few important needs. Ease of use was highly important due to the exposed context. An overall result of the interviews is presented below.

1	What is the normal activity?
	Communication – working in team, SOS, warnings and alarm handling, get information Information – navigation, weather, avalanche situation Technical maintenance – fault tracing, measurements, repair
2	What kind of technology is used and how is it used?
	Mobile phone, communication radio, navigation tool, measure tool, mechanical tools
3	What is critical in their activity?
	Avalanches, fire, cold, electricity, tiredness, carving injuries, falling from heights, other health problem
4	How do they protect against critical situations?
	Communication, working together, protective clothing (glove, jackets, trousers, special shoes)

The result from the interviews shows that the mobile-phone or a communication radio is an important tool when handling different tasks and keeping the situation secure. There are also other functions that could make use of the connection to the mobile-phone, like weather information. The essence is still the idea of using communication and that the mobile-phone or radio is connected through a wireless link to the mobile phone, offering easy communication when it is worn. It is also the comfort of not having to remove the gloves under cold weather conditions. To communication two concepts using mobile technology in different ways, were added, which made the whole concepts consists of:

1. Communication, make call, receive call, increase/decrease sound
2. Information, get certain information like weather, navigation
3. Open function, different services to the system you log on to. It is called identification and it can work like a fingerprint, giving access to ski-lifts or avalanche warnings, for example. This identification could also be used as support for working teams.

4. INTERACTION AND PRODUCT DESIGN PROPOSAL

The extended concept opens up for further questions like: How should the interaction between the extended concept and the user be designed? How could the textile structure be used in order to improve the interaction?

According to the tests, communication performs well, both in terms of function and interaction. The principle of communication was kept, except for one change; the headphone was moved to the upper part of the thumb in order to be less exposed, see figure 3.

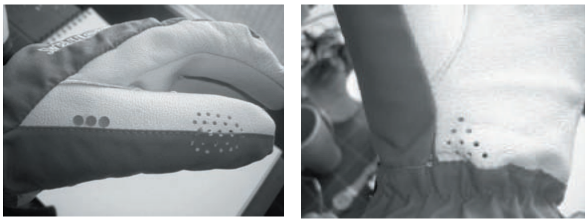


Figure 3 Communication: headphone and microphone

When using a stretch material it is somehow interesting to define gestures that allow stretch in the material. By bending different fingers for example it is possible to both stretch the textile material in a well defined direction. And it is also possible to use different fingers as options. It is possible to reach different functions with different fingers or combination of fingers, figure 4.

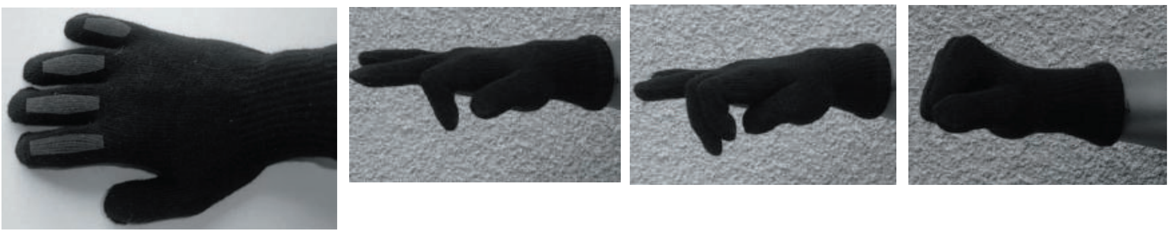


Figure 4 “Sensors placed on each finger, activated by bending.

To avoid mixing goal directed gestures with more unconscious gestures it is necessary to have a general on/off part different hand gestures. In the first prototype the on and off area were placed on the upper part of the thumb and that position was is kept, fig 5. The area is easy to access in different ways and that it is not a very exposed area.

Figure 5 On and Off area and different ways of activating

Getting access to different information can be seen as an act in at least two steps. The first thing can be to get certain information, for example weather or navigation. And the second, to get a certain weather information, actual weather or weather forecast.
Access to actual weather situation by bending the index finger. By bending another finger or combination of index finger/other finger it is possible to navigate in weather information getting access to for example weather forecast. By bending index finger twice other information like navigation can be reached.
the information mus also be shown somewhere. Using a display in smart clothes is common and sometimes it gives a computerised look and feeling. At the same time a display shows clear information and research with printed displays on paper [1] shows that in the future display may be integrated more in the textile structures. In the glove there are though two ways to integrate a display without to much exposure or “computerised” look; the Velcro strap that regulates the fit of the glove or to insert a thin and flexible display on the upper part of the glove, fig 6.

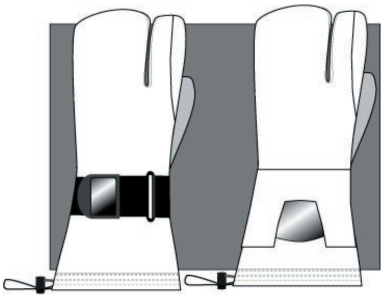


Figure 6 Information displays

The open function differs from the other because of its flexibility. For the user it is just to log on by to the system, identification, and thereafter make use of it in different situations. Identification is like a fingerprint, and is visualised by a mark or an application placed on the thumb, fig 7.

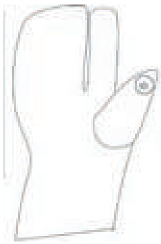


Figure 7 Identification placement

4.1 Final design proposal

The final design shows a glove where the functions are integrated in different part, fig 8

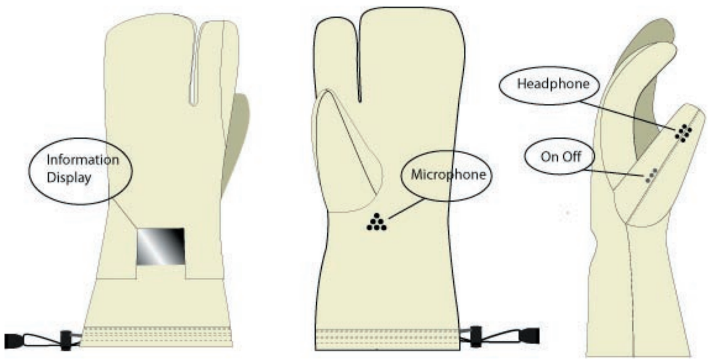
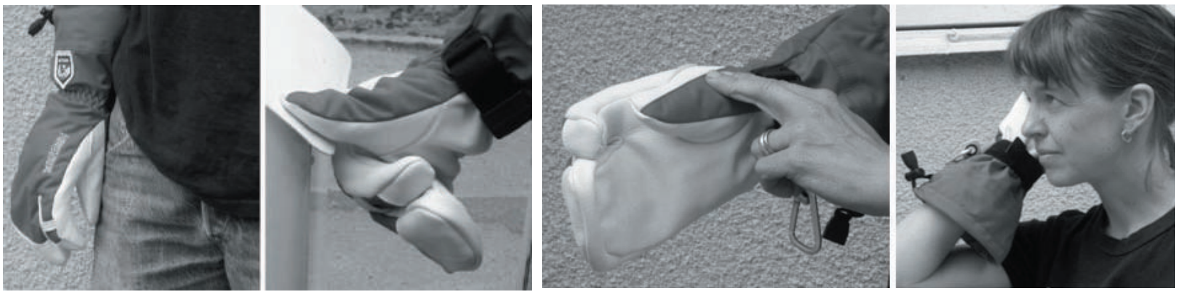


Fig 8 Glove concept, outer glove and inner glove

The following scenarios are designed for the use of the extended concept:

Scenario 1 The user activates the connection to the mobile phone and login to the system. After a while there is a phone call and the user activates in order to answer the call.



Scenario 2: By activating and bending the index-finger the user gets access to actual weather information, by bending the whole hand the user gets access to the weather forecast.

5 CONCLUSIONS AND FUTURE WORK

The aim with this project has been to use experimental product design in order to find out how mobile technology and a stretch sensing textile structure could be used in a textile product. The result is a quite general design proposal where a glove is an alternative user interface to the mobile phone. The three functions that were chosen represent different type of need, use and interaction. The interaction design shows the potential of using a glove as an alternative user interface to the mobile phone. A glove allows a lot of hand gestures in the interaction with technology and as many other projects show there is a richness of expressions in such interaction. The potential of "sensor" textile structures generates interesting interaction design ideas and is also one of many necessary steps to move from embedded technology to textile material in such applications. The use of mobile technology in daily life as well as in this project shows the potential of mobile-phone as an intelligent terminal supporting smart clothing and smart textiles. At the same time smart clothing and textile have a great potential in acting as a user interface to the mobile phone.

Future work for this project must first of all be focused on implementing the ideas in a product and to combine it with earlier prototypes [2]. To do that it is necessary to get deeper in the phenomena that some combinations of material and technique make a textile structure sensitive to stretch. Further basic research on how textile structure and conductive materials affect the electric properties is necessary and should continue together with applied research, like experimental product design.

Concerning further potential research I think that research depends very much on improvements and developments in technology. Today all connections between components are textile structures. What happens when a microphone is a part of textile instead of an electronic object? How will the development of textile display affect this kind of product? A better integration will also affect the design choices in the interaction and product design. Future work in this area should concentrate on better integration between traditional technology and textiles. By exploring that area and merging two types of technologies will make smart clothing more flexible and sustainable.

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Paper III

Spookies: Combining Smart Materials and Information technology in an interactive toy

ABSTRACT
This paper decsribes the use of textile as a user interface to an interactive toy called Spookies. Both tradtional textiles and smart textiles has been used in order to commuicate the technology and the interaction. The projects have generated ideas that can be used both in Spookies concept as well as interactive toys in general.

Keywords
Interactive toys, smart textiles.

INTRODUCTION
Minimisation of electronic components makes it possible to implement electronics in products that we already have in our environment, for example children toys. This opens up for design of toys with more computer-related behaviour and with a more complex interaction between the child and the toy. At the same Textile material science has developed new textile materials, so-called smart textiles [3][14]. These materials represent the next generation of materials and they are often described as textiles that can think for themselves. They can react to stimulus from their environment and thereafter, in different levels, adapt their behaviour to the circumstances

Combining electronic devices and new textile materials gives an opportunity to develop new interactive products in textile with a new type of behaviour and use, and a new type of user interface. The traditional computer user interface, input by a keyboard and output by a display, will then be changed to something else. Several projects show the potential of combining smart textiles with data processing units. The application areas differ between play, games, music, medicin or sports. Smart textiles could be used for data transmission using optical fibres as in the smart shirt project[4]. In the smart shirt project signals from electrodes is transmitted through optical fibres to a data processing unit. Another example of signal transmission is to weave conductive fibres into the textile architecture [2]. There are also examples where smart textiles are used when constructing textile keyboards [5] [12]. Textile antennas and electrodes are other examples where smart materials and textile constructions creates traditional electronic components in textile. The embroidered music balls [11] describe textile as a user interface to music performance. The balls are made of textile and integrated with sensors that allow children to perform and manipulate music with physical hand gestures such as squeezing and stretching. The idea is an example of physical use of an abstract material, the music and the textile is suitable for required gestures. In procceding of IDC 2003 Eisenberg [1] discusses the potential of using Smart materials in future educational technology from different aspects. A potential benefit of smart materials can for example be to fill the gap between complex computional technology and understanding.

This paper discusses textile as a user interface for an interactive toy by relating it to the state of art in smart textiles. Textile as a user interface is also described through two design examples, using tradtional textiles and smart textiles.The research method is research through design. This method could be described as a method where a design concept, idea or product is used as a tool in the research. The tool is used in order to find the question in a certain research problem. In this case the tool for the research is an existing toy concept called Spookies. Questions addressed in this project have been. How can textile be used as a user interface to Spookies? What are the possible smart materials to use in order to communicate the interaction? How can smart material be applied in the toy? How will the use of smart material affect the product?
The paper begins with a description of the Spookies concept, functionality and interaction design, The design of and use of traditional textiles, are therafter described, followed by an analyse of smart textiles and the possible use of the material in Spookies.

Spookies concept

"Spookies" is a toy that encourages a free play. A free and active play could be defined as a play including the following parameters [6] [7]:

Pretending: lets children use their imagination, act and be creative

Spontaneity and Improvisation: distinguish the play from games and sports letting the children change the play spontaneously.

Physical activity: provides a richer more interactive and engaging experience

Social Interaction: a central aspect, the joy of being together with friends.

The concept of "Spookies", figure 1, contains 14 different units organised in seven pairs. Each unit has one function and units in a pair are wirelessly connected. The play can be based on the communication between the units but there is also possible to combine the units in order to build more complex units.

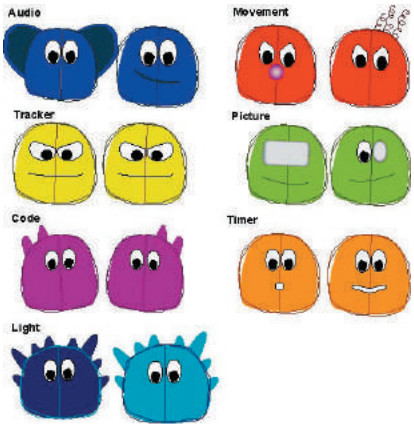


Figure 1 Spooikies concept

The Audio pair represents a central part in the concept enabling direct communication between the children, the couple is specialised in transferring sound. The listener is equipped with a microphone to pick sound and the speaker returns all sounds received from the listener. This pair gives an example of a pair that contains an input- and an output unit. Tracker is a pair that does not consist of an output and input unit. Instead both units can receive and display information, always reflecting the state of the other unit. The tracker pair measures the range to one another and the output consists of eight diodes. The distance is related to the number of diodes that lightens up. Code is a pair without input and output units that support interests in sending secret signs, codes and languages. A message is sent by pressing a horn, the other unit vibrates to inform that a message has been sent. To receive the message the user has to find the very same angel as the sending unit, up, down, left, right, forward or backward. Light spookies input and output units that support play with light and darkness. The dark input unit, recognises two states, light or darkness, and sends a signal to Lighter, which is the output unit. A light signal lights up Lighter with the aids of diodes. Movement is a pair detecting and announcing movement. The Sniffer detects movements and sends a signal to the Vibrator (output unit) who vibrates in order to announce the movement. Picture Spookies is another input- and output pair providing the play with the fun of visual imagery. The Photo unit is equipped with a camera to take pictures and send them to the image spook. Time Spookies is an output and input pair. Timer, the input unit measures and handles time. Whistler, the output units, plays melodies when activated.

Besides the opportunity of playing with each pair using the communication between the units it is also possible to combine them. The combination of different "Spookies" opens up for a more complex function and for a logic play with information technology. The rule of combining is that an upper "Spookie" masters the one below. An example of that is a kind of Spy game; the Sniffer is put above a Listener. The output units, vibrator and speaker may then be placed in another room waiting for a signal that someone has arrived in the other room. On activation, when someone arrives, Sniffer sends a signal to Vibrator who announces that someone is in the other room. It is then possible to use Listener to secretly listen to conversations in the other room, see figure 2. The are a lot of combinations, some of them are not fun at all but it is up to the children to find out that by themselves. It is the children who should find their own way of using "Spookies" as a tool in their play, with or without combinations.

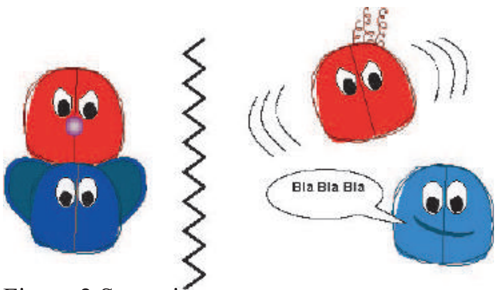
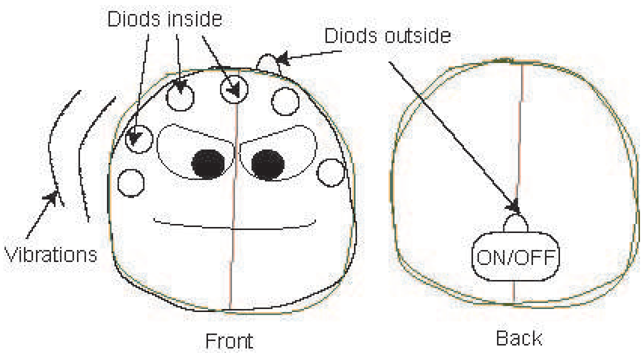


Figure 2 Scenario

The user interface

In the first generation of Spookies it has been explored how a traditional textile in combination with electronics could be used as a user interface to the toy. All units have a primer form with different details that describes the function of each unit. The listener for example, have big ears for. Each unit has an on/off status that is activated by a pressure on the back. In both on/off and activation integrated mechanical buttons and stretch sensors are used. As feedback vibrating motors and diodes are used. In code a diodes light up when there is a communication between the two units. The Tracker pair use diodes in another way, the diodes are placed behind the textile and the numbers of lighted diodes are related to the distance between the units. The closer they are the more diods are lighted. By using Spooikies as pair or organising the units in more complex arrangement the children build and activate their own game. As described, diodes and vibrations are used in several ways to deliver feedback to the user. Figure 3 shows an overview of dynamic feedback delivered from the different units.



Fihure 3 Feedback overview

In order to communicate the difference between the pairs and units even more, "Spookies" were made in a unique knitted fabric [7] with a relief shown in figure 4. With colour, pattern and relief there is both a visual and a tactile feedback that shows the difference between different units and pairs.

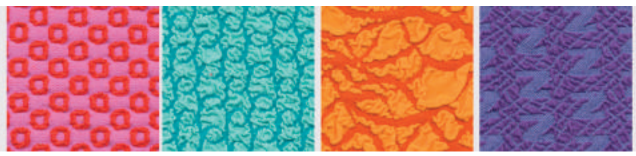


Figure 4 Knitted fabric

Creating prototypes with embedded technology gave the opportunity to test and analyze the concept and product design ideas. The textile design of the unit was important in order to communicate the different functions as well as keeping the play active. For example, letting the units look more like pets, made some children to start taking care of the unit instead of participating in the game. Form and weight was also important. Designing them like balls or making them to light made children to throw them. In designing the knitted pattern design it was more important to create big variations in than trying to visualise the function in a symbolic pattern. The final interface of Spookies is shown in figure 5

Figure 5 First generation of Spookies

SPOOKIES INTERFACE USING SMART TEXTILES

The first generation of Spookies is an example of embedded technology where the technology is hidden behind a textile shell. The textile together with hidden mechanical buttons, diodes and vibrations act as the user interface between the technology and the user. The interaction in spookies is characterised by simple and physically input and symbolic output. Further research has focused on how can smart materials be a tool to enhance and express the interaction?

Concerning smart materials, they can be divided into three groups

1. Passive smart material, can only sense the environment, they are sensors.
2. Active smart material, can sense stimuli and also react to them besides the sensors function, they are sensors and actuators
3. Very smart materials, they can take one step further having the gift to adapt their behaviour to the circumstances.

An interesting aspect is that there is some kind of analogy between input/output and sensors/actuator If so, what are the state of art in sensors and actuators and how could they be used in the concept?

Sensors

The basis of a sensor is that it transforms a signal into another type of signal. There are different materials and textiles constructions that have the capacity of transforming signal into electric ones. Exmples of sensors are:

1. Thermocouple materials transform thermal signals to electrical.
2. The softswitch technology [12]. The softswitch technol-

ogy is a composite material that transforms a mechanical pressure to an electrical signal.
3. Fibre Bragg sensors, from mechanical through optical to electrical sensors.
4. A three layer construction where the outer layers are conductive and separated by a non conductive layer. When pressing the material the two conductive layers will get in contact and the pressure will be transformed to an electrical signal.

Any sensing technology that goes from pressure to electrical signal is of interest to use in the different acts that activates the units. The structured knitted techniqe also opens up for a three layer solution. Other interseting sensors are the thermocouple sneors. When holding a unit there will be a thermal raise from the body temperature which could be used to trigger a function. A very physical and clear way to actvaite a unit, just by holding it.

Actuators
Actuators respond to a signal and make things move like colour change, release substances, change shape and others. Actuators that could be of interest to use are:

1. Shape memory materials transform thermal energy into motion. They are materials that can revert from a shape to a previously held shape due to the action of heat Shape memory exists in the form of threads. The company Corpo Nove [13] has created a smart were the trained memory shape is a straight thread. When heating the shirt after wash all the creases in the shirt disappear.
2. Chromic materials [14] change colour due to different stimuli. The most common ones and the only actually available on the market are those who change colour due to temperature or light. Other stimulus could be pressure, electricity, liquid or electron beam.
3. Electroluminescent materials are wires or coatings that creates a shining texitles [2]. Unfortunately they are example of actuatros that requires a high voltage supply to be acivated.

Shape change material could be used in the structure changing the structure from creases to a smooth surface. When shape memory materials become stronger like a real muscle it could be used to change the whole form of the unit.
A way of merging technology and textile is to use colour change materials instead of diodes. Implementing such a material makes it possible to move the effect into the textile relief and the different parts of the pattern.
The lightning effect of electroluminescent materials has the advantage of being visible in both light and dark environments.

Besides sensors and acuators there is a group of interesting materials that are conductive. Conductive materials are fibres or coatings that transmit signals [2][14]. They are usually not categorised as sensors or actuators but are usable in alo of cases. There are a lot of fbres and coatings with conductive properties.
1. Texturised metals like stainless steel, copper or silver. (Low resistans)
2. Polymers blended or coated with metals. (Relative low resistans)
3. Doped polymers (Low-High resistance)
4. Carbon fibres (High resistance)
Materials with low resistance have high conductivity while high resistance materials generates a heat when conducted to current. Initially conductive fibres were used instead of traditional wires in smart textile applications. There are also applications where aramids or carbon fibres are used for heating like car seats examples. Future potential of these materials is substituting of electronics to electronics made of textile. Examples of that is textile electrodes, textile antennas [2], keyboards and capacitors made in textile. Printing circiuts on textiles is also a future area for conductive coatings. There are several ways to use conductive materials in Spookies. Today electronic components are embedded in foam in order to protect the technology but also to hide it as much as possible to keep the feeling of a soft figure. Making components in textile will change these conditions since it will opens up for possibilities to implement electronics in the filling or in the textile shell in another way. When the research on printing circuits has progressed that is certainaly of interest for this application. High resistant materials can be used in order to generate a heat feedback or to activate thermal actuators like thermochromic colours.

EXPERIMENT: COLOUR CHANGE MATERIAL
The smart textile overview shows the potential and generates ideas of how these materials can be used in Spookies. A question that still remains is how use of smart materialst affects the product. In order to explore that it was decided to apply an actvie smart materials on the knitted fabric. The chosen materials was a thermochromic print that could be applied in different ways. Over the whole fabric or on certain pattern parts. The material could then be combined with the data processing unit in the toy. Chromic materials, as they are called, change colour due to different stimuli. Thermochromic material reacts to temperature change, when temperature raise the colour disappears. Blending thermochromic with traditional colour or printing thermochromic colour on a coloured surface gives the illusion that the actual colour change from one to another. Thermochromic materials was applied in the knitted structures as well on certain details like the eyes and the on/off button. The principal of activating

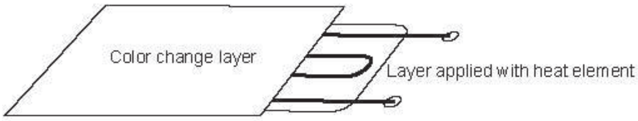


Figure 6 Construction principle

the material was to apply a conductive carbon fibres on the back of the colour change layer in order to heat the area, see figure 6.
The knitted pattern was applied with colour on whole surfaces or on part of the surfaces like the relief. By conducting heat to the surface in different ways following change in the pattern were obtained

The print applied on the whole surface and c the whole surface conducted with heat, see figure 7

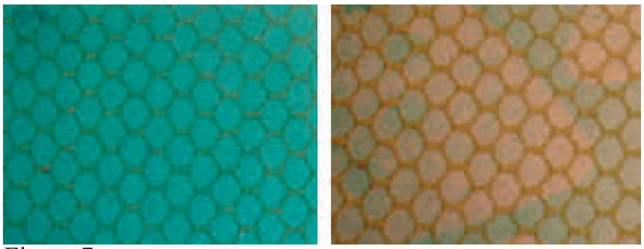


Figure 7

The print applied on the whole surface and different parts of the surface conducted with heat, see figure 8

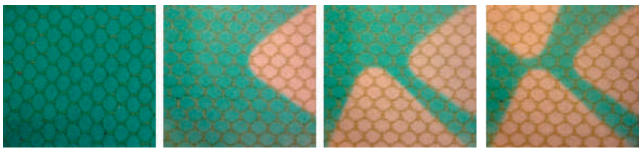


Figure 8

The print applied on parts of the surface, the whole surfae conducted with heat, see fig 9

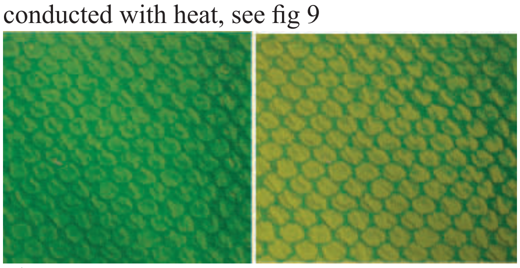


Figure 9

Attributes like the eyes and on/off parts where also printed with colour change materials, figure 10 and 11

Figure 10

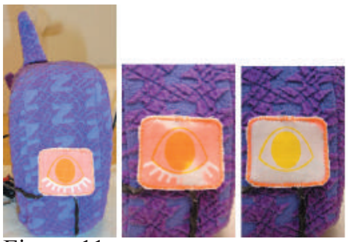


Figure 11

The result from the experiments shows the many variations offered by just using thermochromic materials and carbon fibres. In order to see how the differnt materials could be used in different situations the following desing proposals where created.

Colour change on whole surface could be used in order to change the whole surface on a whole units or parts of it. For example the Listener could change colour on the ears when activated, see figure 12

Figure 12

Colour change on added parts could be used in order to visualize the distance between the units in the Tracker pair, see fig 13

Figure 13

Applying colour in the structure gives feedback in the structure of the fabric could be used as a feedback when differnt units are activated in a built combination, see figure 14

Figure 14

Changing colours could be used on On/Off parts, see figure 15. But it is also possible to change eye colour on units where the visual sensing is an input, in Light or Picture.

Figure 15 Colour change in attributes

DISCUSSIONS AND FUTURE WORK

This project has explored the textile material as a user interface to an interactive toy. The project shows the potential in using both tradtional and smart materials as a user interface for a toy. Using Spookies as a tool for the research has been a useful frame when exploring a new and extensive area of possibilites. Using the concept as a frame for the research has not just generated design proposal for the specific toy. The method has also created general idaes for how smart textiles can be used for interactive products in general.A passive but both expressive and structured textile material communicates the actual function of each unit in Spookies. The use of smart and dynamic materials, on the other hand, communicates the interaction. It is also important to note that the knitted fabric in traditional textiles has served as material that has opened up for a variation in use of the colour change print. It shows that textile interfaces also includes a counsciously creation of tradional materials and techniques. The Smart material overview shows a variety of materials that could be used in Spookies. It also opens up for new interaction models, like using thermocouple materials in activating a toy. By holding it for a while the body temperature activates the toy and gives the feeling of wakeing or slowly starting the toy. The feedback in the experiment was dynamic and enhances each unit uniqueness and own personality. Applying colour change material into the fabric makes the overall all impression that the textile user interface relates to the technology in another way. The feedback fills the gap between the texitle and technology which opens up for a curious exploration of the toy and the technology behind it.

Another aspect of using smart materials is the improvement of the sustainability of the product which is important due to the kind of use. The applied textile feedback is more sustainable than integrated diodes and that is only a start. Electronics in a toy that encourage an active play are exposed and for sustainability over prolonged use it is necessary to examine how that can be solved. Research shows that further electronics are possible to substitute. Today electronic components are embedded in foam in order to protect the technology but also in order to hide it as much as possible to keep the feeling of a soft figure. Making components in textile will change these conditions since it will opens up for possibilities to implement electronics in the filling or in the textile shell in another way.

Thermochromic material is one example of a smart material. Further experiments must continue to explore the possibilities to use others. Besides experiments on feedback activation is another area for investigations. Sensing materials and constructions integrated in different parts or surfaces can substitute mechanical button and sensors. The incentives of developing technology embedded into textile in this direction are both practical and more abstract. Practical in the sense of improving the washability and sustainability of these products, Abstracts in the sense of creating a relation between technology and textile.

ACKNOWLEDMENTS

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Paper IV

TEXTILE MICROPHONE ELEMENTS

L. Berglin, and M. Zetterblom*

The Swedish School of Textiles
University College of Borås
Department of Computing Science and Engineering
Chalmers University of Technology
Margareta.Zetterblom@hb.se

ABSTRACT
The focus of this project is the development of textile microphone elements, like textile surfaces able to sense and transfer sound. Hence, the interesting aspect of a microphone element is its function both as an active sensor and actuator. Textile sound structures offer a variety of applications such as active sound absorber and health monitoring. Among a number of different types of microphone techniques two technologies are obviously familiar with textile structures, piezoelectric and capacitive techniques. Due to a reliable interaction and function we choose to do further experiments with piezoelectric structures. Piezoelectric PDVF materials are available as films suitable to laminate into textiles. This article presents a measurement set-up for a PDVF piezoelectric film laminated in textiles where different sounds are recorded via the textile into the computer for further analysis. The initial results show that these textile sound structures register sound and the signal quality depend on the laminate set-up.

Keywords: piezoelectric, microphone, PVDF, sound, textiles

INTRODUCTION

The focus of this project is the development of textile structures able to record sound. Our motivation to look into this area is that active textile sound structures are rarely explored. Further our focus of interest lies in the microphone element itself, since it functions both as an active sensor and actuator, and the variety of application areas such structures offer.

Since textile is light and flexible, textile sound structures offer alternative integration of sound sensors and actuators in our environment. First there are the obvious two applications; a textile microphone and a textile loudspeaker. An interesting application for a textile microphone could be an active textile sound absorber through active noise cancelling technique [1]. In medical applications, as we have seen in initial trials [2], sound recording could be an alternative measurement of heart rates. In that way it would be possible to overcome a number of shortcomings with textile electrodes and skin contact in heart rate monitoring. Intermittent disturbances are common when bio-medical signals are recorded with textiles because of motion artefacts and high impedances in textile structures affect the signal quality [3]

A microphone is an acoustic transducer device made to capture sound waves and transforms them into electrical signals. The most common microphones use a thin membrane, the microphone element, which vibrates in response to sound pressure and translate this movement into an electrical signal (figure 1). The membrane or microphone elements are based on different types of functionality where capacitor, piezoelectric and dynamic membranes are the most common ones [4].

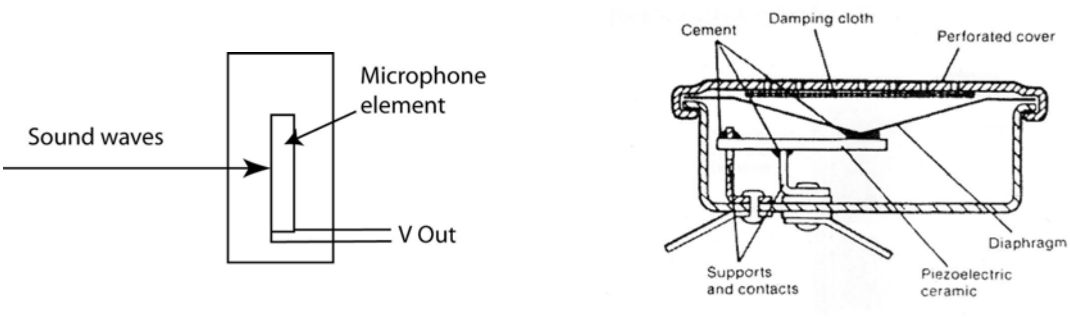

Figure 1. Schematic construction of a microphone

A capacitor microphone consists of two charged condenser plates, one fixed and the other flexible. The flexible plate oscillates concurrently with the sound waves causing a change of the charge across the plates sensible enough to transform the sound waves into electrical signals. A Piezoelectric microphone uses piezoelectric materials that produce a voltage when subjected to pressure, and convert these sound waves into an electrical signal. A dynamic microphone works via electromagnetic induction and consists of a membrane and an induction coil moving in an electromagnetic field converting the sound waves into electric signals. Of these three options capacitive and piezoelectric seems to be the most suitable for integration in textile structures.

We have earlier experienced capacitive and piezoelectric structures as textile press and stretch sensors [5] and due to a reliable interaction and function we choose to do further experiments with piezoelectric structures. Our experience of piezoelectric structures as stretch sensors (figure 2) is that they are basic, robust, self charging and do not acquire complex measurement equipment.

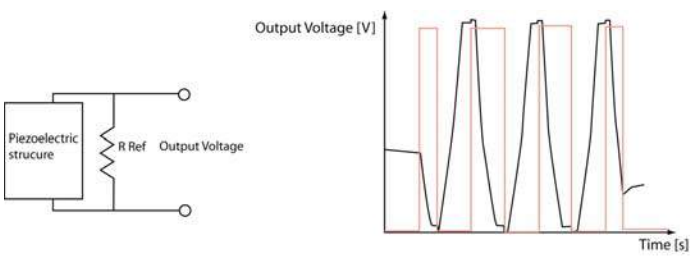

Figure 2. Piezoelectric structure as stretch sensor

Piezoelectric materials generate an electrical potential in response to mechanical pressure, for example obtained from sound waves. This effect appears in certain materials containing crystals where a polarisation of the crystals occurs when the materials is exposed to mechanical stress. (One side of the crystal will obtain a positive charge and the other side of the crystal will obtain negative charge.) Common for all piezoelectric materials is that the crystals in the material have an asymmetric centre. In an unloaded piezoelectric crystal the positive and negative charges are regularly spread and results in zero polarizing. Materials missing a symmetrical centre in their crystals are not automatically piezoelectric in all directions; a deformed crystal must be deformed in a certain direction to obtain an uneven distribution to achieve piezoelectricity.

The transformation of mechanical energy to electrical energy can be expressed with the piezoelectrical generator coefficient g according to the equation where P is polarization and s is stretch

$$g = dP / ds$$

Many natural and synthetic materials exhibit piezoelectric properties; they can be classified into natural crystals (quartz, rochelle salt, and ammonium phosphate), liquid crystals, noncrystaline materials (glass, rubber and paraffin), textures (bone and wood) and synthetic piezoelectric materials [6]. The synthetic piezoelectric materials are divided into piezoceramics, crystallines and piezoelectric polymers.
The development of piezoelectric polymers started when researchers discovered weak piezoelectric effects in whale bone and tendon [7]. In 1969 high piezo- activity was discovered in polarized fluorpolymer and polyvinylidene fluoride or PVDF.
PVDF has a glass transition temperature at – 35 C and is typical 50-60% crystalline [8]. The raw synthetic material (PVDF) is usually isotopic and accordingly non piezoelectric, but can become piezoelectric after a poling process that involves applying an electric filed at a high temperature. The field straighten the molecule dipoles in the material and the dipoles are then fixed into the aligned orientation in the structure when the material is cooled while maintaining the strong field. The result will be that the poled piezoelectric structure will deform in the presence of an electric field and polarize when subject to mechanical stress. Accordingly, in a piezoelectric PVDF the intertwined long-chain molecules attract and repel each other when an electrical field is applied or the material is mechanically distorted (figure 3). These characteristics are most useful in sensor applications.

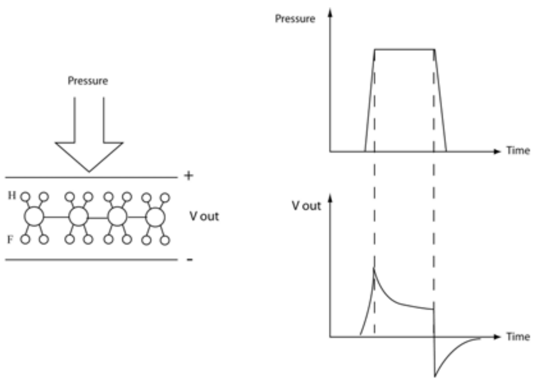

Figure 3. PVDF structure and electrical behaviour

PVDF materials are available as films used in a variety of sensor applications, for example vibration and sound control [9]. Microphones built with piezo film are low cost and inherently immune to moisture suitable for the integration in textiles which most likely will be exposed to water.

METHODS

As mentioned earlier in the text Piezoelectric PDVF materials are available as films which are suitable to integrate in textiles. Even in small sizes these films offer a big contact surface to sound waves. In the construction of the samples in this project we have used ready-made charged piezoelectric films from MSI Sensor [8]. Piezoelectric films vary in size, thickness and metallization options. For the textile microphone application we choose a thin (28 micrometer) silver ink compliant because it is most suitable for flexible applications where mechanical stress is being applied (figure 4).

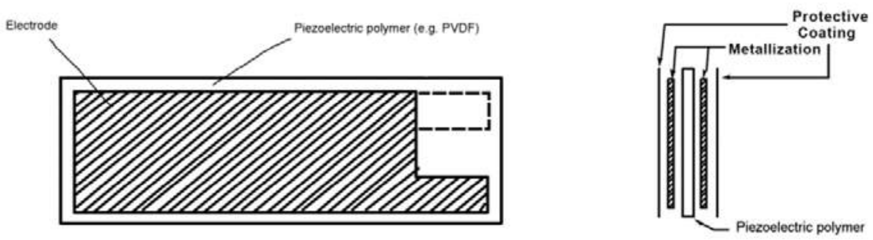

Figure 4. Sketch of a piezoelectric polymer film with electrodes.

The PVDF films (1x2 cm) were laminated between different textile fabric structures and the samples were in the size of 11x15 cm. In order to explore if the textile structures affect the recording of sound signals we choose textiles of different thicknesses, densities and manufacture techniques as woven, warp knitted and non woven textiles (Table 1).
The lamination was done in different ways; either the piezoelectric film was laminated between two layers of the same material or between two textile layers of different qualities and structures.

Nr	**1**	**2**	**3**	**4**	**5a**	**5b**
Photo						
Material	Polyamide/ Polyurethane	Polyamide	Polypropylene	Polyester	Polyamide/ Polyamide	Polyamide/ Polyamide
Technique	Weave/ Coating	Weave	Weave, heat calendered on one side	Non woven, porous structure	Spacer/ Weave	Weave/ Spacer
Weight	190g/m^2	50g/ m^2	350g/m^2	550g/m^2	500g/m^2	500g/m^2

Table 1. Sample overview

A piezoelectric film was laminated between two layers of fabric by means of a polyurethane web with the weight of 30g/m^2. In sample 1-4 the piezoelectric film is laminated between the same materials while nr 5a and 5b is a combination of a spacer fabric and the woven fabric sample nr 2 (figure 5). The procedure of the lamination process was performed in laboratory lamination equipment, in a temperature of + 80 C° during 1 minute.

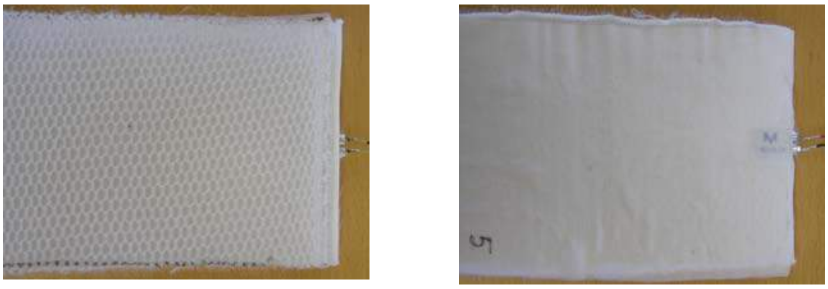

Figure 5. A three layer construction of samples 5a and 5b.

The textile samples were joint up with a measurement set-up (figure 6). Different sounds were recorded via the textile sample into the computer for further analysis. The only filtration of signal was a 45-55 Hz filter to eliminate the most common noise emanating from other electrical devices in the measurement environment. Besides this filter we decided to keep the raw format of the signal in order to make necessary adjustments due to future applications.

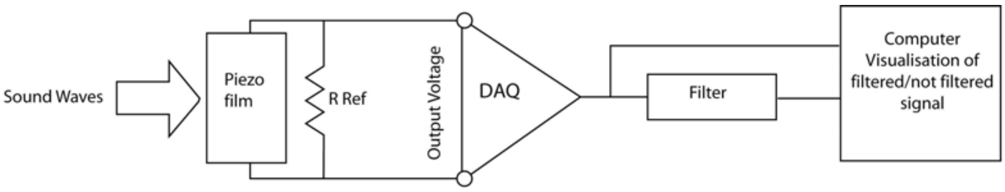

Figure 6. Measurement set-up

Each textile sample was investigated through identical audio tests in a vertical position allowing a free space around the sample and in a horizontal position on a contact surface. Three types of measurements were recorded and documented; a reference test without any sound, a test procedure with a hand clap (air borne sound) and finally a test scratching directly on the fabric surface (contact sound). Output voltage amplitude was measured for the three methods (figure 7).

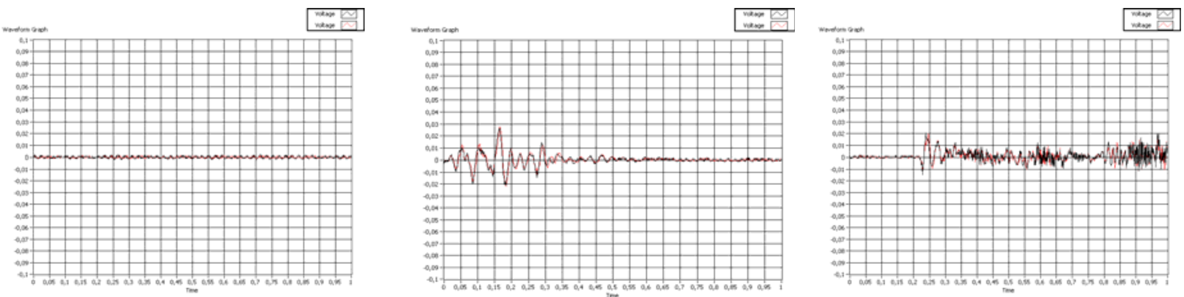

Figure 7. Output voltage from test without sound, handclap (air borne sound) and scratch (contact sound).

RESULTS AND DISCUSSION

All test results were put together in two bar charts, one for air borne sound (figure 8) and one for contact sound (figure 9).

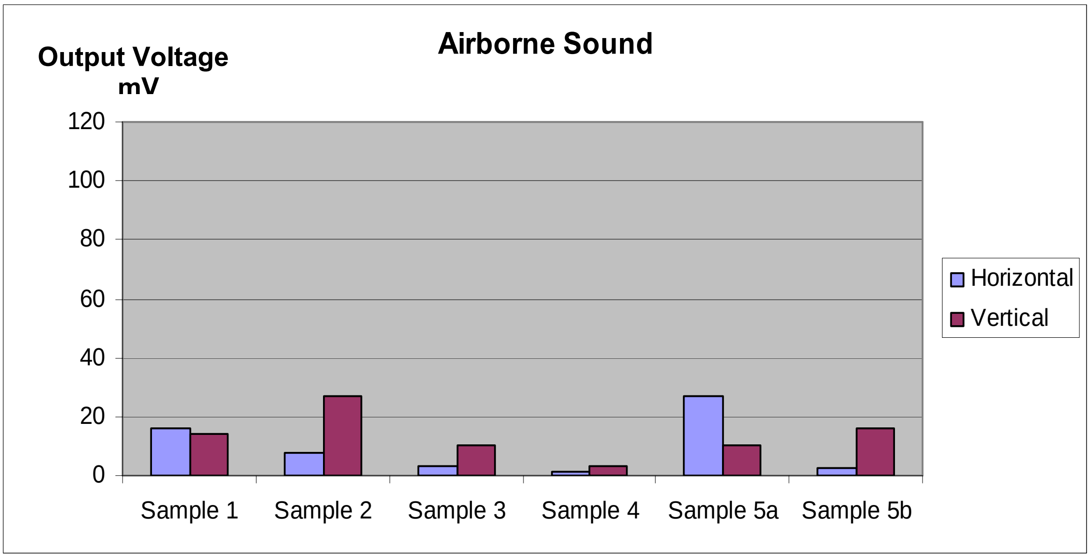

Figure 8. Output voltage for air borne sound.

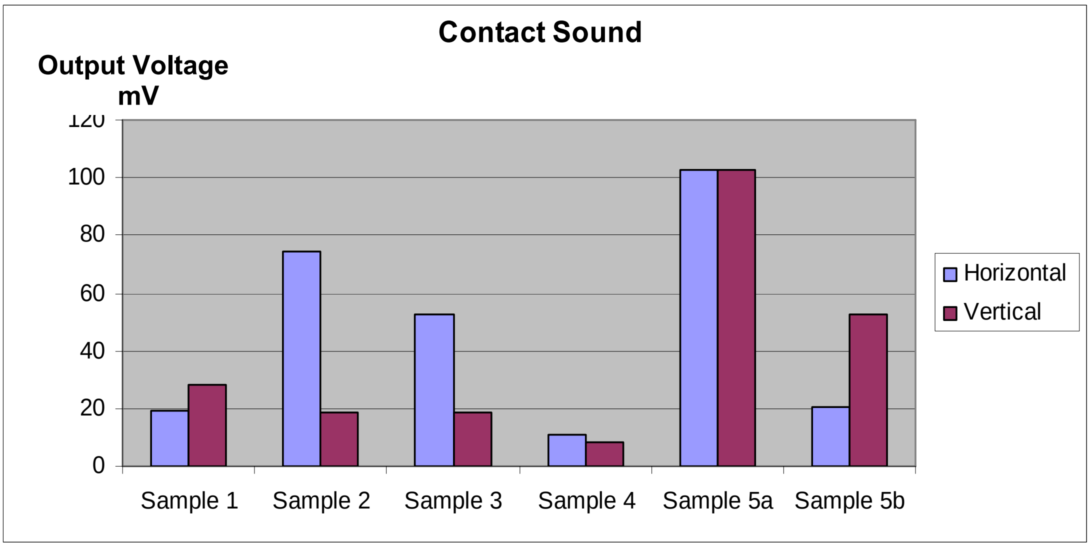

Figure 9. Output voltage for contact sound.

The most significant test results with the textile samples are:

1. All samples are more sensitive to contact sound than to airborne sound which probably is due to the chosen sensor element; the piezoelectric effect is frequently used in contact microphones.

2. The construction of the fabric seems to have an impact on the sound sensitivity (ability to sense sound signals). Thin structures as well as porous but thick constructions seem to record airborne sound most effective.

3. Sample, 5a, with the spacer fabric side directed towards the signal, is the most sensitive fabric in relation to both airborne sound and contact sound in a horizontal position.

The sound sensitivity of most samples seems to depend on their position. Most samples react best to contact sound in a horizontal position while most samples react to an increasing extent to airborne sounds in a vertical position, except sample no 5a (the thick spacer fabric with a thin fabric directed towards the sound). The sample no. 2 (the thin polyamide fabric), reacts to airborne sound in a vertical position as good as the sample no. 5a in a horizontal position. This sample reacts also very well at contact sound in a horizontal position. Sample no 4 (a heat calendered polypropylene fabric) shows the slightest reactions to contact sound and almost no reaction to airborne sound independently of its horizontal or vertical position. Sample no 1 (a coated Polyamide/Polyurethane fabric) seems to react with the smallest differences in relation to its position to both airborne and contact sound.

CONCLUSIONS

We have shown that recording of sound in textile is possible by laminating a piezoelectric film between two textile layers. The experiments show that the signal quality depends of the laminate set-up, the textile structure affects the ability to record sound. A thin textile quality (approximately < 150 g/m^2) seems to pick sound more easily than a thicker textile quality (approximately > 150 g/m^2). The use of advanced measurement equipment makes it possible to record a sound signal from a textile sensor, visualise it by a curve and make an analogue output. This technique makes it possible to compare different textile sound sensors to find the best solution for intended end use application. Today we have a textile sound sensor sensing contact and airborne sound. Such a technology offers a wide range of possible end use areas. In order to develop this general technology into more sophisticated end use areas we need to do further measurements. We also have to evaluate the result in general and towards specific applications which will result in different types of signal processing. Due to the different applications we have to consider suitable filtrations of the recorded sound.

To further elucidate the sound sensibility of our samples we will expose them to just one specific sound frequency which makes it possible to validate the specific advantages of each sample in relation to high or low sound frequencies. Next step is to compare a reference recording done with a regular microphone with a sound recorded by the textile structure.

The ability to pick environmental sound involves the development of sound sensors on different levels. On a general level we could integrate a textile surface sensitive to air borne and contact sound in any space. A more specific application to make use of the capacity to pick contact sound would be to monitor heart rate through a sound sensor. In conventional health monitoring the signal is achieved via gel-based conductive surfaces directly attached on the skin. A textile sound sensor could replace monitoring using skin-contact and gel-based technologies. Conventional passive sound absorbers perform best at high and middle frequencies while active sound absorbers are effective at lower frequencies. The combination of a passive textile exhibiting sound absorbing qualities at the same time working as a microphone connected with active loudspeakers will provide sound affecting possibilities for a wide spectrum of frequencies.

In future projects we also aim to replace the conventional piezoelectric films with a more textile construction. On example of that is to create our own PVDF structures, knitted, woven or non woven by either charging PDVF these structures or using charged PVDF yarn or fibres in the creation of these structures. Another way is to try out capacitive structures.

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Paper V

Self-administered long-term ambulatory monitoring of electrophysiological signals based on smart textiles

L. Sandsjö[a,b], L. Berglin[c,b], U. Wiklund[d,e], K. Lindecrantz[f], J.S. Karlsson[d,e]

[a] *National Institute for Working Life, Göteborg, Sweden*
[b] *Product and Production Development, Chalmers University of Technology, Göteborg, Sweden*
[c] *School of Textiles, University College of Borås, Borås, Sweden*
[d] *Department of Biomedical Engineering & Informatics, University Hospital, Umeå, Sweden*
[e] *Department of Radiation Physics, Biomedical Engineering, Umeå University, Umeå, Sweden*
[f] *School of Engineering, University College of Borås, Borås, Sweden*

Abstract

Smart textiles is a generic term for textile materials and products that interacts with the environment and users. In combination with wearable electronic devices, clothing with integrated sensors based on smart textiles has the potential to significantly increase the possibilities to perform long term ambulatory monitoring and making such activities fully self-administered. In this study we have focused on recording of electrophysiological signals using smart textiles integrated in a T-shirt to acquire heart activity (ECG) and myoelectric signal (EMG) from the trapezius muscle. The goal was to achieve ECG signal quality good enough to perform heart rate variability analysis to monitor stress and EMG signal from the trapezius muscle to monitor muscle activity during regular work. Although further improvements are needed our current experiences indicate that a smart textile T-shirt allowing long term recordings of heart and shoulder activity may be available to the research community in the near future. This would extend current possibilities in simultaneous long term monitoring of e.g. trapezius muscle activity and heart rate and heart rate variability, indicators of psychological stress highly interesting in studies of musculoskeletal disorders of the neck and shoulder.

Keywords: Smartwear, Wearable,EMG, ECG, work-related musculoskeletal disorders

1. Introduction

Smart or *Interactive* Textiles are generic terms for textile materials and products that, in some nontrivial sense, are self-active in use, i.e. interacts with environment and users. Combining electronic devices and new textile materials gives an opportunity to develop interactive products in textile and fashion with new types of behaviour and functionality. Clothing, for example is not just something we wear to protect and express ourselves, clothing can at the same time be used for measuring health status or facilitate communication.

Smart textiles and *wearable technology* research is an interdisciplinary area where wearable technology intersects with advanced textile technology and textile design. The research follows three main lines: smart materials, wearable technology, and integration of electronic functionality in textile structures, but also the integration of these three lines is a major area of research.

Smart materials can be classified on the basis of their ability to act as sensors or actuators [1]. A sensor is a device that transforms one type of signal into another type of signal. An actuator is a device that responds to a signal and perform some action like moving something, changing colour, releasing a substance, changing shape or similar. Moreover there is a group of materials that are conductive. Conductive materials are fibres or coatings that can transmit electrical signals or energy.

Health monitoring is an example of an area where integrative research and development in wearable technology is done. The Georgia Tech Wearable Motherboard [2], was one of the first health applications integrated in a garment. The motherboard creates a system for the soldier that is capable of alerting and sending vital sign information to medical triage. The sensors in the motherboard are connected to a personal status monitor. Another example of a wearable computing health monitor is the Life Shirt [3], which is a multi-function ambulatory system monitoring health, disease and medical intervention in the real world.

The demand on textiles products with respect to sustainability, flexibility and wash ability has turned the research to integration of electronic functionality in textile structures. This includes for example sensing textile structures and textile electronics such as textile antennas. Integration of textile based sensors for EKG recording has been demonstrated in several projects, Vtam [4], Wealthy [5], research at Ghent University [6] and the Swedish School of Textiles [7]. In the project WEALTHY [5] conductive and piezoresistive yarns in knitted garments are used as sensors and electrodes, in an attempt to monitor cardiac patients.

1.1. Aim of the study

In this study we have integrated textile sensors in a T-shirt to record electrophysiological signals, focusing on heart (ECG) and trapezius muscle (EMG) activity. The aim is to facilitate long-term ambulatory monitoring of information of interest e.g. in studies of work-related disorders, and to make such monitoring fully self-administered. By integrating sensors in textile, participants are not depending on someone assisting to apply e.g. ECG electrodes. This way of easily put on ECG- or EMG- electrodes has two downsides. Firstly, as the electrode is not affixed directly to the skin the electrode position may change slightly or the electrode may lose contact during the recordings. Secondly, using “dry”, non-gelled, textile electrode may result in poorer recording conditions than conventional electrodes.

Figure 1. The prototype T-shirt housing smart textile based ECG-electrodes

As a step towards improving the usefulness of textile-based electrodes for recording of electrophysiological signals, this study aims at testing various methods to cope with the above difficulties inherent in these devices. A specific goal was to detect ECG signal good enough to monitor heart rate and heart rate variability using smart textiles.

2. Methods

As monitoring of heart activity depend less on the exact position of the sensors, the smart textile approach is better suited to ECG than EMG recordings. An ECG signal for detection of heart rate can be recorded from many positions of the trunk, allowing multiple channel recordings to contribute the wanted information and thereby reducing the risk of data loss due to problems in a single channel. In the current project we have developed an advanced signal processing technique that allows us to monitor both heart rate and heart rate variability from multi-channel recordings where the signal in some channels may be disturbed or even missing. This multi-channel approach addresses both the above-mentioned difficulties inherent in using smart textile.

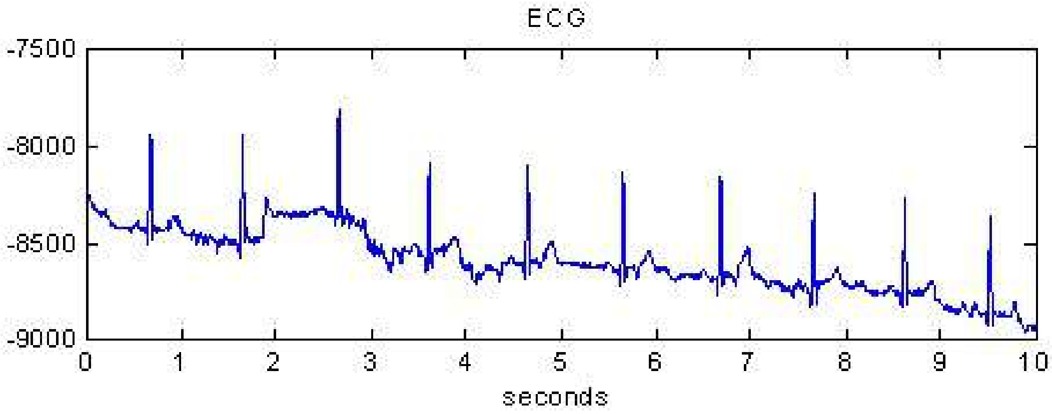

Figure 2. An ECG-sequence recorded by means of the prototype T-shirt.

3. Results

We have made a prototype T-shirt housing textile electrodes that enables multi-channel recording of the ECG-signal (Figure 1). During favourable conditions an ECG signal as depicted in Figure 2 can be recorded, which allows for heart rate and heart rate variability analysis without adopting advanced signal processing methods. The multi-channel approach can be used during less favourable situations, e.g. when the subject is moving resulting in that one or several of the ECG-electrodes provide a bad signal or even lose contact.

At the time of writing no EMG signal has been recorded using textile electrodes. An intermediary solution is to use a padded structure above the trapezius muscle housing commercially available dry electrodes [8]. Apart from the extra pressure on the EMG-electrodes provided by the padded structure resulting in an increased contact between electrode and skin, the padding also contributes to a better-defined recording position over the trapezius muscle.

4. Conclusion

Although further improvements are needed, our current experiences indicate that a smart textile T-shirt allowing long term recordings of heart and shoulder activity may be available to the research community in the near future. This would extend current possibilities in e.g. simultaneous long term monitoring of trapezius muscle activity and heart rate and heart rate variability, which is highly interesting in studies of musculoskeletal disorders in the neck and shoulder. An additional value is that the use of smart textile sensors integrated in clothing allows such studies to be fully self-administered.

Acknowledgements

The authors would like to thank Tomas Bäcklund, Marcus Karlsson and Nils Östlund, Deapartment of Biomedical Engineering & Informatics, University Hospital, Umeå, for their contribution to the study.

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Paper VI

Med Bio Eng Comput (2007) 45:515–523
DOI 10.1007/s11517-007-0183-0

ORIGINAL ARTICLE

Adaptive spatio-temporal filtering of disturbed ECGs: a multi-channel approach to heartbeat detection in smart clothing

Urban Wiklund · Marcus Karlsson · Nils Östlund · Lena Berglin · Kaj Lindecrantz · Stefan Karlsson · Leif Sandsjö

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Abstract Intermittent disturbances are common in ECG signals recorded with smart clothing: this is mainly because of displacement of the electrodes over the skin. We evaluated a novel adaptive method for spatio-temporal filtering for heartbeat detection in noisy multi-channel ECGs including short signal interruptions in single channels. Using multi-channel database recordings (12-channel ECGs from 10 healthy subjects), the results showed that multi-channel spatio-temporal filtering outperformed regular independent component analysis. We also recorded seven channels of ECG using a T-shirt with textile electrodes. Ten healthy subjects performed different sequences during a 10-min recording: resting, standing, flexing breast muscles, walking and pushups. Using adaptive multi-channel filtering, the sensitivity and precision was above 97% in nine subjects. Adaptive multi-channel spatio-temporal filtering can be used to detect heartbeats in ECGs with high noise levels. One application is heartbeat detection in noisy ECG recordings obtained by integrated textile electrodes in smart clothing.

Keywords Multi-channel ECG · Textile electrodes · Heartbeat detection · Independent component analysis · Noise reduction

1 Introduction

This study focuses on heartbeat detection in multi-channel ECG signals with high noise levels and intermittent signal loss. These types of disturbances could result from poor contact between the electrodes and the skin, as when using textile electrodes in smart clothing. Smart clothing is an evolving technique for monitoring of physiological parameters in various situations, such as home monitoring of elderly or patients with chronic

U. Wiklund (✉) · M. Karlsson · N. Östlund · S. Karlsson
Department of Biomedical Engineering and Informatics, University Hospital, 901 85 Umeå, Sweden
e-mail: urban.wiklund@vll.se

M. Karlsson
e-mail: marcus.karlsson@vll.se

N. Östlund
e-mail: nils.ostlund@vll.se

S. Karlsson
e-mail: stefan.karlsson@vll.se

U. Wiklund · S. Karlsson
Department of Radiation Physics, Biomedical Engineering, Umeå University, Umeå, Sweden

L. Berglin
School of Textiles, University College of Borås, Borås, Sweden
e-mail: Lena.Berglin@hb.se

K. Lindecrantz
School of Engineering, University College of Borås, Borås, Sweden
e-mail: Kaj.Lindecrantz@hb.se

L. Sandsjö
National Institute for Working Life, Göteborg, Sweden
e-mail: leif.sandsjo@arbetslivsinstitutet.se

L. Sandsjö
Product and Production Development, Chalmers University of Technology, Göteborg, Sweden

diseases, or monitoring during sports activities [1, 4]. A textile electrode consists of a textile conductive surface that substitutes a traditional electrode. The conductive surface can be made of any conducting material, but the most common ones are silver-plated yarns or stainless steel yarn [3, 19]. Textile electrodes integrated in clothing differ from traditional electrodes, not only in terms of material and structure used for the conductive surface, but also in that they do not make use of electrode gel and they are not affixed to the skin. The use of textile electrodes can allow for flexible health monitoring systems integrated in clothing, such as the continuous monitoring of heart rate.

Disturbances are common in ECGs recorded with textile electrodes: this mainly because of movements in the textile structure [13] and movement artefacts. Disturbances can also be generated by intermittent loss of signal from individual electrodes and by electromyographic (EMG) interferences. Because of all these disturbances, it could be difficult to detect heartbeats in ECGs recorded with textile electrodes. By integrating many electrodes and by using multi-channel algorithms, heartbeat detection may still be feasible in textile ECG signals even in the presence of occasional signal loss in a single or a few channels or high noise levels.

Algorithms for heartbeat detection must determine the time instant for each heartbeat with high precision. High precision is important both to analyse beat-to-beat heart rate fluctuations and to detect abnormal changes in the morphology of the ECG. Although single-channel heartbeat detectors can handle relatively high noise levels, intermittent signal loss in different ECG channels can only be handled by analysing many ECG channels simultaneously. Moreover, since the redundancy of a multi-channel system is higher, a multi-channel detector would probably outperform a single-channel detector for heart beat detection in noisy ECG recordings.

Few studies have described methods for heartbeat detection in multi-channel ECG recordings. One previously suggested method is the length transform, where the samples of each channel are regarded as points in a vector space [7]. The length of the vector is calculated using data from a segment of approximately the same length as the QRS-complex, and the transform gives the highest value at those time instants when a heartbeat occurs. Another approach is to separate the ECG and noise sources by blind source separation (BSS), which is a method to estimate source signals by using their linear mixtures. In practice, this is often performed using independent component analysis (ICA) [9]. ICA-algorithms have been used to separate ventricular and atrial activity in the ECG [17], to characterise ECG signals [12], to suppress noise in ECG [2], and to separate foetal and maternal ECGs [20, 22]. To our knowledge, ICA has not previously been used as an explicit heartbeat detector.

In this study, we propose a method to detect heartbeat events in disturbed ECG recordings using adaptive spatio-temporal filtering [21]. This multi-channel filter is designed to give distinct peaks in the output signal at the time instants when heartbeats occur. The method was originally developed for extraction of motor unit action potentials in surface electromyograms [21]. In a preliminary study, we applied spatio-temporal filtering to eight-channel ECG recordings [16]. The results showed that heartbeats could be detected even though the ECG recordings had high levels of interferences, such as disturbances generated by muscular activity and electrode displacement.

This study evaluated the performance of adaptive spatio-temporal filtering in multi-channel ECG recordings with high noise levels and intermittent signal loss in single channels. We compared the performance of adaptive spatio-temporal filtering with the length transform and regular ICA. The multi-channel algorithms were evaluated using data from the PhysioBank archive. We also evaluated adaptive spatio-temporal filtering using data recorded with a garment with textile electrodes. Our aim was to investigate if adaptive spatio-temporal filtering would be a suitable technique to use for heartbeat detection in noisy ECGs recorded with smart clothes.

2 Methods

2.1 Multi-channel spatio-temporal filtering

The proposed multi-channel filter is designed to produce an output signal having distinct peaks that correspond to the time instants where the QRS complexes occur. Such a signal resembles a spike train, where most of the data points have an amplitude value close to zero, but where the peaks have significantly larger values. Thus, the signal values have a super-gaussian distribution, with a marked tail in the histogram.

To maximise the super-gaussianity of the output signal, the adaptive multi-channel filter uses both spatial and temporal filtering. The temporal filtering is performed using individual finite impulse filters on each channel i according to

$$z_i(n) = \sum_{k=0}^{K-1} h_i(k) x_i(n-k), \qquad (1)$$

where $x_i(n)$ is the input signal from channel i, $\{h_i(k)\}$ are the coefficients of the temporal filtering, and K is the filter length. In this study the filter size was set to 1, 3, 5, 10, and 20 samples in the time domain.

With M input channels, the spatial filtering is given by

$$y(n) = \sum_{i=0}^{M-1} g_i z_i(n) = \sum_{i=0}^{M-1} g_i \sum_{k=0}^{K-1} h_i(k) x_i(n-k), \tag{2}$$

where $\{g_i\}$ are the coefficients of the spatial filtering.

If $g_i h_i(k)$ is replaced with $w_i(k)$, then

$$y(n) = \sum_{i=0}^{M-1} \sum_{k=0}^{K-1} w_i(k) x_i(n-k). \tag{3}$$

Consequently, the output signal $y(n)$ is a linear combination of time delayed input signals. In matrix form, this becomes

$$\mathbf{y} = \mathbf{W}\mathbf{x}. \tag{4}$$

The coefficients $w_i(k)$ were adaptively determined by maximizing the skewness of the output by using the FastICA algorithm [8]. The input signals were normalised to unit variance. The dimension of the input vector $\mathbf{x}$ was reduced using PCA, keeping 99% of the variability.

Spatio-temporal filtering was performed on blocks of 6-s durations. In each block of the output signal, time instants for individual heartbeats were determined using a threshold detector. The threshold was based on the median of a successive series of peak values for each second. A heartbeat event was detected if a local peak in the output signal was above the threshold limit. If two or more events were detected within a window of 300 ms duration, the event with the highest amplitude of the output signal was kept and the others were discarded.

The multi-channel filter is adaptive because the filter coefficients were determined for each segment of the signal. Therefore, the phase shift was different for successive blocks of the output signal and the blocks were time-aligned as follows [15]: the algorithm first determined the minimum time differences between the last detected beats in one block and the first detected beats in the next partly overlapping block. Then the sum of the absolute values of these time differences was calculated. The difference in phase shift between the two blocks was determined as the value that minimises this sum. All calculations were performed using the Matlab software package (Mathworks, Natick, Mass.).

2.2 Independent component analysis

Assume that the M recorded ECG signals, $x_i(n), \quad i \leq M$, are modelled as a linear combination of P unknown source signals, $s_j(n), \quad j \leq P$. In matrix form this corresponds to the basic BSS model given by [9]

$$\mathbf{x} = \mathbf{A}\mathbf{s}, \tag{5}$$

where $\mathbf{A}$ is the linear mixing matrix. If $P = M$ then $\mathbf{A}$ is a square matrix, and the source signals can be estimated by computing its inverse

$$\mathbf{s} = \mathbf{A}^{-1}\mathbf{x} = \mathbf{W}\mathbf{x}. \tag{6}$$

In standard ICA, the matrix $\mathbf{W}$ is estimated as the one that gives source signals (independent components) that are as non-gaussian as possible. This comes from the idea of using the central limit theorem ''backwards''. The central limit theorem states that by summing independent variables the sum will eventually have a normal distribution regardless of the distribution of the independent variables. A common way to measure ''non-gaussianity'' is to use higher order cumulants, often kurtosis.

From Eq. (6), it follows that BSS using ICA is similar to spatio-temporal filtering with $K = 1$. Thus regular ICA can be regarded as a pure spatial filtering, whereas spatio-temporal filtering also uses the temporal information of the data. Moreover, in ordinary ICA, we obtain as many independent components as recorded data signals, whereas our proposed filtering technique results in a single output. In this study, we implemented ICA using the FastICA algorithm, where we selected the output signal with maximum kurtosis. This is the same approach as previously suggested to separate QRS-complexes from atrial activity in 12-lead ECGs [5].

2.3 Length transform

The length transform of a multi-channel ECG recording is given by [7]

$$L(M, q, n) = \sum_{k=n}^{n+q-1} \sqrt{\sum_{i=1}^{M} (x_i(k) - x_i(k-1))^2}, \tag{7}$$

where M is the number of input channels, and q is a window with size approximately equal to the duration of the QRS complex. In this study, $q = 65$ was used. The input signals were high-pass filtered and normalised. Heartbeat events were determined in the output signal using a similar threshold detector as described above.

2.4 Database recordings

The multi-channel heartbeat detectors were evaluated using recordings from the Physikalisch-Technische Bundesanstalt (PTB) Diagnostic ECG Database (http://www.physionet.org). We selected the first ten recordings from healthy controls and analyzed the first 2 min of each 12 leads-ECG recording. The sampling frequency was 1,000 Hz. The signals were high-pass filtered (cut-off frequency 0.01 Hz) to suppress baseline drift.

Pseudoreal signals were generated by adding four different noise signals to each of the ten database recordings. Two recordings with noise typical in ambulatory ECG recordings were downloaded from the MIT–BIH Noise Stress Test Database (http://www.physionet.org). The first recording consisted of electrode motion artefacts (record 'em'), and the second recording contained muscle artefacts (record 'ma'). The sampling frequency was 360 Hz, but was increased to 1,000 Hz by interpolation and re-sampling. Each noise recording consisted of two channels of 30 min duration. Data were divided into 2-min segments, resulting in a total of 30 blocks of data for each noise type. Twelve of these thirty blocks were randomly selected and added to the each of the twelve channels of the ECG recording. Two different noisy ECG signals were generated: (1) ECG with electrode motion artefacts only, and (2) ECG with the sum of electrode motion artefact noise and muscle artefact noise. The signal-to-noise ratio (SNR) was defined as the ratio of the variance of the ECG signal and the variance of the noise signal. As a result of the used procedure an equal SNR was achieved in all channels.

The noisy ECG signals described above were also used to test the effect of intermittent signal loss due to poor electrode contact. To simulate a short interruption of the signal, we added short pulses modelled as a randomly occurring rapid transition to the maximum value followed by an exponential decay [6]. The duration of these pulses was randomly selected with a uniform distribution between 0.1 and 3.0 s, and the time constant of the decay was set to 4 s. The pulses were randomly distributed in different channels with an average interval of 15 s between pulses. SNR was calculated before adding the simulated pulses with signal loss.

The performance of the multi-channel algorithms was evaluated using different noise sources at three different SNRs (0, –5, and –10 dB) and at three different numbers of channels: four (leads I, II, III and AVR), eight (leads I, II, III, AVR, AVL, AVF, V1, V2 and V3), and all twelve ECG channels. Reference values of time instants for the heartbeats were determined by using each algorithm on all 12 channels without any additional noise.

2.5 Recordings with textile electrodes

Data were recorded from ten healthy male subjects (age 21–47 years, mean 30 years) using a T-shirt with integrated textile electrodes. The data acquisition unit had a wireless transfer of data to an ordinary PC system [10, 11]. The modular-constructed acquisition unit consisted of a main module with a single-chip microprocessor (8051-core), an application-specific signal conditioner module (including A/D converters), and a digital wireless module (Bluetooth). All modules can be exchanged depending on the specific measurement situation. In this study, ECG was measured using amplifiers with fixed gain, high resolution and oversampling 16-bit A/D converters. The wireless multi-channel data acquisition unit was configured for recording of eight ECG channels at 500 Hz. Baseline drift was suppressed by analogue high-pass filtering at 0.1 Hz.

Seven ECG channels were recorded using an elastic garment with textile electrodes placed on the chest and shoulders (Fig. 1). ECG was measured bipolar with a textile reference electrode placed near the waist. In addition, one ECG channel was recorded with two conventional Ag/AgCl electrodes placed on the wrists (lead I). This signal was recorded as a reference signal to confirm the detected heartbeats. The textile electrodes were made from stainless steel and knitted in pieces of approximate size 2 × 2 cm. Snap buttons were mounted on the textile pieces with electrical insulation between the back of the buttons and the skin of the test subjects. Standard ECG cables were used for connections of the textile electrodes to the wireless data acquisition system. All recordings were performed with dry textile electrodes.

Data were recorded for approximately 9 min. During the recording, the subjects generated intermittent disturbances by moving or by high levels of muscular activity: walking, changing between sitting and standing, flexing the breast muscles, and push-ups. Heartbeat events were detected

Fig. 1 T-shirt with integrated textile electrodes and the ECG monitor with a wireless transfer of data to a PC. White dots indicate positions of electrodes

using spatio-temporal filtering. All heartbeat event times were manually confirmed. Detection errors were found by visual inspection of the ECG recordings and the determined *R*–*R* intervals.

2.6 Scoring of results

A heartbeat event was labelled as true positive (TP) if it belonged to a window of 128 ms duration around the *R*-peak [14], if not, it was labelled as false positive (FP). Undetected *R*-peaks were labelled as false negatives (FNs). The probability of detection was measured by the sensitivity and precision:

$$\text{sensitivity} = \frac{\text{TP}}{(\text{TP} + \text{FN})} \quad \text{precision} = \frac{\text{TP}}{(\text{TP} + \text{FP})}.$$

Results were presented as boxplots, which showed minimum and maximum values, 75% percentile, median, 25% percentile and outliers. Outliers were defined as values smaller than (25% percentile) – 1.5(median – 25% percentile). The error in the determined time instants for all beats classified as TP was estimated by the mean-squared error (MSE), given by the average of the squared deviation from the corresponding reference values.

2.7 Statistical analysis

The performance of the different multi-channel algorithms was compared using the Kruskal–Wallis test. In all tests, a *p* value of less than 0.05 was considered statistically significant.

3 Results

3.1 Database recordings

Figure 2 shows one example of the performance from the evaluation of the proposed algorithm for adaptive spatio-temporal filtering using the database recordings. In this example, the SNRs were –10 dB for all input channels. The figure shows three input signals, but a total of 12 noisy ECG channels were used to determine the output signal with maximum skewness. For reference, the top panel shows the corresponding noise-free ECG.

Figures 3 and 4 show the results from the evaluation of the algorithms for different SNR and number of input channels. The boxplots show the pooled results for all four generated types of noise: the boxplots represent 40 values each. As shown in the figures, the poorest performance was obtained for the length transform. Therefore, the length transform was excluded from further analyses.

When SNR was –5 dB, spatio-temporal filtering with eight channels and filter length 20 resulted in a mean sensitivity of 99.7% with a mean precision of 99.7%. The corresponding results for ICA were 99.0 and 98.2%, respectively. At SNR = –10 dB, the best results were obtained for 12 channels and spatio-temporal filtering with filter length 20 with a mean sensitivity of 98.2% and a mean precision of 99.3%. ICA with 12 channels resulted in a mean sensitivity of 89.9% and a mean precision of 84.6%. Although there was a tendency to increased sensitivity with increasing filter length in the spatio-temporal filter, the only statistically significant differences were found between filter length 20 and ICA ($p < 0.001$). Regardless of filter length, the precision was statistically significantly higher for spatio-temporal filtration than for ICA ($p < 0.001$). Table 1 shows the average MSE for the detected heartbeat event times. The average MSE was below 1 ms for spatio-temporal filtration with at least eight channels.

3.2 Textile electrode recordings

Figure 5 shows the performance of adaptive spatio-temporal filtering (using $K = 20$) in one recording with textile electrodes while the subject was doing push-ups. As seen in the figure, all input channels contained severe muscular interferences. These interferences were suppressed in the multi-channel filter, as shown by the time instants of the spikes in the output signal before and after the onset of muscular interferences.

Table 2 shows the results of adaptive multi-channel filtering in the recordings with textile electrodes. No statistically significant differences were found between spatio-temporal filtering and ICA. There was a tendency that the number of heartbeat detection errors was reduced for spatio-temporal filtering when the filter length was increased from 1 up to 20. Using filter length 20 and all 7 channels, the sensitivity and the precision was higher than 97% in 9 of 10 subjects. The majority of misclassifications were made when the subjects were doing push-ups. One subject had a lot of hair on his chest and his recording had very poor quality, with a maximum sensitivity of 93% and precision of 93%. The length transform was not used to analyse the textile recordings because of its poor performance on the database recordings.

4 Discussion

Our primary goal was to evaluate whether adaptive spatio-temporal filtering was a suitable method to use in smart clothes where frequent disturbances in the ECG can be expected. Our idea was to integrate many textile electrodes

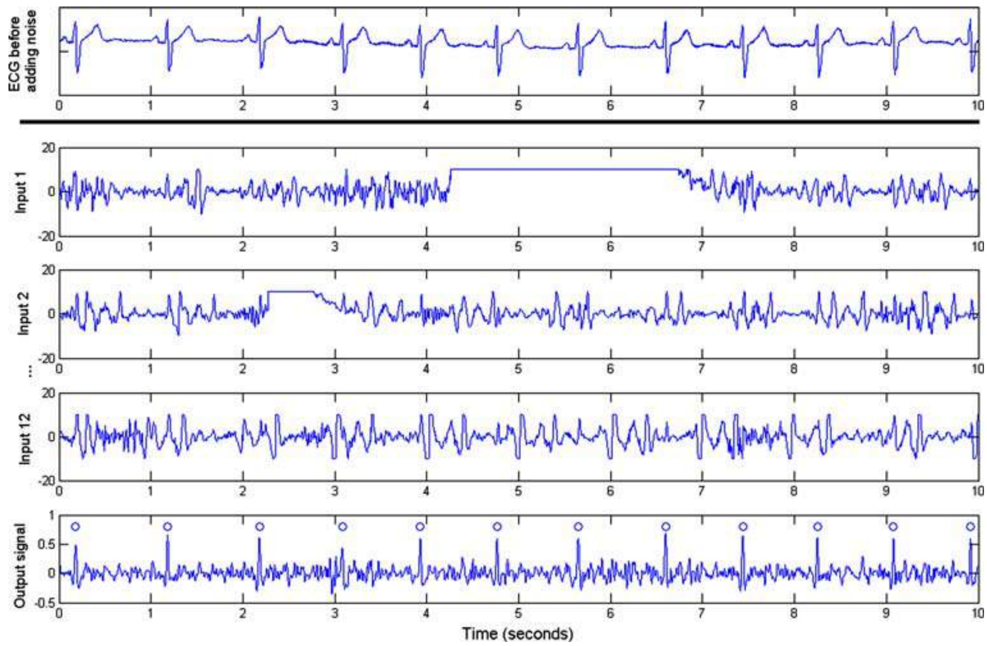

Fig. 2 Adaptive spatio-temporal filtering of a database recording using filter length 20. *Top panel* Original noise-free ECG. *Middle panels* Three input signals with SNR = –10 dB and intermittent signal loss. *Bottom panel* Output signal with maximum skewness. *Circles* indicate determined time instants for heartbeat events

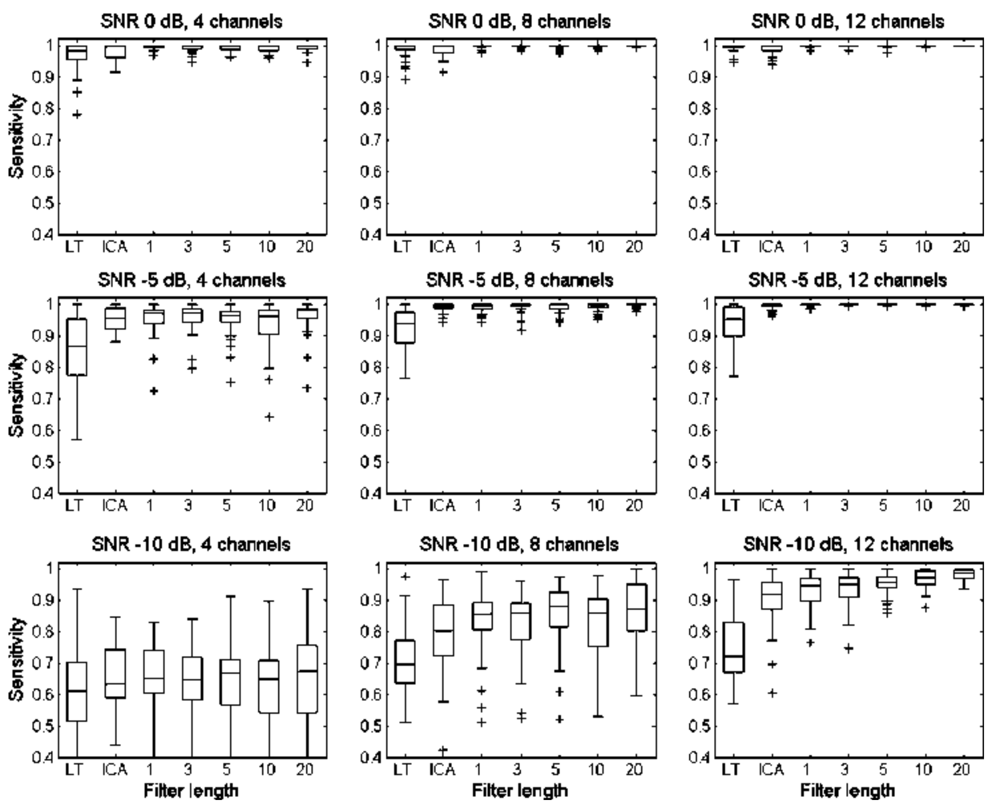

Fig. 3 Results from database recordings: sensitivity for different SNR:s and different number of channels for the length transform (*LT*), independent component analysis (*ICA*), and for different filter lengths of adaptive spatio-temporal filtering

in a T-shirt and use advanced signal processing to extract heartbeats. Therefore, we evaluated different methods for heartbeat detection in multi-channel ECG recordings with high noise levels and intermittent signal loss. We found that spatio-temporal filtering outperformed both regular ICA and the length transform when SNR was low. The performance of the multi-channel increased with increasing number of channels. We also found that the performance of the filter increased when the length of the temporal filter was increased. Thus the combination of spatial and temporal filtering reduced the number of detection errors in the database recordings with high noise levels. We also applied

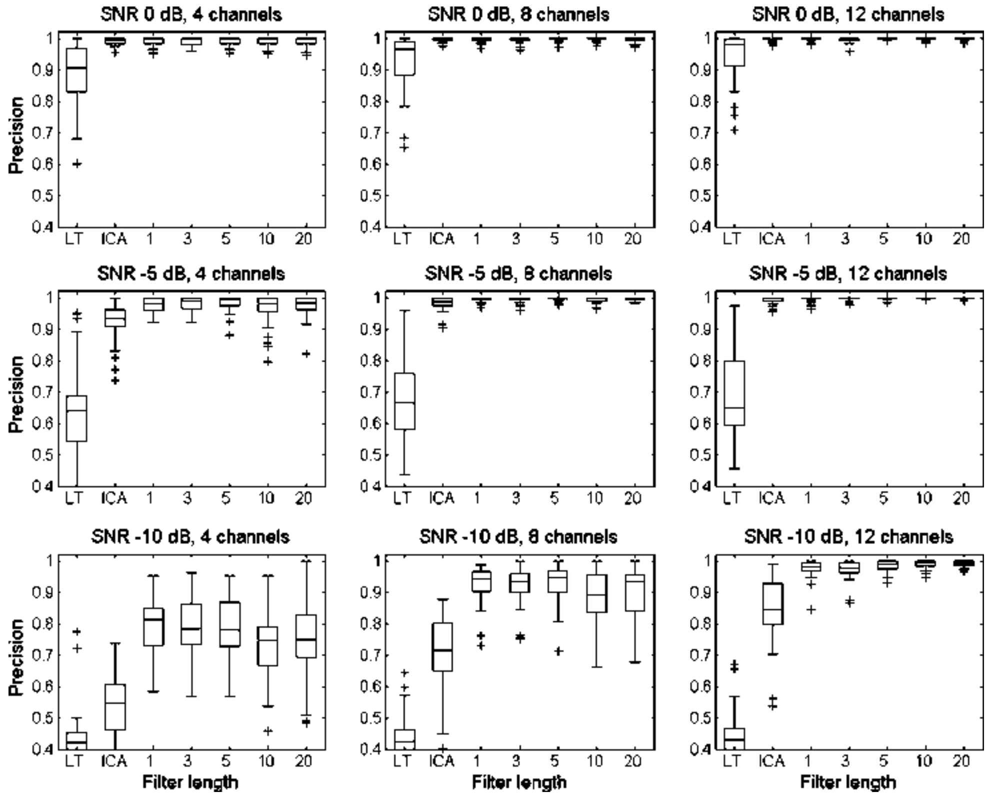

Fig. 4 Results from database recordings: precision for different SNR:s and different number of channels for the length transform (*LT*), independent component analysis (*ICA*), and for different filter lengths of adaptive spatio-temporal filtering

Table 1 Mean square error (MSE) for the determined heartbeat event times for all 40 pseudoreal noisy ECG signals

	ICA			K = 1			K = 20		
Number of input channels	M = 4	M = 8	M = 12	M = 4	M = 8	M = 12	M = 4	M = 8	M = 12
MSE (ms) SNR 0 dB	0.09	0.06	0.05	0.06	0.06	0.05	0.08	0.12	0.11
MSE (ms) SNR –5 dB	0.39	0.07	0.06	0.12	0.06	0.06	0.15	0.14	0.12
MSE (ms) SNR –10 dB	2.15	1.28	0.58	1.43	0.62	0.28	1.58	0.66	0.20

Results are presented for independent component analysis (ICA) and adaptive spatio-temporal filtering with filter length 1 and 20

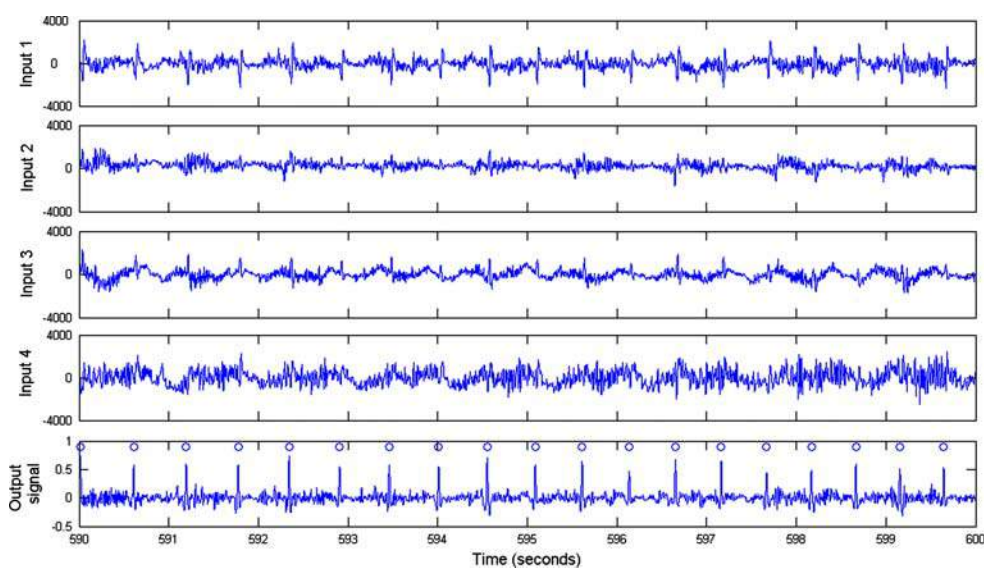

Fig. 5 ECG recording made with the T-shirt with integrated textile electrodes in a healthy subject while doing push-ups. *Bottom panel* Output signal from adaptive spatio-temporal filtering

Table 2 Sensitivity and precision for textile ECG recordings from ten healthy subjects

	ICA			$K = 1$			$K = 20$		
Number of inputchannels	$M = 2$	$M = 4$	$M = 7$	$M = 2$	$M = 4$	$M = 7$	$M = 2$	$M = 4$	$M = 7$
Mean sensitivity	0.963	0.951	0.956	0.966	0.955	0.959	0.981	0.981	0.979
Mean precision	0.965	0.957	0.960	0.964	0.962	0.962	0.983	0.984	0.979

Results are presented for independent component analysis (ICA) and adaptive spatio-temporal filtering with filter length 1 and 20

adaptive spatio-temporal filtering to multi-channel ECG data recorded with textile electrodes. Although the noise level was very high in some of the channels, 97% or more of the heartbeat events were extracted in recordings in nine out of ten healthy subjects.

In this study, spatio-temporal filtering was used to automatically extract one output signal—the one with the maximum skewness. The same filtering approach can also be used with other criteria and algorithms than the FastICA algorithm. Previously, kurtosis was used as criterion in spatio-temporal filtering of EMG signals [21]. Kurtosis is also more common in regular ICA applications. A preliminary study showed that skewness tended to be more robust against ECG disturbances than kurtosis [15], which was also found in this study as indicated by the higher precision for spatiotemporal filtering than for ICA. At present, we are developing the algorithms for adaptive multi-channel filtering to obtain an even more robust selection of the ''best'' output signal.

ICA has been used on multi-channel ECG in order to suppress noise [2], but not explicitly as a robust heartbeat detector. Compared to ICA, spatio-temporal filtering has the advantage that the use of time information decreases length of the signal corresponding to a heartbeat, thereby making the heartbeat easier to detect. In this study, this is seen as an improved performance with increasing time length of the filter.

The maximum filter length used for spatio-temporal filtration was 20, which corresponds to a time window of 20 ms duration. Thus, one would expect that the filter performs better for removal of muscular interferences than most movement artefacts. If the electrodes are spatially distributed, electrode movement artefacts probably only occurs in a few channels simultaneously. Similarly, muscle interferences in different channels are probably independent. This could be the reason why the proposed method seems to handle rather large noise levels. We performed tests where the filter length was increase to 50. The performance did not improve, but there was a marked increase in computational time.

ICA is used to recover the source signals from a linear combination of mixed signals [9], whereas spatio-temporal filtering extracts time instants for heartbeats without preserving the shape of the ECG. The shape of the QRS-complexes can be estimated in individual channels by using time instants for successive heartbeats and noise-reduction by averaging. Time delayed input signals have been used in variants of ICA to separate the foetal ECG from the maternal ECG [18, 20].

We accepted detected heartbeats if they were found within 128 ms around the corresponding *R*-peak, but the estimated error in heartbeat event time was below 1 ms for spatio-temporal filtration with eight channels**.** We have performed preliminary tests on recordings with ectopic beats. These tests indicate that additional functionality will be needed to fully separate ventricular ectopic beats from sinus beats. Supraventricular ectopic beats will probably be detected in the same way as sinus beats.

We investigated the performance of the multi-channel algorithms in two different situations. The pseudoreal signals based database recordings were analysed with the same SNR in all input channels. In this case, the performance improved markedly by adding more input channels. The textile recordings had different SNR in different channels. In several subjects, the first two ECG channels were of relatively high quality with low noise levels. There was no significant improvement in performance when adding more channels or when the filter length was increased. On the other hand, these results indicate that the performance did not decrease when more noisy data channels were added. In smart clothes, the electrodes may have good contact with the skin at certain times, whereas they will have poor contact at other times. By using many textile electrodes and the proposed algorithm, it may not be necessary to identify data channels of poor quality before the heartbeat detection. One disadvantage with using many electrodes is that more data needs to be recorded.

Another disadvantage with adaptive spatio-temporal filtering is the complexity of the algorithm. Many simple one-channel algorithms are available that can detect heartbeats in relatively noisy ECGs but not during temporary signal loss. Spatio-temporal filtering could be used as a robust reference method when developing simpler multi-channel algorithms.

The textile recordings were performed with a T-shirt with integrated textile electrodes and conventional cables attached to snap buttons. Movement of electrode cables caused additional disturbances, disturbances that may be avoided using integrated textile cables. Dry textile electrodes were used and there were no preparations of the subjects' skin before putting on the T-shirt. The missed beats were mainly in the segment where push-ups were performed and in the less successful recordings from subjects with most chest hair. The effect of body movements may also be reduced by using other electrode positions than those used in this T-shirt.

Smart textiles, i.e., clothing with integrated textile sensors have large potential in areas such as clinical monitoring, health surveillance, ergonomics, and sports medicine. The technique enables a heart patient to be continuously monitored at the clinic or in the patients home by just putting on a T-shirt including textile electrodes. Fire-fighters can be provided with smart clothing for continuous monitoring of vital signs during rescue operations in order to not expose individuals beyond safe conditions. Another possible application of smart clothing is monitoring of heart rate variability, which can be used to evaluate the cardiac autonomic modulation during different experimental conditions as well as during stressful situations.

5 Conclusions

Multi-channel spatio-temporal filtering may be a suitable method for heartbeat detection in ECG measurements with high noise levels and intermittent signal loss, e.g., when textile electrodes are used in smart clothes. Heartbeat detection using spatio-temporal filtering can also be applied to other multi-channel ECG recordings with high noise levels and/or temporary signal loss in some channels, such as Holter-ECGs and stress-test ECGs.

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Paper VII

Wireless Monitoring of Heart Rate and Electromyographic Signals using a Smart T-shirt

J. Stefan Karlsson[1#], Urban Wiklund[1], Lena Berglin[2*], Nils Östlund[1], Marcus Karlsson[1], Tomas Bäcklund[1], Kaj Lindecrantz[3], Leif Sandsjö[4]

[1]*Department of Biomedical Engineering & Informatics, Umeå University Hospital, SE-901 85 Umeå, Sweden.*
[2]*School of Textiles and* [3]*School of Engineering, University College of Borås, SE-501 90 Borås, Sweden.*
[4]*Occupational and Environmental Medicine, Sahlgrenska Academy at University of Gothenburg, SE-405 30 Göteborg, Sweden.*

[#]stefan.karlsson@vll.se
[*]Lena.Berglin@hb.se

***Abstract*— We have developed a prototype T-shirt with integrated electrodes for wireless monitoring of heart rate and muscular activity. Monitoring of heart rate is insensitive to the actual placement of the textile sensors by recording ECG from many positions of the trunk: This approach reduces the risk of data loss due to problems in a single channel. A multi-channel heartbeat detector was developed, which is robust to disturbed or even missing ECG-signal in single channels. For recording of electromyographic signals, our current intermediary solution is to use a padded structure above the trapezius muscle housing commercially available dry electrodes. By extra padding over the electrode site, the positions of the electrode are more well-defined and local sweat production is stimulated which enhance the recording conditions. The T-shirt has a specially designed textile electrode system for flexible integration in clothing.**

Further improvements are needed, but our intention is that our textile T-shirt soon will be available to the research community. In addition to personal health monitoring, the system would allow long-term monitoring of trapezius muscle activity and heart rate variability, indicating psychological stress, which is of high interest in studies of musculoskeletal disorders of the neck and shoulder.

I. Introduction

Advances in novel textile materials and structures, as well as in communication technology have opened up for a new generation of health care systems. Health monitoring is an example of an area where integrative research and development in wearable technology is performed. The Georgia Tech Wearable Motherboard [1], was one of the first health applications integrated in a garment. The motherboard creates a system for the soldier that is capable of alerting and sending vital sign information to medical triage. The sensors in the motherboard are connected to a personal status monitor. Another example of a wearable computing health monitor is the Life Shirt [2], which is a multi-function ambulatory system monitoring health, disease and medical intervention in the real world.

The demand on textile products with respect to sustainability, flexibility and washability has turned the research to integration of electronic functionality in textile structures. Integration of textile-based sensors for ECG recording has been demonstrated in several projects such as Vtam [3], WEALTHY [4], research at Ghent University [5] and the Swedish School of Textiles [6]. In the project WEALTHY [4] conductive and piezoresistive yarns in knitted garments are used as sensors and electrodes, to monitor cardiac patients.

Recent development in wearable health systems have resulted in a variety of prototypes integrated with textile sensors ([7] - [10]). Such systems, offer mobile and flexible surveillance of different user groups within health care, extreme working conditions, sports, etc.

Textile electrodes offer a flexible and soft solution that can easily be integrated in garments.. However, intermittent disturbances are common in bio-medical signals recorded with such solutions due to problems to get as good contact between the electrode and the skin as is achieved using a regular pre-gelled electrode pasted to the skin. To overcome these problems we have applied novel adaptive method for heartbeat detection in multi-channel ECG signals with high noise levels and intermittent signal loss [10]. The method was originally developed for extraction of motor unit action potentials in surface electromyograms (EMGs) [11], and later adapted for ECG applications [10]. A combination of signal processing using multi-channel methods and careful electrode design and a proper design of the whole system are ways to overcome the shortcomings. Our system consists of multiple textile electrodes and data transfer structures in a three textile layer construction.

In this study we have integrated textile sensors in a T-shirt to record electrophysiological signals, focusing on trapezius muscle (EMG) activity and autonomous control, as measured by heart rate variability assessed via ECG.

The overall aim is to facilitate long-term ambulatory monitoring of parameters of interest e.g. in studies of work-related disorders, and to make such monitoring fully self-administered. By integrating sensors in clothing, participants are not depending on someone assisting in the application of EMG or ECG electrodes. This specific aim of this study is to demonstrate simultaneously recorded EMG and ECG signals using electrodes integrated in a T-shirt.

II. METHODS

A. Experimental protocol

The goal with the measurements was to evaluate the T-shirt (Fig. 1) during computer work with different positions of the arm controlling the computer mouse. After the T-shirt was put on, the subject was seated for two minutes before the recording was started. At the beginning a reference EMG measurement was made, the subject stretched his arms for 10 seconds straight at 90 degrees, in the coronal plane, with the back of the hand turned upwards. The computer work consisted of moving the mouse pointer around on the screen for six minutes during two different positions of the arm that controls the mouse. During the first three minutes the wrist and the elbow were supported and the arm was held close to the body (ergonomic position). After a rest of 30 seconds the last three minutes was performed with unsupported wrist and elbow and with the arm held from the body (non- ergonomic position). Three healthy male subjects (age 29-49) participated.

Fig. 1 Example of a prototype T-shirt housing smart textile based ECG-electrodes. Commercially available dry electrodes were housed in a padded structure over the shoulder, i.e. over the trapezius muscle.

B. ECG and EMG recordings

Three ECG and two EMG channels were recorded at 1 kHz, using a wireless multichannel data acquisition system (Fig. 2) [12]. Baseline drift was suppressed by analogue high-pass filtering at 0.1 Hz. In addition, the EMG signals were digitally high-pass filtered at 20Hz to remove possible movement artifacts in the low-frequency region. The ECG was measured bipolarly and the textile electrodes were located on the chest.

Surface EMG signal was obtained from the right upper trapezius muscles using commercially available dry electrodes (Roessingh Research and Development, Enschede, The Netherlands), attached 20 mm apart to the T-shirt. Regular, pre-gelled Ag-AgCl electrodes (Medicotest, Ølstykke, Denmark), were placed 20 mm apart (center-to-center distance) next to the dry electrodes and used to obtain a traditional EMG to facilitate comparisons. The electrodes were attached at a point two-thirds of the distance from the spinous process of the seventh cervical vertebra (C7) to the lateral edge of the acromion. A large textile electrode located at the back was used as a reference electrode for both the dry and the regular pair of electrodes. A test contraction was made before measurement to secure good electrode-skin contact in both conditions.

In order to normalize the muscle activity to a well-defined effort, the subject stretching both arms at 90 degrees in the coronal plane was used as a reference contraction. The myoelectric activity recorded during a reference contraction is called RVE (reference voluntary electrically activation) and is assumed, in this case, to correspond to about 10% of the maximal voluntary contraction (MVC).

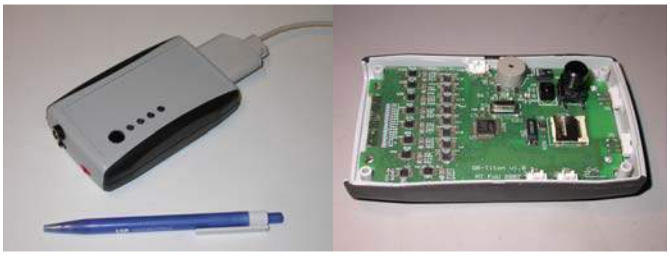

Fig. 2 Left photo: 8-channel Bluetooth acquisition prototype unit. Right photo: The modular-constructed acquisition unit containing, CPU, signal conditioner (incl. A/D converters), bluetooth (for real-time transmission) and memory-card (for possible logger functionality).

C. Data processing

1) ECG - Heart beat detection

The basic idea behind our multichannel approach is to design a filter where the output signal has distinct peaks corresponding to the time instants where the ECG QRS complexes occur, and are close to zero elsewhere. In that signal, most of the data points have an amplitude value close to zero and the peaks have a significantly larger value and occur as a marked tail in the histogram, i.e., has a super-gaussian distribution. The aim with the filter is to maximize the super-gaussianity of the output signal.

In order to maximize the super-gaussianity, an adaptive multichannel filter, which combines both spatial and temporal filtering was used [10]. The time filtering is performed using individual finite impulse response filters on each input channel i according to:

$$\mathbf{z_i} = \mathbf{h_i} * \mathbf{x_i} \qquad (1)$$

where $\mathbf{x}_i$ is the input signal and $\mathbf{h}_i = [h_{i1}\ h_{i2}\ ...\ h_{ip}]$ is the filter kernel.

With M input channels the spatial filtering is accomplished as

$$\mathbf{y} = g_1\,\mathbf{z_1} + g_2\,\mathbf{z_2} + ... + g_M\,\mathbf{z_M} \qquad (2)$$

Substitution of $g_i\mathbf{h}_i$ with $\mathbf{w}_i$ the filter equation yields:

$$\mathbf{y} = \mathbf{w_1} * \mathbf{x_1} + \mathbf{w_2} * \mathbf{x_2} + ... + \mathbf{w_M} * \mathbf{x_M} \qquad (3)$$

Obviously, the output signal $\mathbf{y}$ is a linear combination of time delayed input signals. The filter coefficients were determined adaptively for blocks of length N=3000 using FastICA, with skewness as cost function. The algorithm was stabilised, by high-pass filtering the input signals, to suppress base line drift. In addition, the signals were normalised to zero mean and unit variance. For more details see Wiklund et al. [10].

2) EMG - Exposure Variation Analysis

In order to quantify the EMG activity, an Exposure Variation Analysis (EVA) was performed as proposed by Mathiassen and Winkel [13]. The EMG signals was RMS filtered using a moving average window of 0.1 s, and normalized to the corresponding RVEs. The signal was then averaged in consecutive intervals of 1/3 s and categorised according to length of uninterrupted intervals spent in specific amplitude levels. The signals were categorised in periods of 0-0.3–1–3–7–15 s and amplitude levels of 0-1-3.3–10-23.3-50-103.3-210 % RVE. This resulted in a matrix where each element represented percent of time in a “period per amplitude category” (Fig. 3). The categories were logarithmically arranged in order to increase the sensitivity for variations at low amplitude levels with short period lengths. Plotting the EVA-matrix resulted in a three-dimensional representation of EMG activity, where each column represented percent of total time spent in each level per period category (Fig. 3).

Short, unconscious interruptions in EMG activity (i.e., EMG activity less than 0.5% MVC) are referred to as “gaps”. Further, interruptions lasting for 0.2-0.6 s as short gaps and interruptions lasting longer than 0.6 s as long gaps. In the EVA matrix, gap levels are therefore represented by the shadowed elements in the lowest amplitude level (0-1% RVE) that corresponds to periods of 0.3 s or longer (Fig. 3).

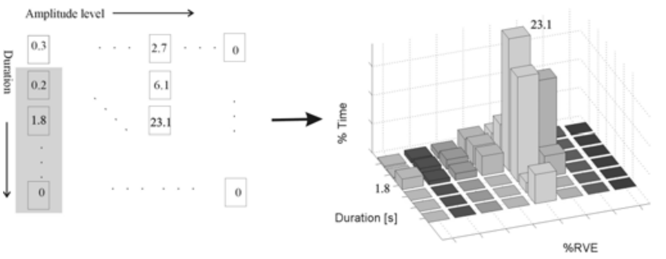

Fig. 3 Description of the Exposure Variation Analysis (EVA) matrix used in the analysis of the trapezius muscle activity pattern. Each element in the matrix represents percent of total time that the subject spent in a specified level per period category.

III. Results

Fig. 4 shows a typical part of one recording, where computer work was performed. In all measurements, the EMG signals recorded with the dry electrodes were similar (except for some spikes) to the EMG signals recorded with ordinary gelled Ag-AgCl electrodes.

An example of the EVA matrices of the two different tasks can be seen in Fig. 5 from one of the subjects. The results showed that, for this subject, the non-ergonomic working situation had higher muscle electrical activity and less variation as compared to the more ergonomic situation. The recorded EMG signals had sufficient quality for EVA analyses for all of the subjects.

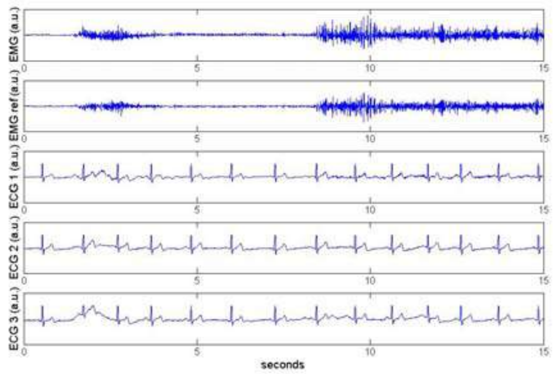

Fig. 4 Typical example of a recording. EMG muscle activity (from top: dry resp. gelled electrode) from right trapezius muscle and corresponding ECG activity during computer work.

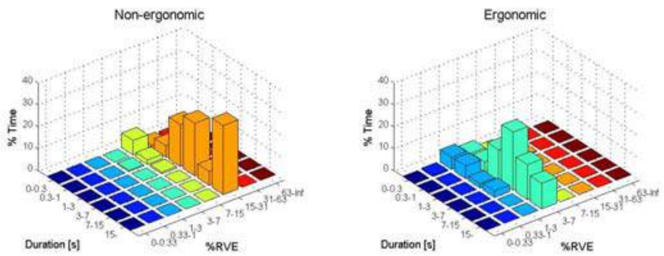

Fig. 5. EVA matrices from two different tasks, where one of the tasks was more ergonomic, see the method section for more details.

IV. Discussion and Conclusion

We have developed a prototype T-shirt housing textile electrodes that enables multi-channel recording of ECG (Fig. 1). Apart from the described T-shirt, the idea of a general solution incorporating both textile electrodes and data transfer has also been proved in a cardigan (Fig. 6) and a chest-band. During favourable conditions an ECG signal as depicted in Fig. 4 can be recorded, which allows for heart rate and heart rate variability analysis without adopting advanced signal processing methods. The multi-channel approach can be used during less favourable situations, e.g. when the subject is moving resulting in a bad, or even lost, signal from one or several of the ECG electrodes (Fig. 7).

The use of smart textile sensors integrated in clothing allow ECG and EMG recordings to be fully self-administered, i.e. independent of someone assisting to apply electrodes, which opens up a vast field of research and health monitoring possibilities.

Fig. 6 Prototype for ECG monitoring in home health care situations. ECG signals are registered using textile electrodes integrated in the left and right wristlet.

A. Methodological considerations

In textile electrode design there are three main problems to consider. The motion artefacts in textile structures add noise to the bio-signal. Textile electrodes are preferably used dry without conducting gel, which leads to a relative high impedance and that also affects the signal quality. Disturbances can also be generated by loss of signals from individual electrodes. Motion artefacts from the textile structures are decreased by using a stable textile structure, a woven structure for example gives less motion artefacts than a knitted [14]. Padded structures reduce high impedances since pressure on the electrode together with a sticky coating keep the electrodes in better contact with the skin.

At the time of writing no EMG signal has been recorded using textile electrodes. Monitoring of heart activity depend less on the exact position of the sensors, thus, the smart textile approach is better suited to ECG than EMG recordings. Our solution is to use a padded structure above the trapezius muscle housing commercially available dry electrodes [15]. Apart from the extra pressure on the EMG-electrodes provided by the padded structure resulting in an increased contact between electrode and skin, the padding also contributes to a better-defined recording position over the trapezius muscle.

B. ECG detection

Normally, ECG is recorded for arrhythmia analyses based on the heart rate and also for analysis of the morphology of the complexes. An ECG signal for detection of heart rate can be recorded from many positions of the trunk, which allows multiple channel recordings without demands on the actual location of each electrode However, the latter is crucial for determination of cardiac conduction disturbances and morphological changes after myocardial infarction.

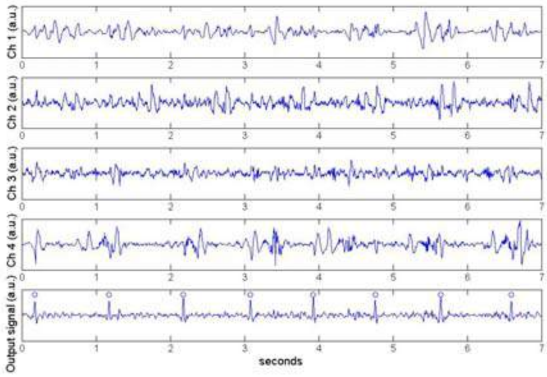

Fig. 7 Example of a noisy ECG recording and the result using the spatio-temporal filter. The bottom panel show the adaptive filtered ECG signal.

We have developed an advanced signal processing technique that allows us to monitor both heart rate and heart rate variability from multi-channel recordings where the signal in some channels may be disturbed or even missing (Fig. 7). This multi-channel approach addresses the above-mentioned difficulties with frequent disturbances that are inherent in smart textiles.

The T-shirt is more comfortable than today's traditional Holter systems, which makes it suitable for long term monitoring of heart rate, e.g. cardiac patients at the clinic or in the patients home. The system may also be used for real time monitoring of arrhythmias due to the robust heartbeat detection in ECG measurements.

C. EMG analysis

A possible limitation of our study concerns the reference contraction. Naturally, the choice of sub-maximal reference contraction will influence the position of the 3D EVA pattern along the amplitude axis, as the EMG data are normalised to the myoelectric activity (RVE) recorded during the chosen contraction. The aim of this study is to demonstrate the value of the signal recorded by means of dry electrodes housed in the prototype T-shirt rather than providing data to be considered in the evaluation of computer related tasks.

A possible extension of the EVA method is principal component analysis, PCA, can be used in order to classify the EMG activity pattern of the subjects at a group level. PCA involves a mathematical procedure that transforms a set of correlated response variables into a smaller set of uncorrelated variables called principal components. The first principal component accounts for as much of the variability in the data as possible and each succeeding component accounts for as much of the remaining variability as possible. For more information see Fjellman-Wiklund et al. [16].

D. Possibilities

The remarkable progress in mobile and ubiquitous computing as well as development of wearable products for clinical applications will break the limits inherent in current monitoring schemes. Wearable wireless devices that can intermittently or continuously process and monitor relevant physiological signals will provide new diagnostic and therapeutic avenues for patient care. In addition, real-time feedback to the patient can be used, either as a warning of impending medical emergency or state of concern, or as a monitoring aid during e.g. exercise. Taken together, these new possibilities represent a revolution in health care monitoring which has a vast potential to significantly decrease the number and length of hospitalisations.

E. Conclusion

Although further improvements are needed, our current experiences indicate that a smart textile T-shirt allowing long term recordings of heart and shoulder activity may be available to the research community in the near future. This would extend current possibilities in e.g. simultaneous long term monitoring of trapezius muscle activity and heart rate and heart rate variability, which is highly interesting in studies of e.g. musculoskeletal disorders in the neck and shoulder.

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