Clevertex

Development of a strategic Master Plan for the transformation of the traditional textile and clothing into a knowledge driven industrial sector by 2015.

Report on Intelligent Textiles

State of the art

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1 Introduction

The textile and clothing industry is facing a structural change taking place for decades. The relocation of production facilities to low-wage countries and increasing fierce of global competition characterise this situation. Nevertheless, the textile and clothing industry still presents one major industrial sector in Europe that employs about 2.2 million people in the EU-15 and remains one of the main players in textile exports and is therefore still of major importance for the social and economic welfare in Europe. The three main activities in this industry are clothing (46% of total production), home and interior textiles (32% of total production) and technical textiles (22% of total production).

To preserve its leading role in the global market place the focus is increasingly directed on creative fashion design, quality, innovation and re-organisation in manufacturing as well as vertical integration and consumer brand building. The removal of import quotas in 2005 for textile products due to the liberalisation of industrial nation's markets enhances the necessity of the industry to differentiate itself even more.

Differentiation is possible by specialising on the products' quality and functionality as well as on the flexibility and quick response of the services rather than on the price alone. The necessary precondition to achieve this goal is the deployment of the latest research results and active research in intelligent textiles, a field ranging from materials science, textile engineering, chemistry, electronics and informatics by a highly qualified workforce. It will further require applied research at different levels, namely long, mid and short term, to transfer the technology to companies which must adapt the knowledge and consequently bring new and value-added products to the market.

The trend towards differentiation is additionally supported by the constant decline of consumer income spent on clothing and on textiles for home decoration. Consumers' preferences gained in the field of health care, well-being and sports activities as well as performance and protective equipment which resulted in increasing profits of clothing sectors like outdoor and sports wear, protective clothing and work wear. Many new enterprises specialising in niche markets in the field of innovative and functionalised textiles and clothing came up in the last years. They achieve competitiveness by exploiting the opportunities of new and innovative materials and non-conventional textile applications [1].

This project aims at contributing to the economic and social progress of the European Union, in particular the textile and clothing sector, by identifying areas of research in intelligent textiles that can have a direct and positive impact on the health and living conditions of European citizens.

Against this background, the present report aims at giving an overview on the state of the art of intelligent textiles worldwide. Research projects, which have been completed or are currently going on, and the products that have already been commercialised on the market are identified and pointed out. As the scale of the report is limited, it is neither possible to make acknowledgement to all the work that has been done in either developing or using textile products and which is listed in the database, nor to go to any depth. We hope that the drawing together of even this limited amount of material will be of some use and hence we hope that the report will provide an opportunity to set a direction for future research and technological development and to determine the priorities of research and product development plans in research organisations, industry and policy decision makers.

In order to present an overview to which extent these principles are already applied in the textile and clothing sector, three product groups will be considered: clothing, interior textiles and technical textiles.

1.1 Background

We are living in a knowledge driven society that is facing an increasing impact of science and technology on all aspects of life through products and services, and consumer needs. The field of smart textiles is not yet a discrete area; it is more an interdisciplinary subject incorporating science, technology, design and human sciences, and its future lies in the potential of combining different technologies. The convergence of textiles and electronics can be exemplarily pointed out for the development of such an intelligent material that is capable of accomplishing a wide spectrum of functions, found in rigid and inflexible electronic products today. Intelligent textiles will serve as a mean to increase the well-being of society and they might lead to important savings on the health budget. Moreover, they will increase consumption, as they are not only a high value product, but an immaterial concept that satisfies the consumer needs and demands such as creativity and emotional fulfilment.

Consequently, the CLEVERTEX project aims at contributing to the economic and social progress in the European Union. Identifying areas of research in intelligent textiles at the earliest possible stage may have a direct and positive impact on society. Within the scope of the project, a comprehensive roadmap will be realised that provides a valuable tool for direction-setting in future research and technological development in the field of smart textiles. Thus, it will provide a plan for transforming the European textile industry in a knowledge driven, competitive and sustainable sector.

1.2 Definition

To describe the state of the art in intelligent textiles, a general definition of what is understood by "intelligent" textiles is presupposed. There is no precise definition of the term "intelligent" or "smart" with reference to textiles. However, in the following we are trying to approach the term in scope of the aforementioned material.

The essence of intelligence is being able to sense the surrounding and to react upon it.

Intelligent or smart materials are hence able to react upon stimuli from the surrounding.

These stimulating factors can be of various origins, like temperature, light, humidity, electricity, force, pressure, mechanics, chemicals or magnetism.

The concept of intelligent materials was first defined in Japan in 1989. In the U.S. this kind of materials are called Smart Materials. The discovery of shape memory materials in the 1960s and intelligent polymeric gels in the 1970s were however generally accepted as the birth of smart/intelligent materials.

Shape memory silk yarn was introduced as the first smart textile in Japan in 1979.

It was not before the late nineties that the concept of intelligent textiles was commonly known in the textile industry. There have been technical textiles, functional textiles and now a new discipline, intelligent textiles, has arisen.

According to the manner of reaction, intelligent textile materials can be classified into three categories: passive smart, active smart and very smart.

Passive smart materials can only sense their environment or external stimuli, they are sensors.

Active smart materials sense stimuli from the environment and react to them; they are sensors and actuators. Very smart materials sense, react and adapt their behaviour to the given circumstances [2].

In principle, a smart textile is the integration of sensors, actuators, computing, such as data transmission and processing, and power sources into the textile, the whole being part of an interactive communication network. It is not of necessity for a textile to contain all these five functions.

The change in environmental conditions will cause the material to change instantaneously in form, colour or structure.

Sometimes, the change in the material is clearly visible, but sometimes it also takes place on a molecular level, completely invisible to the human eye.

These smart materials are incorporated into the textile structure by different technologies. Among those are spinning, extruding, weaving, knitting, making a non woven, braiding, embroidering, sewing, coating, finishing, laminating and printing. The resulting intelligent textile will have self-regulating properties on the basis of changes that occur in its surrounding [3].

A search to the first intelligent textile material could lead us all the way back to 1929. The research of March and co-workers studied the crease recovery of cellulose fabrics in wet and dry state.
One of the first examples considered as an intelligent textile is GORETEX[1]. It was developed about twenty years ago. The fabric is a breathing membrane exuding sweat without admitting the rain to get in. In a strict sense, it is not a smart material as its properties do not change under the influence of the surroundings. It can better be classified as a functional textile, its function being the breathability [3].

A study about intelligent textiles is in a first stage reduced to a study about smart materials.
In a second phase, it is to be considered in which way these smart materials can be processed into a textile material.
A textile material is traditionally a woven fabric, a knitted fabric, a braided fabric or a non-woven. The building stones of the textile material are fibres, which can be further developed into yarns or filaments. Innumerable combinations of these source materials result into a whole range of textile materials. Each of these materials already has a number of properties, such as:

- dimensions : length – width – thickness
- transformability
- permeability
- absorptive power
- stiffness
- tensile strength
- ...

It is clear that the intelligent character of the textile material can be introduced on different levels.
It can occur on fibre level, a coating can be applied, other yarns can be added to the textile material, and it is even possible to closely connect completely independent appliances with the textile.
As mentioned before, three components may be present. Sensors provide a nerve system to detect signals, thus in a passive smart material, the existence of sensors is essential. The actuators act upon the detected signal either directly or from a central control unit; together with the sensors, they are the essential element for active smart materials. At even higher level, like very smart materials, another kind of unit is essential, which works like a brain, with cognition, reasoning and activating capacities.

[1] **GORE-TEX** is a membrane from polytetrafluoroethylene (PTFE) with a very small pore size. This prevents water droplets, which are 20.000 times bigger than the pores, from penetrating into the membrane whereas vapour molecules exuded by a transpiring body can migrate through the pores.

Such textile materials and structures are becoming possible as the result of a successful marriage of traditional textiles/clothing technology with material science, structural mechanics, sensor and actuator technology, biology, electronics, etc.

Advances in all these technologies, coupled with advances in textile materials and structures results in a conversion of traditional passive clothing into active textile systems that increase situational awareness, communication, information, and more general overall performance [3].

2 Technologies

2.1 Conductive materials

2.1.1 Description

Since a long time the textile industry uses metallic yarn in weaving and knitting for aesthetic and decorative purposes. The first known conductive fabric was Silk organza, which consisted of two types of fibres: a plain silk thread running in the warp direction and the weft threads which are made of silk thread wrapped in thin copper foil. This metal yarn is highly conductive; the silk core provides high tensile strength and withstands high temperatures. This kind of cloth has been woven in India for the last century utilising also silver, gold and other metals for ornaments and embroidery.

In the 1920s and 1930s metallic threads were also used for ecclesiastical and courtly robes to give them to appearance of ‘golden clothes’. In the 1950s, Lurex, made from a thin strip of aluminium, entered the market that could be varied with a number of conventional fibres to create metallic fabrics, which were highly demanded at that time. The company Jakob Schlaepfer Co. AG in Switzerland created fabrics composed of silk and steel threads for fashion and interior applications in the middle of the 1990s [4, 5].

Another example for malleable and aesthetic fabrics is the ‘copper cloth’ designed by Reiko Sudo of Nuno Corporation that can be formed into complex and subtle shapes. The designer was inspired by a car industry process when a protective finish of stainless steel is finely sprayed underneath the car [5, 6].

However, let’s now turn away from aesthetic purpose of metallic threads in clothing and take a look at the functional aspects that metallic thread can fulfil. Since few years research goes into manufacturing conductive material for functional purposes in smart textiles. In textiles the mainly used metals are aluminium, copper and stainless steel due to lower costs compared with the more expensive materials like titanium, silver and gold [7].

Besides metal fibres and yarns also other types of materials are used, for instance conductive polymers, coatings and inks. In the following section a range of conductive materials are depicted and explained.

2.1.2 Technology

Initially, conductive materials were mainly used in technical areas. Textile structures that exhibit conductivity or serve an electronic or computational function are called electrotextiles [8]. They can have a variety of functions, like antistatic applications, electromagnetic shielding (EMI), electronic applications, infrared absorption or protective clothing in explosive areas.

Electronics may be integrated into textiles using electro-conductive fibres/threads, which can be then processed, e.g. by weaving, knitting or braiding, into a textile structure mostly in combination with conventional textile threads. Especially for clothing, tactile properties such as stretch, recovery, drape, shear and handle are important properties. For this reason fibres that are used should be fine and fabrics should have a low weight per unit area (usually not more than $300 g/m^2$). These demands are inconsistent with the materials and geometries that are needed for an electrical conductivity, because the incorporation of elements such as metal wires within textiles increases stiffness and reduces elasticity. Whilst this may applicable in outer garments like jackets, it would impact the wearing comfort in garments close to the body such as underwear or shirts. In the longer term, an integration of electrical devices with the textile substrate is desired. Both, connections between components and interfaces are likely to be based on textile transmitters using modified textiles, such as fibres and yarns or the application of coatings and prints.

Until now, there is still a lack of norms specifying or characterising a metal fibre, its production process and application areas. Thus, often in literature no distinction is made between metal wires and metal fibres. However, the company Sprint Metal defined metal fibres and wires according to their diameter. While a fine wire has a diameter between 30µm to 1.4mm, a metal fibre possesses a diameter of 2 to 40µm [9].

On the contrary, the Belgian company Bekaert Fibre Technologies defined metal fibres as very thin metal filaments with diameters ranging from 1 to 80µm [10]. Comparing solely these two definitions, it gets obvious that an overall valid definition is needed to avoid confusion and misunderstandings.

Besides its diameter, a metal fibre may also be defined according to its production process. In the following a short overview of the possibilities to achieve in electro conductive fibres is presented [11].

2.1.2.1 *Electro-conductive fibres*

Electro conductive fibres have already been used for years in various industrial applications for the purpose of controlling static and electromagnetic interference shielding. Today, conductive fibres find new applications in the development of electronics and smart textiles. They can be classified into two general categories, namely intrinsically conductive fibres and fibres that are specially treated to gain conductivity. Different production methods are used to produce electro conductive fibres, among them are wire drawing, bundled wire drawing, cutting production method, melt spinning and melt extraction.

Intrinsically conductive fibres

These fibres are pure metals, such as nickel, stainless steel, titanium, aluminium and copper, a metal alloy or carbon. Recently, also the development of intrinsically conductive polymer fibres has been reported, which is described at the end of this paragraph. In general, intrinsically conductive fibres conductors without adding a conductive substance.

The conventional process to produce metal fibres is wire drawing, a mechanical production process.
This process is characterised by its various drawing steps, called coarse, medium, fine and carding train. The drawing die, used to draw the fibre, consists of a steel mount with a core out of ceramics, carbide or diamond. The initial diameter of the metal wire varies depending on the material. For copper, for instance, it is usually is 8mm, while for iron it is 5mm. After drawing, the wire is annealed in steel at temperatures ranging between 600 and 900°C. Subsequently, they are quenched. The fine metal wire is then wrapped onto a revolving wire drawing cylinder.
The wires produced in this way are used today in metal spun yarns which are produced by wrapping the wire around a core yarn or are used to be processed further, e.g. by the bundling drawing process that is briefly described below [12].

Another mechanical metal fibre production process is the bundle drawing procedure. In this process 1000 to 2000 conventional drawn wires are bundled to one strand and are wrapped by a thin metal cylinder. The method is illustrated in Fig.1.

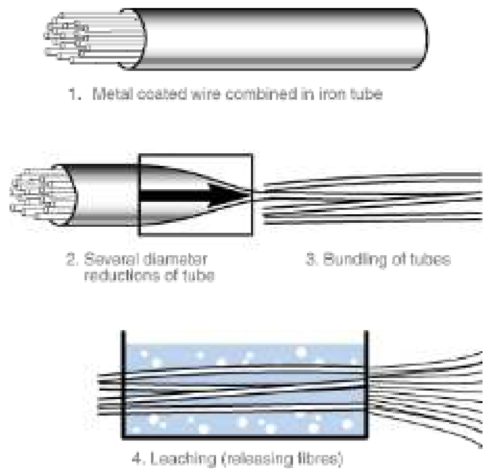


Fig. 1 Diagram of the bundle drawing procedure [10]

The thin cylinder is used to enable further drawing of the whole bundle, because the drawing of a single wire would lead to wire breakage. As the cylinder material is chemically less stable than the wires, is can be removed by dissolving the whole system in an acidic bath. Finally, the process results in individual and parallel fibres of adjustable diameter between 4 to 25µm. These can afterwards be spun to multifilament or broken into staple fibres with a length of 50 to 150mm [10, 12].
The company Bekaert Fibre Technologies credits a U.S. patent with the description of the bundle drawing production process of metal fibres. Their product range includes BEKINOX® VS, a 100% metal fibre in silver form or bulk, and BEKINOX® VN out of 100% stainless steel that can be applied in antistatic textiles, for signal and power transfer, cut resistant fabrics, heat resistant sewing and thermal conductivity. Therefore, the yarn is suitable to be applied in the sector of protective clothing but also in fashion for the metal look [13].

Besides using the bundle drawing procedure, Bekaert also produces metal fibres by shaving them endlessly off the edge of a rolled metal foil, as shown in Fig.2.

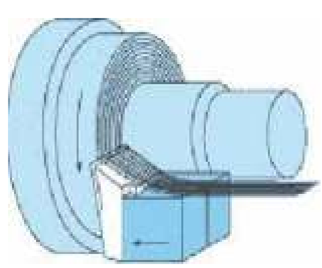


Fig. 2 Fibre production using the shaving process [10]

With this process it is possible to obtain several fibres per cutting section. Subsequently, the metal fibres are bundled into fibre skeins and spooled onto a roll.

These fibres are branded under the name Bekinit®. In contrast to bundle-drawn fibres, Bekinit fibres® have a rectangular cross section. Additionally, they are thicker, compose of more crimp and are less expensive due to a shorter production process time. It has to be noted that the bundle-drawing process takes approximately six months [10].

Metal fibres may also be produced by thermal methods based on processing the fibres through direct extrusion from the melt. The challenge of metal melt spinning compared to melt spinning of glass or polymers is that the melt viscosity of metals is approximately 100 times lower than of glass and polymers. Thus, it might occur that melt fracture easily arises and instead of fibres only droplets are formed. In the following, we refer to some methods for metal fibre production by using a coagulation bath.

In the Taylor process a metal rod is utilised, which is put into a glass tube. Both, the material and the glass tube, need to possess a comparable melting point to draw them at the same time. When heating the whole system, the metal rod melts and the glass tube gets soft. In this state, the glass tube can be drawn and forms a very thin hollow glass thread, with the metal as a filler material. The glass casing is afterwards removed from the metal either by crushing with a roller, or by ultrasound or chemical separation and the result is a very fine metal fibre (diameter < 50µm).

Continuous production of metallic fibres is achieved by melt spinning in a rotating fluid. During this process, metals or their alloys are molten and overheated in a gas atmosphere at high temperature and pressure. The liquid surface is charged with an inert gas excess pressure. Due to the high pressure, the melt can be pressed through a nozzle. Having been pressed through the nozzle, the fibre is submerged as a free jet at a defined angle in a laminar flowing cooling agent. The solidifying fibre is accelerated through the rotation and through the density difference between the metal and the cooling agent at the inside of the drum, where it cools down to the temperature of the cooling agent. Extraction takes place either continuously or discontinuously depending on the batch size.

A further possibility to result in melt spun metal fibres is the usage of the melt extraction process. In this procedure, a water-cooled extraction roller rotates in the melt batch. The roller is usually a multiple blade with v-shaped edges with which the mass is solidified and short fibres are pulled out. A magnetic field is created at top of the melt batch to prevent waves occurring at the melt's surface. With this procedure, it is possible to process materials like aluminium and tin fibres that cannot be produced by conventional methods due to their brittleness.

The advantages of metal fibres are their strength, biological inertness and ready availability in textile form at low costs. Due to its inertness it is not sensitive to washing or sweating.

However, they cannot provide uniform heating and their brittle characteristics can damage spinning machinery over time. Additionally, they are heavier than most textile fibres making homogeneous blends difficult to produce [10].

It is a common method to blend metal fibres or wires with conventional fibres and thus result in a conductive yarn. In the following, some producers of such yarns and their commercially available yarns are pointed out.

As mentioned before, Bekaert is a company specialised in the production of metal fibres for technical applications. They introduced a Polyester spun yarn with 20% Bekinox® stainless steel fibres under the brand name Bektex BK® to the market. This yarn may be used to gain antistatic or heating properties in textiles, which is important, for instance, for conveyer belts, Flexible Intermediate Bulk Containers or woven filter cloth. Additionally, it can be used in the field of signal transfer and electro-magnetic shielding.
The Belgian company also commercialised Bekinox® PES yarn which is a blended yarn containing 50% Polyester fibres and 50% Bekinox® stainless steel fibres [10].

The Swiss company Elektrisola Feindraht AG produces metal monofilaments that can be blended with all sorts of fibres or that can be directly used in weaving and knitting. The products range from copper (Cu) and silver-plated copper (Cu/Ag) filaments, brass (Ms) and silver-plated brass (Ms/Ag) filaments, aluminium (Al) filaments to copper-clad aluminium (CCA) filaments [14].

The company Swiss-Shield® is specialised in producing metal monofilaments which are incorporated into base yarns like cotton, polyester, polyamides and aramides. The metal monofilaments are made out of copper, brass, bronze, silver, gold, aluminium, for instance.
The following picture shows a typical conductive yarn with base fibres and a metal monofilament twisted around them [15].

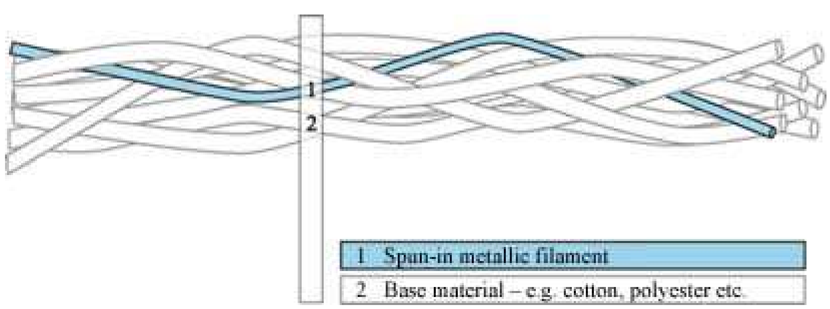


Fig. 3 Conductive yarn by Swiss-Shield

Next to metal fibres or wires, also carbon fibres can be incorporated into conventional fibres. Another method additionally is to produce hollow Nylon or polyester fibres and fill them with carbon.
As an example the No-Shock™ fibre by the company Monsanto can be pointed out. It is a nylon fibre having an integrated carbon-filled stripe comprising 2% of the polymer. Further, the company offers staple fibres, available in finenesses of 6 or 12 den, which can be cut depending on the specification [16].

As mentioned before, there are also intrinsically conductive polymeric fibres existing. A research group at the Intelligent Polymer Research Institute, University of Wollongong, in Australia succeeded in synthesise organic conducting fibres. Via wet spinning they produced fibres out of Polyaniline and carbon nanotube dispersion.

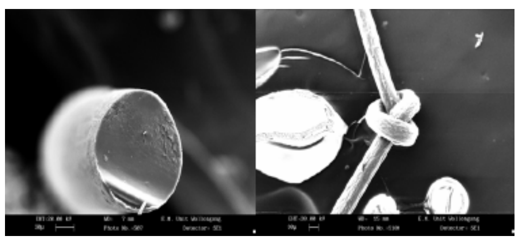


Fig. 4 PANi-CNT fibre viewed with scanning electron microscope [17]

Due to their high conductivity, the fibres can be possibly used as light weight wearable batteries or as artificial muscles in a rehabilitation glove.

Specially treated conductive fibres

Electrically conductive fibres can also be produced by coating the fibres with metals, galvanic substances or metallic salts. The advantage of coatings is that they are suitable for many fibre types and they produce good conductivity without significantly altering existing substrate properties such as density, flexibility and handle. Coatings can be applied to the surface of fibres, yarns, or even fabrics to create electrically conductive textiles. Nevertheless adhesion between the metal and the fibre as well corrosion resistance can lead to problems.
Common textile coating processes include electroless plating, evaporative deposition, sputtering, and coating the textile with a conductive polymer.

The Textile Research Institute of Thuringia-Vogtland (TITV) succeeded in producing conductive threads by coating a conventional yarn with metal layers, called ELITEX®. They used Shieldex Nylon 66 threads that are coated with a thin silver layer as base material. With a specific conductivity of about 1.2 10^3 Scm^{-1}, the threads have a specific resistance of about 8.34 Ohm mm^2 per metre. Hence, the resistivity is too low to conduct current.
Therefore, researchers at the institute modified these fibres with a galvanic and electrochemical after-treatment. They additionally coated the fibres with gold, platinum, copper and silver. With these modified and fortified metal layers it is possible to use the threads as material for conductors, sensors and actuators [18, 19].

The Swiss company Swicofil AG Textile Services is specialised in producing and commercialising aluminium metallised Nylon, polyester, acetate or cotton yarns, or a combination of those. In a first step of the coating process aluminium metallised polyester film is lacquered with protective epoxy resin to keep a shiny looking metallised surface. In order to achieve different colours, appropriated quantities of metal complex dyestuffs are mixed with the resin. Subsequently, the protective lacquered film is cut into small "pancakes". A "pancake" role is slit into various sizes while a film passes through a cutting head and is wound on a spool. In a final step, this metallic yarn is twisted, covered or supported with conventional yarn [20].

DuPont also produces metal coated fibres, commercialised under the tradename ARACON®. ARACON® fibres are based on the same technology that created DuPont KEVLAR®, a high-strength para-aramid fibre. With the addition of nickel, copper and silver coatings of varying thicknesses, these fibres provide a versatile combination of physical and electrical properties for a variety of applications. The fibres are one of the conductive fibres used in the SmartShirt (see chapter 2.1.4.3). Lately, DuPont has sold its ARACON® technology to Micro-Croax Corp..

The company Syscom Technology, Inc., introduced a high-strength and high-modulus Zylon fibre coated with a metal under the brandname AmberStrand™ to the market [21].

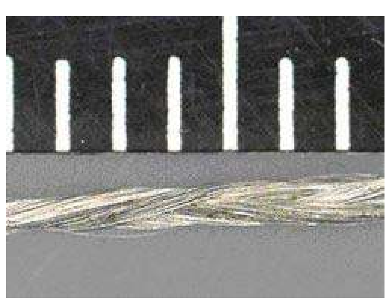


Fig. 5 Sample of AmberStrand™ conductive coated yarn consisting of 3 strands under a millimeter scale [21]

X-Static™ by Sauquoit Industries is a nylon filament that has been permanently plated with silver through an aqueous bath. Staple fibres in 3.8, 5.5 or 8.25 dtex are offered in lengths suitable for blending with wool. X-Static™ continuous filament products are also available [22].

Thunderon™ (Nihon Sanmo Dyeing Co) fibres have a conductive layer of copper sulphide. The base fibre may be acrylic or nylon. Thunderon™ acrylic fibre is available for blending with wool 3 denier 76 mm, 5 denier variable cut, 7 denier 76 mm or 7 denier 102 mm staple. A range of pre-dyed colours is offered. A finer fibre is used in fine spun yarns and filament acrylic is also available. Thunderon™ nylon is available as flat or textured filament nylon. Thunderon Super™ is acrylic filament, acrylic spun yarn, or glass filament with higher conductivity than Thunderon™ [23].

Despite metal coatings, it is also possible to produce carbon microfibres that can be processed into a conductive film.
Mitsubishi Materials Corp of Tokyo, Japan and Hyperion Catalysis International Inc of Cambridge, Massachusetts, U.S., have developed such a hollow carbon microfibre, which can be processed into a transparent electrically conductive film. Carbon fibres are made by thermal treatment of polymers such as rayon, PAN (polyacrylonitrile) and aromatic aramides. As only a very small number of microfibres per surface unit is needed, one has succeeded in keeping the film transparent. The suspension, into which the microfibres are dispersed, can be coated on a substrate. When the film has dried, a transparent electrically conductive coating is obtained [24].

2.1.2.2 Conductive fabrics

There are different ways to produce electrically conductive fabrics. One method is to integrate conductive yarns in a textile structure, e.g. by weaving. However, the integration of conductive yarns in a structure is a complex and seldom a uniform process as it needs to be ensured that the electrically conductive fabric is comfortable to wear or soft in touch rather than hard and rigid. However, on the other hand, woven fabric structures, for instance, can provide a complex network that can be used as elaborated electrical circuits with numerous electrically conducting and non-conducting constituents, and be structured to have multiple layers and spaces to accommodate electronic devices. Some examples of woven conductive fabrics are listed below.

Researchers at the Electronics Department and the Wearable Computing Laboratory at the ETH in Zürich produced a plain woven textile structure consisting of polyester yarns that are twisted with one copper thread.

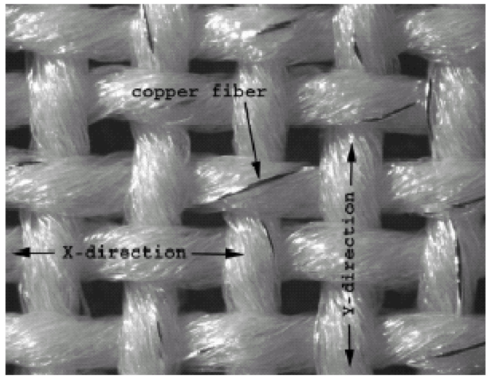


Fig. 6 Woven fabric with metal yarns [25]

They examined different woven fabric structures to be used as textile transmission lines in wearable computing applications. They altered the structure by inserting the copper fibre either in one or two directions and by different yarn finenesses [25].

Bekitherm® by Bekaert Fibre Technologies is a woven fabric, a knitted fabric or a needle felt consisting of 100 % metal fibres or of a mixture of metal fibres and a natural or a synthetic fibre. It is used in the production process of complex glass forms (car windows, bottles, TV tubes) and saucepans from stainless steel. It is also incorporated in plane engines to protect components against the heat and the vibrations of the engine block [10].

The Danish company Chr. Dalsgaard Project Development ApS works with the development of weaving electronics into fabrics, electronic conductors in clothing, operating panels in textiles (soft keyboards, displays etc.) and micro-sensors. The company serves predominantly knowledge in the field of electronic textiles and works through joint ventures with textile companies. They developed, for instance, conductive ribbons for different purposes, such as loudspeakers and microphones. The conductive yarn they use is a copper thread, plated with a silver layer and coated with polyester [26].

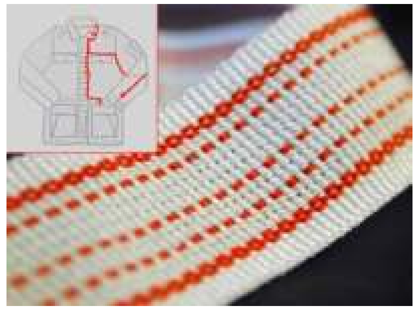


Fig. 7 Conductive ribbon sample that can be integrated into a jacket [27]

The British company Baltex uses the knitting technology to incorporate metal wires in textile structures. Their fabrics, which they market under the name Feratec®, can be used mainly for two purposes, namely heatable textiles and electro-magnetic shielding materials [28].

However, textile fabrics cannot only be made electrically conductive by incorporating electro-conductive fibres, but also by treating the surface of a fabric, for instance by apply a conductive layer, by carbonising the surface or by polymerising a polyester fabric with pyrrole [12].

The Spanish company Carbongen offers activated carbon fabrics. Their starting material is a viscose fabric which they carbonise and activate by a heat treatment under oxidative atmosphere [29].

The American company Thremshield LLC produces metallised woven nylon fabrics in different shapes and profiles. The metals they use are silver, copper or a combination of copper and nickel [30].

Gorix Limited of Southport, UK, uses the carbonising process to develop electrically conductive textiles that provide constant heat at low voltages. The carbonising process involves processing the textile in a carbonization furnace at 1000°C to create an electrically conductive textile. The resulting carbon textile is encapsulated by a reflector and moisture wicking layer, for durability and user comfort. The textile is then connected to a power source (power pack or battery). As low voltage current is passed through, the fabric is warmed according to changes in resistivity with temperature allowing the simple circuitry to be used to control the temperature within 0.5°C. Gorix is a non-flammable textile that will not melt or react with water. Presently, the company is developing outlets for its Gorix fabrics in Europe and the United States [31].

At the University of Pisa, polypyrrole treated fabrics are used for monitoring body kinematics and analysing posture and gesture [32]. In this application sensors are realised starting from conventional textile fibres or fabrics coated with a very thin layer of a conducting polymer. Because of its elasticity, ergonomic comfort, and high piëzoresistive coefficients, a combination of polypyrrole (PPy) as conducting polymer and Lycra® as fabric, are used.

Further, a research group at the Intelligent Polymer Research Institute at the University of Wollongong, Australia, uses intrinsically conductive polymers to coat textile structures. With the use of conventional textile dyeing equipment they coat textiles with PMAS (Poly(2-methoxyaniline-5-sulfonic acid)), a water-soluble and commercially available polymer. However, the moderate resistivity restricts the range of possible applications [33].

Another possibility to achieve in a conductive fabric is to attach a conductive structure to a ground structure by using the embroidery technique. In 2000, the Massachusetts Institute of Technology Media Laboratory proposed a way of stitching patterns that can define circuit traces, component connection pads, or sensing surfaces designed with traditional CAD tools for circuit layout and rendered on numerically controlled embroidery machines using conducting and insulating threads, named e-broidery. That allows precisely specifying the circuit layout and stitching pattern in a computer-aided design (CAD) environment, from which any number of articles can be sewn under machine control. This process also allows control and integration of yarns with different electrical properties, for instance, different resistances.

Embroidery offers advantages over knitting or weaving. Conductive thread and yarn embroidery can be accomplished on single or multiple layers of fabric or can be applied on various types of textile and apparel products in one step. An example for an embroidered fabric keypad used for a Musical jacket is given in chapter 2.1.4.1 [11, 34].

Other existing techniques to embed electric circuitry in a fabric include soldering surface-mount components directly onto metallic organza, bonding components to a substrate using conductive adhesives, stapling components into a conductive stitched circuit (i.e., pressure-forming their leads to grip circuit pads), joining a component's “threadframe” directly to a stitched fabric circuit (where components are formed with a single conductive thread) [34].

Interactive electronic textiles can also be produced by using conductive inks. Conductive inks are produced by adding metals such as copper, nickel and gold to traditional printing inks. These specialised inks can be printed onto various materials, among them textiles, to creative electrically active patterns. The conductive ink technology was originally developed for the production of smart cards or printed circuit boards, used for example for computer applications, communication, automotive and industrial electronics. Generally, a distinction can be made between rigid and flexible printed circuit boards. We will only consider the latter case in this report. The demand for flexible circuit technology is increasing as electronic and telecommunication devices are becoming more and more compact and lightweight. Next to bending capabilities of 360°, flexible circuitry offers reduced circuit sizes. Further, the use of conductive inks for flexible printed circuits has increased in popularity because they have a substantial price advantage over other plating methods.

The National Textile Center of the North Carolina State University is currently working on a project dealing with 'Printing Electric Circuits on Non-Woven Fabrics' used to produce a prototype for a physiological monitoring garment that measures ECG, heart-rate, respiration and temperature. In the scope of the project they work together with conductive ink manufacturers. For their experimental investigations and to succeed in producing samples of antennas having been printed on non-woven textile structures, they use Evolon® by Freudenberg KG, Tyvek® by DuPont™, FiberWeb Resolution™ Print Media by BBA FiberWeb™, as well as conductive inks donated by Precisia LLC and Creative Materials Inc.[35].

2.1.3 Enabling technologies

The different technologies discussed previously are used to produce textile materials with the ability to conduct electricity. Components including input and output devices, sensors, data processing devices, data storage devices and power supplies provide necessary technologies for interaction, hence creating an electronic textile.

Input devices including keyboards and switches are two examples beings explored for interactive electronic textile data entry.

The output devices being explored for displaying data include Cathode Ray Tubes (CRT's) and Liquid Crystal Displays (LCD's), but also mirror displays and flexible light emitting displays. An overview of textile displays and research work being done in this field is discussed in chapter *2.3* [36].

2.1.3.1 Conductive materials as sensors

Sensors add features and functionality to electronic textiles. Conductive textiles that change their electrical properties as a result of environmental impact can be used as sensors. Typical examples are textiles that react to deformation such as pressure sensors, stretch sensors and breathing sensors.

2.1.3.1.1 Pressure sensors

Pressure sensors are commonly used either to monitor vital signs of the user, such as heart rate, blood pressure or the user's motion, or also to use them as switches and interfaces to control mp3players and mobile phones. They have been developed and are marketed for instance by Canesis Ltd., Eleksen Limited, Logitech Inc., Pressure Profile Systems Inc. and Intelligent Textiles Ltd..

The New Zealand-based textile research and development organisation WRONZ and an electronic materials company Peratech Ltd of Darlington, County Durham, UK have jointly developed Softswitch™ technology [37].

Peratech has produced a range of elastoresistive polymers with a unique and diverse set of electronic properties. The material is described as a “variable resistive” quantum tunnelling composite, providing proportional control of an electronic device in addition to simple on/off switching. This means that with a touch of a finger the material can change from an insulator to a metallic-like conductor. The resistance can be reduced from hundreds of millions of ohms to less than one ohm under finger pressure. In 2004, Canesis Ltd. has taken control of the Softswitch™ technology.

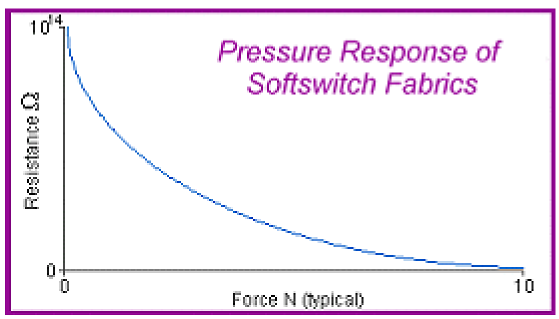


Fig. 8 Pressure response of Softswitch fabrics [37]

The Softswitch™ technology has a lot of possible applications, such as pressure sensing, switching and interfacing. SOFTswitch™ enables the portability and softening of traditionally large hard plastic devices. In use, they retain the benefits of textiles as they are washable, handleable, durable and mouldable to 3D forms. At the same time, they also provide the functionality of electronic controls – such as enabling a snowboarder to control an iPod from her sleeve or a doctor to identify when and where a bed-ridden patient is in danger of developing a pressure sore [37].

For example Burton used the SOFTswitch™ technology to commercialise a jacket with an integrated Sony mini disc player in the sleeve. The mini disc player is sewn inside the pocket of the jacket; no wires are needed, instead it is the material that delivers the signal needed to change the track or regulate the volume. More example and application fields of the SOFTswitch™ fabrics are discussed in the following chapters.

Fig. 9 SOFTswitch™ fabric integrated in the sleeve of a jacket [37]

Wronz is also looking at the possibility of adding the polymer at the yarn stage to build electro-mechanical fabric sensors.

The British company Eleksen Limited, formerly Electrotextiles, commercialises a soft and flexible textile based sensory fabric under the tradename ElekTex® Smart Fabric Interfaces [38]. It is a combination of conductive fibres and nylon. This combination results into a durable, reasonably priced, washable and even wearable 3D structure. The principal applications are focussed on XY positioning and pressure measurements. The point where pressure is being exercised on the fabric can be localised by means of this XY positioning. This technology is already applied to make “soft” telephones and a folding keyboard. For instance, the smart fabric touchpad controller can be integrated into bags or backpacks for cellular phones and iPods. The fabric is capable to remote music control functions, e.g. the volume. The ElekTex® scroll volume control touchpad consists of a control sensor, an electronic interface box and a stereo output connector.
Additionally, the ElekTex® fabric is also used in the development of car seats, with the aim of having an optimal weight distribution in order to increase the seating comfort.

Fig. 10 Products manufactured from Elektex™ [38]

The American-based company Logitech Inc. manufactures a soft-touch KeyCase^{TM} keyboard that can wrap around a personal digital assistant (PDA) for storage and protection. The keyboard is lightweight and made out of textile. There is no more use of stylus as the keyboard puts the most popular editing functions at the fingertips and one-touch keys give the user instant access to his/her most used applications. The pressure-sensitive scroller enables quick navigation [39].

Fig. 11 Soft-touch KeyCaseTM by Logitech [39]

The U.S. company Pressure Profile Systems, Inc. designs, develops and manufactures high performance multi-element pressure and tactile sensing systems, called Tactarray and ConTacts.

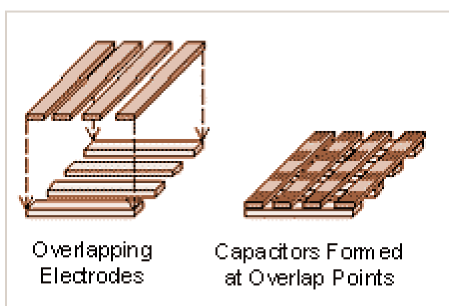


Fig. 12 PPS sensor design

TactArray and PresStrip sensors use overlapping electrodes to form arrays of sensing elements. Elements are formed at each point where a Drive strip overlaps a Sense strip. By selectively measuring the capacitance between a particular Drive and Sense electrode, our proprietary electronics can scan through an array of sensing elements at high speed [40].

The team of the Design for Life Centre at Brunel University in Surrey has developed a fabric (the Sensory Fabric) that can be used by handicapped children to make themselves understood. It should be noted here, that the researchers of the Centre, Stan Swallow and Asha Peta Thompson, lately made up their own company, named Intelligent Textiles Ltd. [41].
This momentary push switch comprises electrically conductive fabrics as outer sheets and a non-conductive mesh sandwiched between the outer layers to separate the two conductors from each other. When pressure is applied to the top conductive sheet, it is pushed through the holes of the mesh resulting in an electrical contact with the lower conductive fabric.

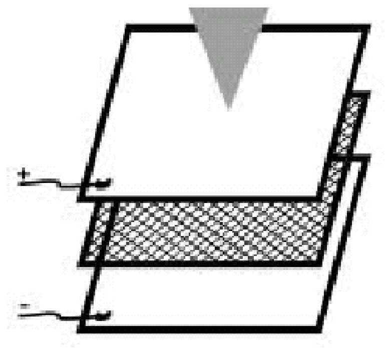


Fig. 13 Sensory Fabric switch

A jacket was designed from a unique electrotextile material, which is connected with a speech computer. By touching the sensory fabric, the child can ‘speak’. In the woven fabric, a mesh of carbon-impregnated fibres is incorporated. When pressure is being exercised on it (by touching), a low-tension signal is led through the fibres to a computer chip. The chip can locate where the fabric was touched.
The Sensory Fabric consists of two layers of electrically conductive textile, divided by a layer of non-conductive mesh. When the textile is pressurised, one conductive layer comes into contact with the other, as a result of which an electric stream can flow. The pressure necessary to make contact between the two outer conductive layers depends upon the size of the meshes and the thickness of the insulating layer. In this way, the fabric can be adapted to its application. The Sensory Fabric feels as an ordinary fabric and can be interwoven with a range of support fabrics.
It can sense the position, shape, force or velocity of an interaction, and can replace a variety of input devices such as switches, keyboards, mice and touch pads [38, 42, 43]. Research is now also on the way (together with the Australian Wool Innovation Ltd.) to use wool in the development of the Sensory Fabric.

2.1.3.1.2 Stretch sensors

Stretch sensors are predominantly used for sensing and monitoring body parameters, as the textile is in contact with the skin over a large body area. This means that monitoring can take place at several locations at the body.

Some examples of body parameters that can be monitors with means of a stretch sensor are:

- Heart rate and ECG,
- Motion: respiration, movement,
- Pressure: blood.

These parameters are measured at the surface or in the upper body layers.

Textile materials composed of fibres form complex networks of conducting parts that make multiple contacts. During deformation a number of mechanisms take place:

- The number of contact points changes
- Fibres are extended
- Fibre cross-section is decreased

The number of contact points changes drastically at low extension values, where real fibre deformation rather takes place at higher levels of strain. An increase in number of contact points reduces the electrical resistance, whereas fibre extension and reduction of cross-section lead to an increase of the electrical resistance. As a result, the electrical resistance changes due to deformation in a way that depends mainly on the textile structure.

This gives textile structures piëzo-resistive properties enabling their use as strain or deformation sensor. From such signals, motion and even position can be extracted. Indirectly, such structures can be used to estimate the level of pressure exerted by a bandage on the skin which is an important parameter for instance for prevention of scar formation [24].

We are taking a close look to heart rate measurements. Heart signals are one of the basic parameters in health care. The heart is basically a muscle that is controlled by the brain though electric impulses. The body being a vessel filled with aqueous electrolyte, these signals can be detected in all of its parts. Small metal plates are commonly used to capture these signals while instruments are analysing the results, extracting the required parameters such as frequency, phases etc..

Several research projects are being conducted that use electro-conductive textile structures instead of the metal plates.

The Intellitex suit is the name of a prototype suit that was developed by a Flemish consortium of universities and companies, among them the textile department of Ghent University. It is a biomedical suit meant for the long term monitoring of heart rate and respiration of children at the hospital. To measure the heart rate and even an ECG, the Textrodes were developed. The Textrodes have a knitted structure and are made of stainless steel fibres (Bekintex). Electrogels are not being used in order to overcome skin irritation. This enables long term monitoring but has a negative impact on the contact with the skin. For children, a nice design makes them want to wear the suit, and they can be monitored without disturbing them.

The Textrodes make direct contact with the skin. Test results have shown that the electrode's textile structure is an important parameter. When changing the structure, a different contact surface with the skin is obtained. Finer structures with more protruding fibres for instance will more easily adapt to the heterogeneous skin surface, which results in a more intense contact between the electrode and the skin. In turn, this results in a lower impedance of the skin electrode system. Thus a compromise has to be found between the sense of comfort and the intensity of the contact with the skin. A knitted structure has the advantage of being stretchable. Elasticity is a required property for close fitting of the suit around the thorax.

To measure the ECG, a three-electrode configuration is used. Two measurement electrodes are placed on a horizontal line on the thorax, a third one, acting as a reference ('right leg drive'), is placed on the lower part of the abdomen

In order to assess their performance, the signal originated from a conventional electrode (gel electrodes by 3M) and the textile electrodes were recorded at the same time.

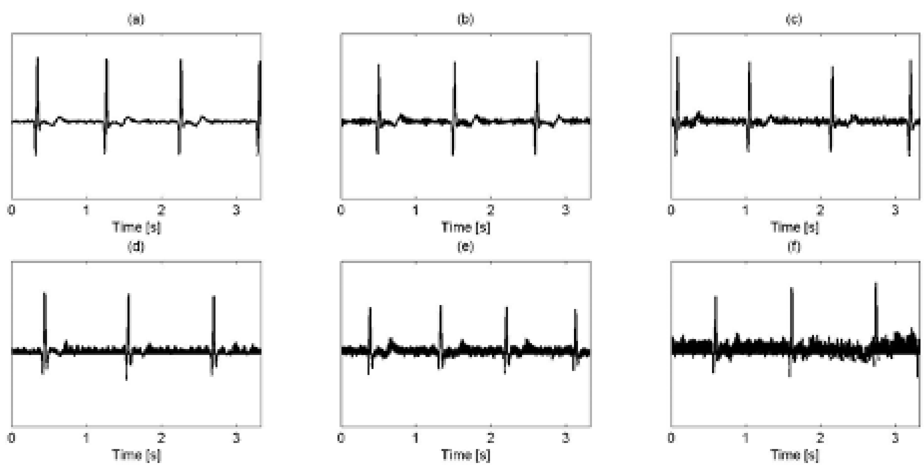


Fig. 14 Conventional electrodes (a, b, c) versus textile electrodes (d, e, f) in 3 different configurations

The figures demonstrate the accuracy of the signal of the textile electrodes. The quality and the reliability of the signal will be compared to standard electrodes in extensive clinical testing.

Further examples on strain sensors and projects in which they have been used are pointed out in chapter 2.1.4.3 [3].

However, next to monitoring device of body parameters, stretch sensors are used as entertainment device, for instance to control the volume of tracks. A stretch sensor was developed by the Philips Research Laboratory in Redhill, UK, which can be integrated into a garment. The stretch sensor, which is produced out of conductive and elastic yarns knitted together, is based on the fact that the electrical resistance changes with stretching the sensing material. Thus, it can be used to control the volume of music or changing the track [78].

2.1.3.2 Conductive materials as actuators

During the last 15 years, new polymers have been emerged that respond to an electrical stimulus by changing either the size or shape. These electroactive polymers (EAPs) can be classified into two categories according to their actuating capability into

- Ionic EAPs
- Electronic EAPs

Actuators are needed to transform electrical signals into physical phenomena, so that they adapt themselves to a situation, affect the human body or serve as a display. For example a research group in the U.S. developed electroactive polymers that change shape and size when stimulated by an electric current or voltage [44, 45].

De Rossi and his team from University of Pisa are involved in the development of artificial muscles and skin [46]. Artificial muscles are produced by fibres that are capable to contract when they receive an electronic signal. His research team develops and uses different types of sensors, generators, protection systems and other functional analogous structures and devices to mimic properties shown by biological skins of humans and animals. Such properties include tactile sensing, thermal sensing/regulation, environmental energy harvesting, chromatic mimetism, ultra-violet protection, adhesion and surface mediation of mobility [47, 48, 49, 50].

2.1.3.3 Conductive materials as data processing unit

Sauquoit Industries developed a process that enables etching of electronic circuit boards on fabrics and called it CircuiteX™. A silver metallised fabric with a fine and dense woven nylon structure offers the highest level of conductivity. The silver (99.9% pure) permeates the fabric structure to cover all surfaces of the yarn. A resist is applied to keep the silver in place along the circuit path. Where there is no resist, the silver is dissolved by the etching chemical. Other electronic devices can then be added to the fabric using cold soldering, as shown in **Error! Reference source not found.**.

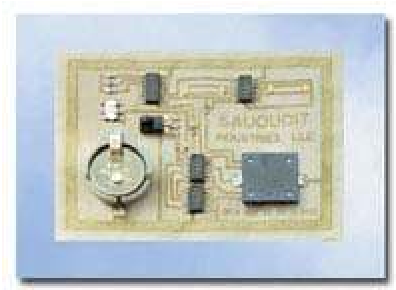


Fig. 15 CircuiteX^{TM} fabric by Sauquoit Industries [51]

2.1.3.4 *Conductive materials as power supply*

Power supply technologies provide the electrical power for activating the components integrated in the electronic textile and it is still a critical issue in the field of wearable electronics. Until now, primary (non-rechargeable) and secondary (rechargeable) batteries are predominantly used to provide electrical power for activating the components integrated in the textile. However, there is a great effort being made to produce very small, powerful and rechargeable batteries. A battery might also be embedded into clothing components, like a button [56].

Fig. 16 Design of an autonomous ‘sensor button’ [56]

The figure shows an autonomous sensor button developed at Wearable Computing Laboratory of the ETH Zürich. It consists of a light processor, a microphone, an accelerator, a microprocessor and a RF transceiver. A solar cell powers the system [56].
An example of a battery capable of providing electrical power for interactive electronic textiles was recently developed by a German research team led by The Fraunhofer Institute for Reliability and Microintegration (FhG-IZM). This research team developed a small battery that can be printed on a

substrate and fabricated at high production speeds in button-sized or coin-type format at cost below one United States Dollar. The battery is fabricated by screen printing a thick layer of a silver-oxide based paste then applying a thin sealing layer. The final result is a textile substrate with a printed 120µm thick AgO-ZN battery. These batteries can be printed on a variety of substrates. In addition to textile substrates, they can also be directly integrated into plastic cards, smart labels, and hybrid circuits. As an alternative to battery power and to further expand power supply technology, research is underway by this team to utilise solar energy and energy created by the human body as a source of electrical power for interactive electronic textiles [52].

The supply of energy by the user's body during everyday actions through leg motions and body heat is also exploited by other research teams. For example, Infineon is currently trying, to recover energy by body movements to feed Mp3 players integrated in a jacket with power (see chapter [53].

An example for power generation by solar energy offers the SCOTTeVEST. The vest with integrated solar panels which is described in chapter 2.1.4.1, has already been brought onto the market.

Research is also on the way in the field of fibres that are capable to store energy. For instance, in 1988 the Canadian sportswear company Descente and the company Unitika developed jointly the fibre material Solar α, which absorbs and preserves the optical energy of the sun and converts it into heat. The fibre is used in ski wear to keep the wearer warm [54].

Also energy converting fibres are on their way. Thermotron (TET, PA/ZrC) from Unitika is a heat-retaining fibre that converts light from the sun into thermal energy, used in sports and outdoor clothing [55].

In the following table, an overview of different possible energy sources and the amount of energy that they can generate is given.

Energy source	Available amount of energy	Remarks
Primary batteries (Li)	400 Wh/kg, 800 Wh/l	
Secondary batteries (Li-Ion)	75 Wh/kg, 200 Wh/l	Lifetime:2000 cycles
Si solar cells	20 w/m^2	Light source needed
Recovery of body heat	0.01 W/m^2	
Power harvesting from breathing	0.4W	Uncomfortable for wearer
Power harvesting from walking	0.25 W	Continuous walking necessary

Microcombustion	10-50 W/cm^3	Fuel needed

Table 1 Comparison of different energy resources

2.1.4 Applications in the clothing sector

In the segment of intelligent clothing textiles, conductive materials mostly find their application in wearable electronics. Wearable systems are characterised by their ability to automatically recognise the activity and the behavioural status of a user as well as of the situation around him, and to use this information to adjust the systems configuration and functionality.

However, the use of clothing as a platform for electronics offers certain advantages due to the direct contact and thus the interaction between the wearer and the garment, but also for comfort reasons. Clothing allows the system to be integrated unobtrusively into the daily life of the wearer, for instance by hiding electronic components in pockets or seams.

Electronics and electronic functions show different integration stages in textiles, ranging from textile-adapted, textile-integrated and textile-based. Certainly, a great tendency towards textile-based solution is observable. However, no matter how strongly integrated, the functional components remain in most cases still non-textile elements, meaning that maintenance, durability, user safety and comfort are still important problems.

In the future a wearable personal health assistant (PHA), which comprises manifold smart miniaturised sensors, connected by a wireless or wired body area network to data processing and communication devices, all devices embedded in the wearer’s daily outfit, may become reality. The PHA continuously monitors the wearer’s vital signs like hear rate, heart rate variability, temperature and motion activities and social interaction. With these parameters it is possible to comprehend the physiological state of the wearer [56, 57].

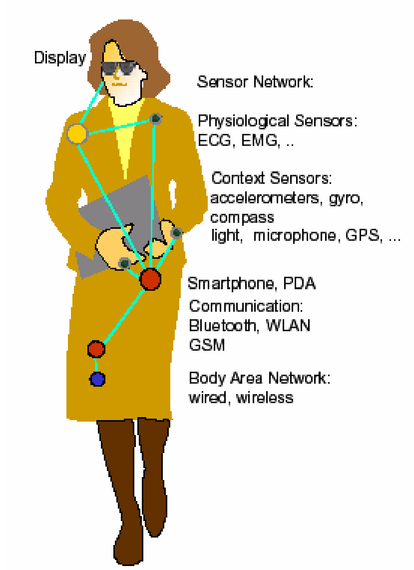


Fig. 17 Structure of a Personal health Assistant [56]

The figure shows a potential implementation of a PHA: several sensors, distributed in clothes, transmit the measured physiological and context data over a body area network (BAN) to a computing unit, which fuses the sensor data out of them, estimates the health status and communicates with surrounding networks.

Most of the products and technologies described in the three subsequent subchapters need sensors which either detect body movements or biometrical data like temperature or heartbeat for instance, or which fulfil the function of a switch. Hence, products mentioned in the following need wired and wireless communication and therefore require conductive yarns as well as conductive surfaces. Additionally, power generation could also be a part of the textile infrastructure, using the large area on the outer surface of clothes.
Generally, the section wearable electronics can be subdivided according to its use into three groups, namely communication, information or entertainment, thermal control, and health, fitness or mood [58].

2.1.4.1 Wearable electronics for communication, information or entertainment

According to the International newsletter, wearable electronics for communication, information or entertainment can be defined as garments that use an electronically conductive textile structure as a scaffold for various switches, sensors, displays and other devices for communication, computing, information and/or entertainment.

In the area of business and personal communication, to draw an example, there are many applications and opportunities for electronic textiles. Computers, cellular phones, personal data assistants, beepers, and pagers are common devices used today for mobile communication. Users of these technologies are carrying around a separate display, battery, keypad, speaker, and ringer for each of these devices. Electronic textile technologies can potentially integrate these items directly into textile and apparel products with shared resources. This would eliminate the need to carry such devices and increase mobility, comfort and convenience. The technologies supporting electronic textile communication include integrated input and output devices such as computer keypads and display screens and integrated antennas for mobile phones use, internet connections and downloads.
In the following, examples are discussed that make use of a textile structure to integrate single or several electronic devices.

Although there are many companies and institutes involved in research projects going on in the field of wearable electronics, the US military is still a major sponsor, through such agencies as the US Army Natrick Soldier Center and The Defense Advanced Reseach Projects Agency (DARPA).
A first approach to integrate electronics into textile structure was certainly achieved by gloves wired to the computer that allows it to take input from a user's hand gestures. Sensors in the glove detect the wearer's hand movements, and transmit these to the computer in a digital format which the computer can interpret. The Dataglove™ is one invention made in the late 1980ties that can be exemplary named in this case (others are for example the PowerGlove™ and the Cyberglove®). The Dataglove™ is a trademark of the company VRLOGIC in Germany. The first prototype consists of a Latex glove to which tubes equipped with sensors for each finger are attached by stitching. Hence, ten finger joints could be monitored. Four wires were used for each finger or tube to build up a circuit. The voltages coming out are varying depending on the finger flex [5, 59].

Fig. 18 The Dataglove™ developed by Kevin Mellott [59]

A first step towards wearable electronics for the every day use was the outerwear line, ICD+ (Industrial Clothing Design Plus) at the end of the 90's, which was the result of a co-operation between Levi's Strauss & Co. and Philips Research Laboratories. This line comprised of four wired jackets that combine garment functionality, like water-resistance, with wearable electronics. Wires were used for synchronous control of the Philips Xenium GSM mobile and Philips Rush MP3 player.

(a) (b) (c)

Fig. 19 The Mooring jacket (a); its communication system (b); its speakers and microphone (c)

One of the four jackets is the Mooring, a jacket equipped with a cell phone, a MP3 player, a chest-mounted remote control, built-in speakers, a microphone and a display. A personal area network (PAN) provides the backbone for connecting these electronic devices with each other. The jacket's construction requires that all these components, including the wiring, are carefully removed from the jacket before putting it into the washing machine. The limitation as the maintenance created a high need for further integration.

Limited editions of the jackets were available on the international market; the initial price for the jackets was between US $600 and $900 [52, 60], but the collection is not available anymore.

One year later, the German company Infineon, now Interactive Wear AG, presented a similar prototype with an integrated MP3-player, a headphone, a microphone, a detachable battery-Module and a flexible sensor-pad-keyboard. A great difference to the ICD+ line was that the whole garment is washable. Thus, the researchers at Infineon received the Avantex Innovation Award in 2002.

However, these garments contain conventional cables and miniaturised electronic components.

In co-operation with Rosner, a German clothing manufacturer, they introduced the "mp3blue" jacket, in summer 2004. It is a men's jacket with integrated features such as mobile telephony via Bluetooth and a MP3 player. The electronics are an integral part of the clothing. The electronic features are operated by a keyboard printed on the sleeve. According to Infineon, the 'mp3blue' jacket is the first lifestyle jacket worldwide that implements the complete integration of electronic functions [61].

Fig. 20 mp3blue jacket developed by Infineon and Rosner [61]

In January 2004, a snowboard jacket with integrated MP3 player, named The Hub, was presented by Infineon in collaboration with the O'Neill Company. Electrically conductive fabric tracks are woven into the snowboard jacket. These tracks connect the chip module to a fabric keyboard in one sleeve, built-in speakers in the hood and a microphone sewn in the collar. The chip module contains a full-featured MP3 player and a Bluetooth module via which the snowboarder can control a mobile phone. If the snowboarder wants to make a phone call, the stereo system acts as the headset.

Fig. 21 The HUB jacket by O'Neill and Infineon [62]

The jacket can be bought for US$600 in Europe. The companies promise that the jacket can withstand rain, snow and freezing temperatures, and can be washed without worrying about short-circuit. The manufacturers claim that the MP3 player will provide eight hours of playback time before having to plug the jacket's USB cable into a computer.

However, Infineon is also experimenting to recover body heat to power the system. For this purpose, a miniature thermogenerator uses the temperature difference between the body surface and the surrounding clothing to generate electrical power - a technology previously used in space exploration. It generates enough electricity to power the microelectronic chips embedded in the jacket.

Researchers are also looking at fabrics capable of generating power as they are flexible [63].

The Finnish company Clothing+ released a line of wearable technology in 2001. The so-called Smart Shout parka is sold for about US $700 under the brand Reima.

Fig. 22 The Shout parka by Clothing+

It's being marketed to skiers, climbers and hikers across Europe. It has a detachable body belt that has a built-in loudspeaker, microphone, and GSM mobile phone that can be activated using tags, so hands can be kept free [64].

The company Nike uses the Softswitch™ technology for a snow jacket with an integrated radio, microphone and earpiece. The jacket is marketed under the name Nike ACG COMMJacket for £400 [65].

Fig. 23 Nike Women's 3L Commjacket

The two-way radio is integrated into an ergonomic communication vest. The speakers are positioned near the ear, the microphone near the mouth and a push-to-talk button can be found on the chest.

Burton Snowboards collaborated with Apple to introduce the Burton Amp smart ski and snowboard jacket. The sleeve of the jacket is augmented with the pressure-sensing technology from Softswitch™ to create a soft, flexible, fabric-based keypad that controls an integrated Apple iPod digital music player. Songs can be chosen and volume altered by pressing the soft keys on the sleeve, without the need to access the iPod itself [66].

Further, the ElekTex® fabric touchpad has been used by several companies to launch jackets and backpacks. For example the American apparel manufacturer Kenpo Inc, used the ElekTex® in a men's jacket for the winter season 2005/2006.
Also O'Neill uses ElekTex® in its range of H2 series backpacks and jackets. More examples can be found in [38].

Recently, Burton Snowboards and Motorola Inc. launched a series of Bluetooth-enabled winter jackets, the Burton Audex™ Snowboard jackets. In the sleeve of the jacket one can find an integrated control panel, which allows remote operation of the wearer's phone or iPod. Additionally, the jacket features integrated stereo speakers in the hood, a microphone and chest/battery module embedded within the inside pocket of the jacket. However, these components still stay hard plastic devices.

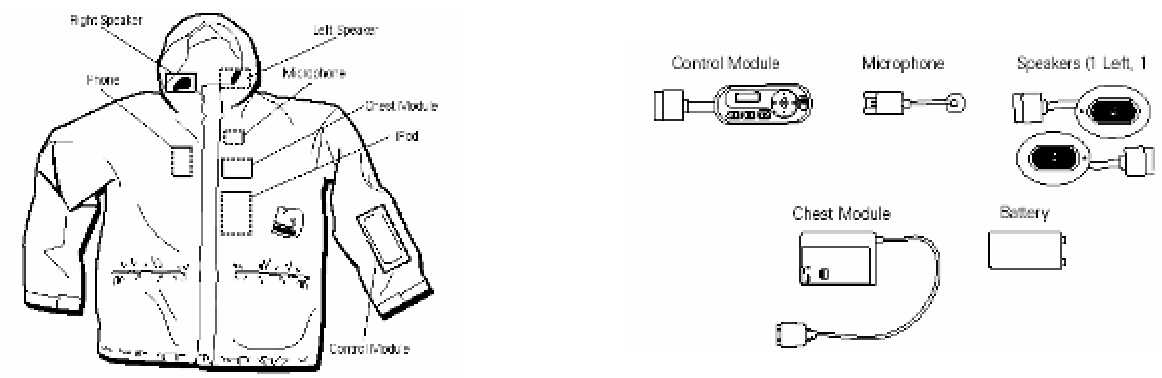


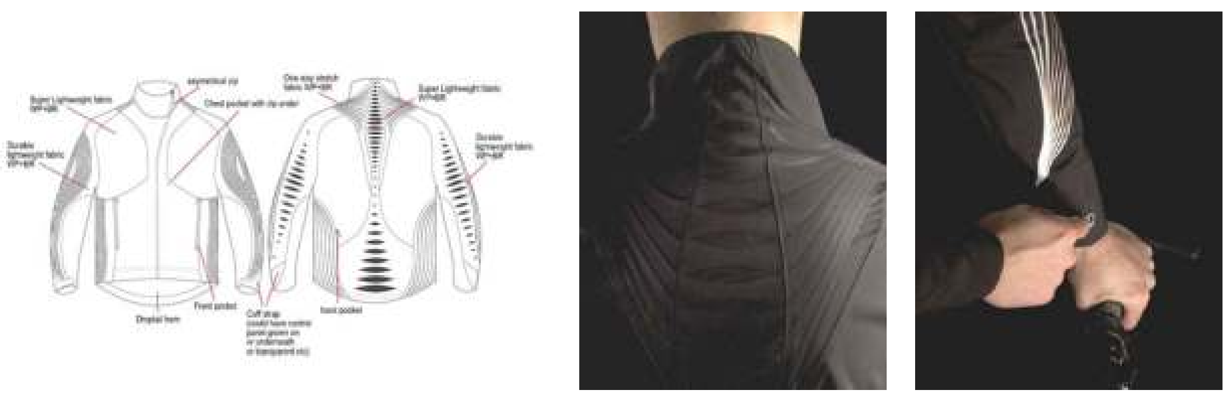
Fig. 24 The Burton Audex™ Snowboard jacket [67]

In the drawing above the Audex™ components are illustrated, which get attached to the jacket. The wearer must ensure that the components are not exposed to moisture and thus they must be carefully removed before washing. The jacket is available in three different styles as a cargo jacket, a down jacket and a duffle jacket for woman. All three styles can be bought for $599.95 at the Burton website [67].

Together with a designer of the University of Applied Sciences in Berlin and Hugo Boss, the Fraunhofer Institute for Reliability and Microintegration (IZM) has developed a communications jacket. It shows how electronics can be integrated into clothing and illustrates the idea of separating the input/output devices from the intelligent part of the system. The latter allows further miniaturising the intelligent part while the system remains usable in terms of display size and keypad size. The purely textile keypad has been developed by ITA at Aachen University of Technology. All the connections between the modules have been embroidered with silver coated polyamide fibres. The display is connected to the jacket via snaps and can be removed simply for washing [68, 69].

Fig. 25 Communications jacket with textile pad [69]

The English design Consultancy Goose Design and the product design agency PDD revealed a concept for a new cycling jacket that combines safety and fashion. The ILLUM jacket is based on technologies including printed electroluminescent ink and printed photovoltaic technology (solar power). The functional parts are arranged all around the jacket and cut into several ergonomic panels with red light at the back, while at the front and the photovoltaic source at the shoulders and top of the back [70].



(a) (b) (c)

Fig. 26 Jacket design showing details and functionalities (a); Printed photovoltaics at the shoulder (b); Switch in the sleeve [70] (c)

Lena Berglin from The Swedish School of Textiles developed a glove wirelessly connected to a mobile phone. She designed the glove especially for persons whose working conditions are exposed to hard weather and physical demanding tasks, like workers on ski-lopes, rescue workers and guides in the artic area. In order to facilitate the communication for these people, a mobile phone is connected wirelessly to a glove, an item that they use anyway. Thus, the group of persons can make and receive calls without picking up the mobile phone. For designing the prototype it was important to develop a type of user interface with no display or button that could be hard to handle with thick glove. Therefore the phone calls can be made and received by hand gestures and the voice. The call is activated by pressure on a part of the thumb, speaking in the wrist, listening at the index finger and exchanging number by shaking hands.

Fig. 27 Lina Berglin's glove design

At the "Intelligent Ambience and Well-Being" conference in 2005, Berglin presented an extended model of the glove. With this model it is possible to get actual weather information by bending the index finger. By bending the index finger twice information on navigation can be accessed. In order to make the information visible a display can be integrated into the glove. This can be achieved either by a Velcro strap or to insert a thin and flexible display on the upper part of the glove, as presented in the picture above [71, 72, 73].

Another glove with an integrated mini joystick controller is marketed by O'Neill under the name 'Fat Controller' since the end of 2005. The joystick has been developed by the British company Fibretronic in order to operate an iPod wirelessly by connecting to an RF transmitter positioned in the cuff of the glove. The joystick is sewn into the glove on the back of the hand. The user can switch between five functions (play, rewind, fast forward, volume up, volume down) by moving the soft rubber stick. The signals from the joystick are then sent wirelessly from the transmitter in the glove to a receiver unit that plugs into the iPod player [74].

Fig. 28 Snowboard glove with integrated joystick

In collaboration with Oak Ridge National Labs, researchers at the North Carolina State University are developing electrotextiles and are creating a computer circuit based on conductive nanofibres. The fabrics may be translated into having a computer keyboard and screen on clothes as well as a cell cellphone incorporated into baseball bats. Research is still going on [75].

Beside wired connection wireless communication channels are also necessary to enable the data exchange between the on-body components and the wearer's environment. Several communication schemes already exist, for example a magnetic induction with textile coils. It can be used to overcome small distances, like between a t-shirt and a trouser, but disadvantageously it has low power efficiency over long distances. Textile antenna that should be integrated into clothes and therefore provide wearing comfort, must provide a flat and planar geometry and require a textile and drapable structure that can bend in all directions at the same time. Researchers at the Wearable Computing Laboratory at the ETHZ have developed a circularly polarised antenna for Bluetooth applications that can be sewn into the garment.
The antenna they developed consists of a polyamide spacer fabric with a thickness of 6 mm; on both sides of the fabric a nickel-plated woven textile as conductive material is attached by ammonia-based textile glue. The performance of the antenna is degraded when bending it [56, 76, 77].

Another device that might be integrated into a garment is a fabric antenna. This kind of antenna has the advantage that it cannot be recognised by the wearer. A patch antenna, integrating into the back of a jacket, for use in combination with a mobile phone, was developed by the Philips Research Laboratory in Redhill, UK[2]. The textile structure used for the radiation surface and ground plane is a nylon fibre coated with copper [78].

[2] The Philips Research Laboratory in Redhill, UK, was closed. The research is done now at the laboratories in Eindhoven /The Nederlands and Aachen /Germany

Foster-Miller also researches on wearable antennas: For the US Army, they integrated data and communication loop-type antennas into a soldier uniform. They first constructed embedded antenna prototypes and evaluated loop antenna designs. The project aims at developing a soldier ensemble of the future, which will monitor individual health, transmit and receive mission-critical information, protect against numerous weapons, but at the same time it should maintain full antenna performance, together with the same ergonomic functionality and weight of an existing uniform [79].

Fig. 29 Soldier Uniform of the future [79]

Scientists at the TITV Greiz developed a textile transponder antenna integrated into a label, which can be attached permanently to textiles. This antenna is flexible, washable and has a good reading range. It consists of three fabric layers serving different functions. Thus, if a contact point of conductive threads is desired, the lower and upper layers are responsible for isolation, while the middle layer incorporates conductive threads in warp and weft direction. For the other case, if no contact point is desired, the conductive threads are inserted in the lower and upper layer, while the middle layer is responsible for isolation. However, the conductive threads in this model can also be brought into contact by a spool structure and therefore can serve as a transponder aerial. As conductive threads, the research group uses silvered metallised polyamide fibres with a silver layer of approximately 1µm. In order to achieve a good conductivity they treated these fibres galvanic. They deposited metals such as gold, platinum, copper, nickel and zinc, as well as the additionally silver on the fibres. However, this woven layer construction is suitable to be used for electroluminescent light sources which still require an optical transparent electrode [18, 80, 81, 82, 83, 84].

Another example of a textile transponder was presented by the German company Deister Electronic GmbH at Avantex 2005, the so-called Textag®. It is a woven textile structure with an incorporated aerial thread along with a RFID chip. The aerial thread is a metal wire supplied by the company Elektrisola Feindraht. The antenna facilitates the storage of production and delivery data directly within the finished product, enabling each individual process such as production, despatch, shelf time and purchase to be recorded at the level of the individual product and monitored until switched off at the cash desk. Further, an integrated EAS (electronic article surveillance) function sets off an alarm if the product should be stolen or enables tracking. When incorporated in technical textiles the ‘Textag’ facilitates a number of applications such as source protection (copyright protection) or the storage of security-specific data [85].

The next examples of wearable technologies not only use the body, but also the space through which a body moves. Therefore, it is the space in which the interactive aspect occurs. The projects issue at the development of technology and the social implications.

In the framework of the Swedish programme “IT+Textiles” coined by the Interactive Institute in Sweden, the project ‘Reach: Wearable Patterns’ was established which focuses on wearable technology, on the one hand as one-to-one communication, and on the other hand for reflecting personal expressions, environmental change and social constructs. For this purpose, it investigates the potential for communication and expression incorporated dynamically and interactively into things we wear everyday, like clothing and accessories. The prototypes they develop include hats, a bag and a scarf. The so-called ‘Reach out hats’ share textile patterns or music when two or more people wearing this hat are in close proximity with one another. The closer one gets to the other, the more the visual or sonic pattern ‘bleeds’ or is shared and experienced with another person. Therefore, the hats explore distances between people in public space. The intention of the hats is to redraw the distances between people, to promote contact and to investigate human perception of space, pattern and sound in relation to others in the environment. In the picture below, an example of a pair of Reach out hats is illustrated. One hat has a dot as pattern; the other uses the shape of a flower. The pattern is printed with thermochromic ink. When the pattern is shared, or two people wearing the hats come into contact with one another, the hat with the dot pattern grows flowers, whereas the hat with the flower pattern receives a dot. This effect is achieved by an under-layer of conductive thread that is heated when two people are within range of one another. For the moment, the hats are only sketches, more work needs to be done as they are not technologically complete so far.

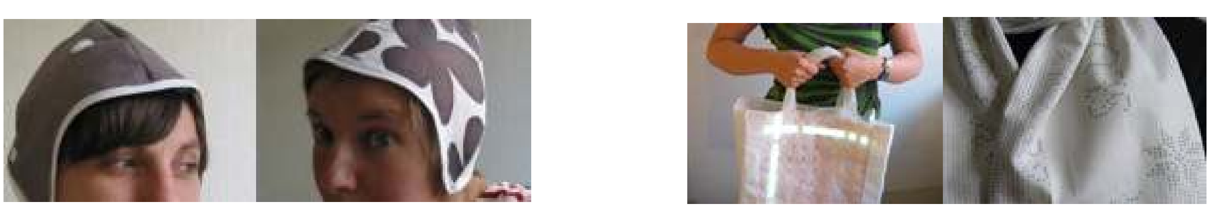


Fig. 30 Prototypes of ‘Reach:Wearable Patterns’

The researchers further designed the 'Torch bag' that is capable to produce light in the dark. Thus, on the one hand light is created for the wearer to be able to see what is around him/her and to create light that makes the content of the bag visible. The bags lights up its interior when it is opened and the light turns off when it is closed or by turning its exterior on in dark surroundings and turning off again in well lighted areas, in reaction to a light sensor or a photo-resistor. The bag is intended for use with several sensors that react to and reflect aspects of the environment. Sensors measure sound level, light and temperature. A chip processes the data input from the external sensors and translates the values into a dynamic textile pattern using a combination of electroluminescent film and synthetic fabric. Currently, the research group investigates means of powers for the hand bag by using solar cells. The 'Reach around scarves' reveal or create patterns and hidden messages based on environmental conditions, such as sunlight, wind and temperature. Additionally they provide warmth as they are heating up and changing patterns when it gets cold. A temperature sensor triggers the heating of conductive threads sandwiched between two layers of the scarf fabric [8].

A less functional but funny product is the 'Puddlejumper' created by Elise Co a former student of the aesthetics and computation group at the Massachusetts Institute of Technology. It is a luminescent raincoat that glows in the rain. Silk-screened electroluminescent panels on the front of the jacket are wired to conductive water sensors on the back and left sleeve. When water hits one of the sensors, the corresponding lamp lights up, creating a flickering pattern of illumination that mirrors the rhythm of rainfall.

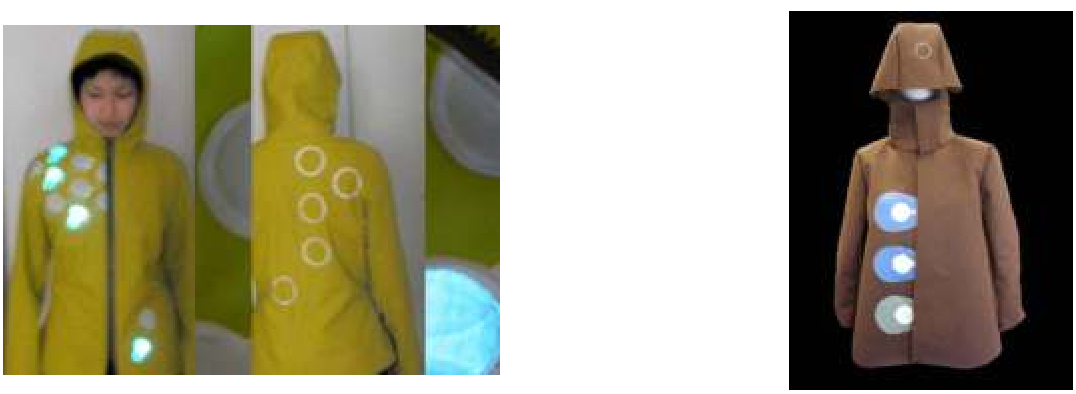
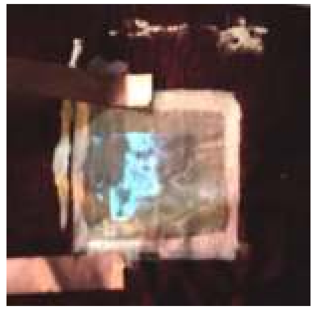


Fig. 31 Puddlejumper [86]

The pictures above show the current state of the Puddlejumper jacket. Custom-silkscreened luminescent patches extend from the front placket, and respond to water contact on raindrop sensors (one visible on the front hood). The final lamp and sensor configuration is being designed.

This project juxtaposes electricity and water in a raincoat that luminescences in response to droplets of rain. Embroidered water sensors act as inputs to a system with sealed electroluminescent panels that illuminate based on patterns of rain [87]. In the following illustration, her samples are shown.

EL lamp silkscreened onto polyester taffeta (off); copper foil is used to contact the silkscreened leads



With charge, part of the silkscreened area phosphoresces blue-green

Samples of embroidered rain sensors. The sensors are embroidered directly onto the body fabric and detect contact with water anywhere on the embroidered area

Fig. 32 Fabric samples used for the Puddlejumper jacket

Another expressive example in fashion is ‘Elroy’ by Megan Galbraith, which is an illuminating dress that encodes time information through the visual arrangement and animation patterns of the electroluminescent panels. Megan Galbraith is also a student of the aesthetics and computation group at the Massachusetts Institute of Technology. In Fig. 27, the electrical dress is illustrated.

Fig. 33 Elroy dress by Megan Galbraith [88]

It is constructed out of a Panasonic EL element, a microprocessor, a copper sided electrical circuit board and a polyester fabric.

Katherine Moriwaki turned a handbag into an interactive product by making it capable to detect environmental irritants (either air quality or audio pollution) and display the information on the surface of the bag, storing it in a “digital data diary” for later review. She developed the Inside/Outside handbag principle at the NTRG, Trinity College Dublin.

Moriwaki's Inside/Outside handbag captures and stores digital information from the surrounding [89]

Prototype of the bag, presented at the Ubicomp 2003 conference in Seattle, U.S. [90]

Fig. 34 Inside/Outside handbag

The handbag uses an air quality sensor and audio microphone input connected to a microcontroller. As the user carries the bag through the city, changes in ambient air quality and noise levels cause conductive embroidery on the bag surface to heat and subsequently cool. Thermo-chromic pigments mixed with acrylic paint applied onto a fabric substrate create a visible colour change that is both controlled and programmable.

Sabine Seymour from Moondial Inc. intends to increase personalisation in fashion with her project SlopeStyle. She and her team developed a functional and fashionable athletic jacket prototype. She utilised several technologies mentioned below that are integrated into the jacket. A display is embedded in the back of the jacket to which images can be transmitted directly or downloaded wirelessly from the internet. Sensors are used to monitor biomimetric data to increase the performance and to improve the safety of the wearer. Additionally, the wearer can locate his/her posse and can communicate and receive information on location of other wearers of the jacket.

Fig. 35 Technical design of the prototype jacket by Sabine Seymour

Sabine Seymour further uses the Outlast® Technology, a phase changing material described in chapter 2.4 to keep the wearer warm [91].

Additionally, XS Labs, a design research studio in Canada, focuses on the development and design of electronic textiles, responsive clothing, wearable technologies and reactive materials, considered in a social and cultural context [92].
Their target is the design of digital and electronic technology that is composed of soft materials such as textiles and yarns, as well as predicated on traditional textile construction methods to create interactive physical designs. It involves the use of conductive yarns and fabrics, active materials, and flexible sensors to enable the construction of electronic circuits on soft substrates. They created garments like a blazer with an emissive display, or a 'SoundSleeve' out of organic silk organza and conductive yarns that can be used as an instrument.

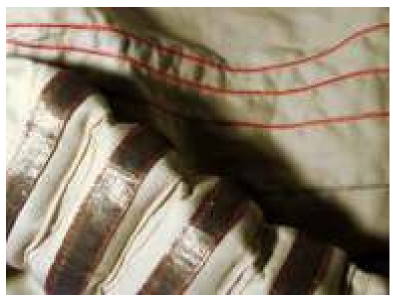


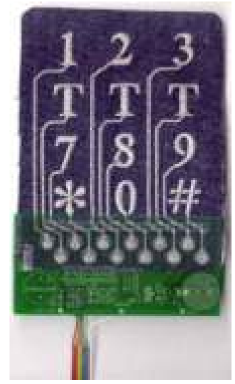
Fig. 36 'SoundSleeve'

On the picture, the 'SoundSleeve' is depicted, that is sensitive to physical contacts. When the user flexes or crosses his/her arms, a sound is synthesised within the sleeves and output through miniature flat speakers. The circuit board that connects all the elements is stitched on the fabric [93].

Further, the Charmed Technology Company in Los Angeles is an MIT Media Lab spin-off and is specialised in incorporating the unwired internet into fashion products [94].

The Levi's Musical Jean Jacket, created by researchers at the MIT Media lab, is a system that uses a stainless steel and polyester composite thread to embroider a keypad. It is flexible, durable and highly responsive to touch allowing the user to play notes, chords and rhythms. A printed circuit board supports the components necessary to do capacitive sensing and output keypress events as a serial data stream. The circuit board makes contact with the electrodes at the circular pads only at the bottom of the electrode pattern. In a test application, 50 denim jackets were embroidered in this pattern. Some of these jackets are equipped with miniature MIDI synthesizers controlled by the keypad.

Levi’s Musical Jean Jacket



Component side of the circuit

Fig. 37 Musical jacket and its circuit

Although the jacket is not in the stores yet, it has been test marketed in Europe [95].

The Wearable Computing Laboratory of the ETH Zürich presented a Music jacket (virtual drums) at the exhibition "150 years ETH" in spring 2005 [96].

The company ADIDAS markets a sport shoe which they claim as ‘The World’s first Intelligent Shoe’. The ADIDAS 1 shoe analyses the wearer’s speed, weight and the terrain underfoot by an electronic unit implanted in the arch of the sole. A magnetic sensor monitors weight, pace and surface a thousand times per minute and the information is send to a microprocessor. The microprocessor is capable to send signals to a motor driven cable system connected to a cushion cylinder in the heel of the shoe. Thus, the cylinder can be loosened and tightened to ensure a good level of cushioning.

Fig. 38 ADIDAS 1 shoe [97]

The shoe is equipped with + and – buttons at the side, above the buttons there are five small amber-colored LEDs. As soon as the shoes are turned on, the middle LED lights up. Switching to another LED, the shoe will start with the automatic adjustment of the cushion. However, the wearer also has the possibility to adjust the shoes to his/her personal preference. The shoe can be either switched off

by pressing the ”+” and ”-” buttons (shown in the right picture of Fig. 32), or the processor will switch off automatically after ten minutes of inactivity. Batteries need to be changed every 100 hours of wearing the pair of shoes.
Advertisements are made on television and the shoe can be bought in retailer shops all over the world for $250 [97].

Scientists at the John Hopkins University in Australia have developed a high security cloth bag made from a fabric with conductive fibres woven in. The electronic fabric resists tampering and can be programmed to respond differently to a variety of situations. The owner of a bag might wirelessly link it to an alarm system which can sound when the fabric is moved. Another possibility is that the fabric can send a call to the owner and authorities in order to alert. The fabric is designed to support a variety of electronic components such as tiny circuits, sensors and wireless communication devices and can be sewn into many shapes. In the following figure, the bag is pictured.

Fig. 39 High security cloth bag

However, the fabric does not only find application as a bag, it might also be used to keep doors and locks safe, or to attach it to the floor of shipping containers to assure that the container remains in place [98].

As described in chapter 2.1.3.4, a matter of concern in the field of wearable electronics is still the power supply. In the field of intelligent textiles, especially the use of solar cells seems to be promising for the energy supply of electronic devices.
In co-operation with Global Solar Energy, SCOTTeVEST Inc., developed and commercialises a solar-powered jacket that can connect and charge portable devices. The jacket can be ordered at the company’s homepage for a prize of $425.
Solar panels are attached to the SCOTTeVEST’s signature jacket, Version 3.0 Finetex, an all-weather jacket with removable sleeves and over 30 hidden pockets. The jacket features SCOTTeVEST’s

patent-pending Personal Area Network (PAN), which conceals wires associated with power sources and earbuds.

Global Solar's PowerFLEX™ solar panels consist of unique flexible thin-film photovoltaic material made from copper indium gallium diselenide (CIGS) sun-absorbing material placed onto a thin stainless steel substrate. The panels convert sunlight into electricity that charges a hidden battery pack about the size of a deck of cards. The battery pack in turn can charge any device compatible with Universal Serial Bus (USB) chargers, including cell phones, PDAs, Game Boys, MP3 players and other mobile devices.

Fig. 40 SCOTTeVEST [99]

The solar panels are removable and can be used separately from the jackets. Typical charge times in direct sunlight range from two to three hours, although direct sunlight is not required. The jacket's battery can begin powering devices almost immediately after the solar panels are exposed to sunlight. Once the battery is fully charged, the panels can be removed and portable electronic devices can tap into the stored power. When attached, the solar panels compliment the jacket's stylish, futuristic design [99].

However, from a physiological point of view, solar cells have some disadvantages. They are water-vapour impermeable that means they are also non-breathable. This is of particular concern when the integrated electronic device consumes higher energy and a considerable area of the clothing needs to be covered with solar cells. This can significantly obstruct the evaporation of sweat through the garment and consequently the thermoregulation of the wearer is impeded [100].

2.1.4.1.1 Published patents

Philips published a patent on deformable loudspeakers (US 6707922), which can be incorporated into garments and upholstery for instance. The cover is made of a heatmouldable textile having a ceramic textile covering. In order to incorporate the speaker into a textile it is stitched to a conventional textile.

In the field of tags that secure clothes from being stolen, the Memminger-IRO GmbH patented a knitted textile with a transponder that is knitted into the structure under WO 02/00993.

Further, Infineon Technologies patented a smart label consisting of a woven textile carrier and a thread-like conductor which is integrated into the textile carrier. The label can be used as RFID tag and store information on the textile to which it is attached (WO 03/042977).

2.1.4.2 Wearable electronics for thermal control

In general thermal control in garments is achieved by incorporating networks of conductive materials supplied by a separate power source to provide heat or to keep the wearer cool.

One example that must be mentioned first is surely the Italian company Grado° zero espace that established the I.O.W. (Intelligent Object to Wear). The I.O.W. is a motorbike jacket with an internal heating mechanism (produced by a specialised English firm).

Fig. 41 I.O.W. by Corpo Nove [101]

This garment is the first portable heating system for motor bikers that can be directly connected to a motorbike or a scooter, and can monitor body temperatures in four different areas of the torso (arms, chest, back and shoulders) and regulate the temperature accordingly. Inside the jacket lining is a computerised microprocessor with hard disk (no bigger than a packet of cigarettes) which controls the body temperature over a series of electric heating pads. The five pads, (located at the lower back, the

shoulders, the chest and the arms) can be individually monitored to desired temperatures and perform the heating in the following manner:
A thin strip of metal is vacuum sealed between two layers of gel and then covered with a fabric made out of Kevlar, a para-aramide. On this thin strip of metal is a chip positioned that sends impulses to the computer relaying messages on the internal body heat inside the jacket.

Textile products for warmth and comfort have also been made by Malden Mills, the manufacturer of Polartec fleeces. They have developed a fleece that conducts heat through proprietary stainless steel fibres that are washable, supple and soft. Land's End has licensed the technology to create the Polartec Heat Blanket, which provides an even distribution of heating without the apparent wiring that is typical in conventional electric blankets [102].
Further, Malden Mills has licensed the technology to North Face, which is using it for the high-end MET5 jackets.

Fig. 42 MET5 jacket [103]

The MET5 jacket is constructed from Polartec Power Shield - a tightly woven, nylon fabric that is highly wind and abrasion resistant - with Polartec heat panels throughout. These panels are powered by rechargeable lithium ion batteries, and are controlled from a pliable switch panel located on the upper left chest of the jacket and welded right into the fabric. (Batteries and AC recharger included) [102].

At the Design for Life Centre at Brunel University, UK, a research group worked on temperature controlled clothing. The basic technology behind the jacket is the 'Sensory Fabric' (see chapter 2.1.3.1.1). In co-operation with the British company Gorix Unlimited they are looking for possible fields of applications of the 'Sensory Fabric' [42, 43]. Eventually, they developed a heating and cooling jacket.

Heating and cooling jacket

Cooling fan of the heating and cooling jacket

Fig. 43 Temperature regulating jacket

The jacket incorporates an electro-conductive fabric, called Gorix E-CT as heating system, which heats the wearer but reacts to body heat to maintain a desired temperature without overheating [105].

Lately, at the "1st International Scientific Conference on Intelligent Ambience and Well-Being" in 2005 researchers of the Wearable Computing Laboratory at the ETH Zürich presented a smart fabric system with temperature sensing and signal transmission capability. The woven hybrid fabric consists of PET yarn and copper wires which are known for their high thermal conductivity. Thus, the fabric itself represents an array of temperature sensors which are capable to measure the temperature profile of a surface, e.g. a human body. This textile structure might be used for instance to monitor the temperature to which fire fighters are exposed during their mission. Beyond that, the fabric can not only be integrated into clothing, but also in car seats for instance.

The warmX®-undershirt is constructed by a jersey knit with integrated silvered fibres in the kidney zone. The silver-coated polyamide fibres warm up directly on the skin, power is supplied by a small battery positioned in a small waist pocket at the front of the shirt. The power controller is connected to the conductive fabric through two snap fasteners. Thus, the power controller and the conductive fabric form an electric circuit around the waist.

Fig. 44 Conductive fabric area of the warmX®-undershirt [104]

The shirt can already be bought at the online shop of the company. The product palette ranges from 100% merino wool shirt, to 100% Polypropylene and 50% cotton and 50% acetate shirt for women and men. The prices range between 248 and 258 Euro [104].

Medical research has shown that infra-red radiation is of benefit in the treatment of soft tissue, muscular injury and strain. The company Gorix therefore developed the ‘INFRA-THERM THERAPY SYSTEM’. The system is of low voltage and consists of an impregnated infra-red emitting element that is encapsulated in a multi-layered sandwich construction. With this construction it is possible to guide the x-rays in the right direction, avoiding that they are radiating out in random manner. They produced heated diving suit and heated blankets for horses [105].

2.1.4.2.1 Patents published

2.1.4.3 Wearable electronics for health, wellness, motion, fitness or mood

Wearable electronic garments can incorporate a variety of medical sensors and monitoring devices to record the physical status of humans as well as their environment on a continuous basis. Information can be stored and downloaded at a later time or directly transmitted in real-time to a monitoring station.
Additionally, sensors are attached to such as bandages to determine factors that impact on a variety of problems, e.g. poor blood circulation or bedsores.
This chapter deals with wearable electronic devices for the detection of specific features like heart rate, respiration rates or body temperature.

In 1998, several partners from industry and also academic institutions (Reima-Tutta Oy, The University Of Lapland, The Tampere University of Technology, Suunto Oy, Polar-Electro Oy and DuPont Advanced Fibre Systems) started a smart clothing project to develop a functioning smart clothing prototype that increases the wearers possibilities of survival in arctic conditions and to increase safety to prevent accidents. This Siberian suit incorporates a heart rate monitor with embroidered electrodes, acceleration sensor, several thermal sensors and a humidity sensor. For these purposes the prototype consists of 3 textile layers:

- the external layer consists of a textile material adapted to outside circumstances
- the middle layer is a fleece which has to produce heat

- the inner layer is made of Coolmax[3] or Outlast®. The heartbeat sensors are embroidered in this layer, using Aracon®. Electrically heated Gorix® panels provide local heat

A specially designed CPU (8MB flash memory and 16 MB RAM), based on a Hitachi H8/3003 micro controller, was integrated in the back of the external layer. Motion sensors and a wireless communication unit were put in the head control unit. In addition, 5 more processing units were incorporated in the suit.

Thin, flexible cables for energy transmission between the different instruments were hidden in the garment structure. Conductive fibres were used for data transmission. A GPS (Global Positioning System), as well as a Cellular engine for mobile communication were integrated in the suit. After testing different possibilities, conventional batteries were chosen for the energy provision. It must be possible for the batteries to operate for 24 hours and to be rechargeable at the snowmobile.

The suit is capable of making autonomously the decision of calling for help when an accident takes place. However, besides emergency functions, the suit can be used for navigation, receiving weather forecasts and present duration of daylight [106].

Another example from the healthcare sector is the LifeShirt marketed by the American company VivoMetrics. It is a vest with embedded electrodes for heart monitoring and three conductive bands that gauge the movement of the heart and lungs from changes in their magnetic fields. The sensors record up to 30 vital variables, such as ECG, respiratory rate and pulse. A belt-mounted device records the data and can send it to a doctor who might notice dangerous patterns and adjust medications accordingly. However, the shirt simply acts as a carrier of conventional cables and electronic devices.

Fig. 45 Optional Serial Expansion Module (SEM) of the Lifeshirt

[3] **COOLMAX** is a high-performant fabric, launched by Du Pont and based on the polyester fibre Dacron®. The fabric transports transpiration fluid from the body to the external layer of the textile, where it dries faster than with a traditional textile.

A similar idea to the LifeShirt is the SmartShirt. But instead of using conventional cables like in the LifeShirt, electrically conductive and optical fibres are woven in the garment that serve as data transmission lines, so that different sensors can be attached directly to the shirt. Initially developed at the Georgia Institute of Technology for a project funded by the United States Navy, the shirt is now produced and marketed by the company Sensatex Inc. by a licensing agreement. The SmartShirt functions like a computer to monitor different parameters of the wearer, like penetration, respiration, heart-rate, temperature, caloric burn and blood pressure. Two prototypes (third and forth generation) are illustrated in Fig. 46.

Fig. 46 SmartShirt

The shirt utilises the so-called Wearable Motherboard™ (described in section 2.3.3.1). Thus, broad based sensors are integrated to eliminate the need for loose wires and discomfort. The technology allows several sensors to be mounted at different locations on the garment and allows information to be transferred to and from the sensor.

The textile platform, illustrated in Fig. 47 collects data from the various parts of the human body and a wireless communication/data management software platform routes it to a small transceiver device attached to the shirt. Collected data is processed and transmitted via the internet for biomedical monitoring and wearable computing applications.

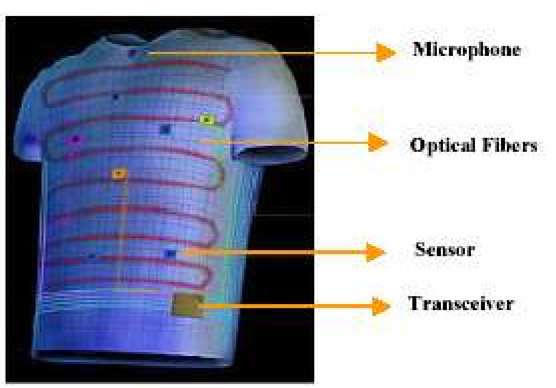


Fig. 47 SmartShirt Texile Platform

Together these platforms form a versatile framework for incorporating sensing, monitoring and information processing devices for biomedical monitoring and wearable computing applications [24].

Turning now the attention to other inventions, it can be stated that the Finnish company Polar introduced a flexible belt with a one-channel ECG and a transmitter to send data to a wrist receiver. The analysis of the heart rate enables the management of fitness, weight, rehabilitation as well as professional training [56].

The American company Textronics Inc., Invista's electronic textiles spin-off company, is involved in the development and marketing of electronic textiles that are used periodically monitor biophysical activities. They follow two different pathway, on the one hand they created textile electrodes for monitoring the heart rate and on the other hand they developed a fabric sensor for dual monitoring – the heart rate and respiration. The former product – integrated electrodes – are compatible with leading heart rate monitoring equipment, whilst the second product uses a proprietary optical technique. Thus, sensing is achieved via light transmission through the textile structure. The working principle is illustrated in the following drawing.

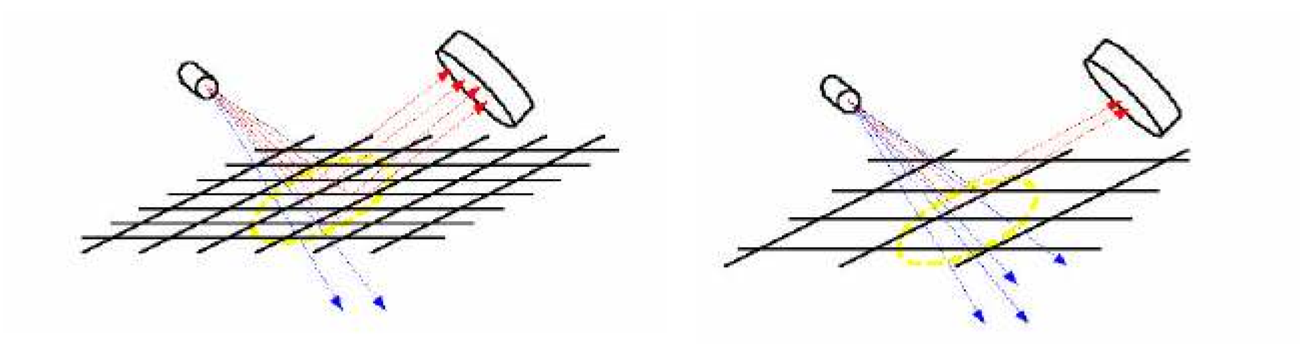


Fig. 48 Working principle of optical sensor [107]

In the left sided picture the initial situation is demonstrated; the optical sensor meets the fabric in a neutral position. Blue arrows indicate transmitted light, while red arrows stand for reflected light. When the wearer of the textile breathes, the fabric expands, as shown in the right sided drawing, and consequently less light is reflected [107].

Textronics Inc. recently founded the trademark NuMetrex, which is a heart sensing sports bra. The system comprises a bra with a knitted sensor into the fabric that picks up the wearer's heart beat and relays it to a transmitter. The transmitter (non-textile) is snapped into the front of the bra, captures the heart rate data and transmits it to a heart rate monitoring watch (also non-textile). The watch displays the wearer's heart rate. In the following, the textile material is depicted:

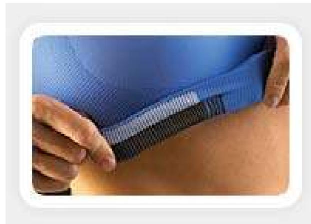


Fig. 49 NuMetrex textile by Textronics

The NuMetrex bra is the first product of the company that is offered to consumers now [108].

Another wearable health system is the Bodymedia Health Wear Armband, which is worn on the back of the upper right arm. It focuses on weight management by measuring movement, heat flux, skin temperature and the galvanic skin response allowing accurate calculations of energy expenditure [56].

The Belgian research group STARLAB has developed a prototype jogging suit which registers the heartbeat, on the basis of which a certain type of music is played. The music is adapted to the heart rhythm and sends the jogger to a higher or lower tempo. Via a mobile telephone, the information is send to the sports club by e-mail. The prototype is a t-shirt consisting of different layers. In the cuffs and in the collar, warmth sensors and microphones are integrated. At the outside, the garment registers the weather conditions and the field characteristics. By measuring all these internal and external factors, the jogging suit can analyse the movements and give suggestions about the duration and the intensity of the exercise.
A smart card holds the data of the personal training programme of the sportsman. When the jogging suit notices that the wearer is getting tired, it can encourage him to continue. If necessary, it can also adapt the training programme of the next session.

The Stanford Lifeguard system has been designed for extreme conditions. It consists of physiological sensors, a cigarette packet sized box and a base station [56].

A pioneer in 'intelligent bandages' is the American firm BioKey of Wauwatosa. They developed an intelligent eye patch used for the treatment of a 'lazy eye', a frequently occurring problem with children. The child has one eye that is much weaker than the other. This leads to a diminished visual sharpness, a decreasing depth sight, and possibly a generally diminished sight. To be effective, the problem should be taken care of at young age. It is not self-evident however to impose the child to a strict schedule of periods it has to wear the eye patch. The attending doctor has to completely rely on the information the parents have given him on the subject. Nevertheless, wearing the eye patch on prescribed periods of time is of crucial importance for the therapy to succeed. The intelligent eye patch aims at providing the doctor with objective data about the eye patch wearing schedule. The eye patch consists of an absorbing cushion and an adhesive strip. The cushion contains a microchip, a contact sensitive sensor, a timekeeper and a battery.

The microchip and the timekeeper register a signal when the eye patch is in contact with the eye and a second signal when the contact is broken off. The duration of the signal is saved in the memory of the microchip. The eye patch stores and processes information that is useful for an appropriate treatment of the aberration. The cushion also has a data port, so that an external link can be made between the microchip and a computer.

For healthcare, wellness and fitness applications, strain-sensitive fabrics, introduced in chapter 2.1.3 are often used for the monitoring of body motion and change of shape [47]. The Intellitex Suit has already been pointed out in a previous chapter. Some more examples can be found below.

For example, University of Pisa constructed an undershirt for continuous cardiopulmonary recording using woven or knitted strain-sensitive fabrics [56].

A foam based pressure sensor was produced at the University College Dublin and Dublin City University in order to measure breathing, shoulder movement and neck movement of the wearer. For this purpose, a polymer synthesis methodology was developed to create a textile-like structure by coating an open-cell polyurethane (PU) foam with a CEP (polypyrrole). The method involved soaking the substrate, the PU foam, in an aqueous monomer and dopant solution. An aqueous oxidant solution was then introduced into the reaction vessel to initiate polymerisation. This lead to the precipitation of doped PPy, which subsequently deposited onto the PU substrate. The foam based sensor was sewn between two garment layers [109].

Fig. 50 Schematic presentation and photographs of the foam-based pressure sensor integrated into a garment structure designed by Lucy Dunne

In the left drawing in Fig. 50 the garment structure and sensor layout is illustrated; on the photographs the prototype pressure-sensitive torso garment can be seen 110, 111, 112, 113].

Research on a special knee bandage based on conductive polymers with integrated sensors is carried out by the Institute for Intelligent Polymer Research at the University of Wollongong. The device is a lightweight fabric sleeve worn around the knee with a specially coated stretchable strip of polymer-coated fabric attached over the patella. The coated fabric acts as a strain gauge and emits an audio tone when the knee bends beyond a pre-set angle. If, on landing, the knee angle is insufficient, immediate feedback is provided to the player by means of no audio tone, allowing the player to adjust their landing technique accordingly until they hear the sound [114, 115].

Another wearable joint monitoring sensor capable has been developed by the Massachusetts Institute of Technology, department of mechanical engineering, that is capable to monitor continuously day-to-day. By integrating conductive fibres into flexible, skin-tight fabrics surrounding a joint, angular displacement of such is possible to be measured [116].

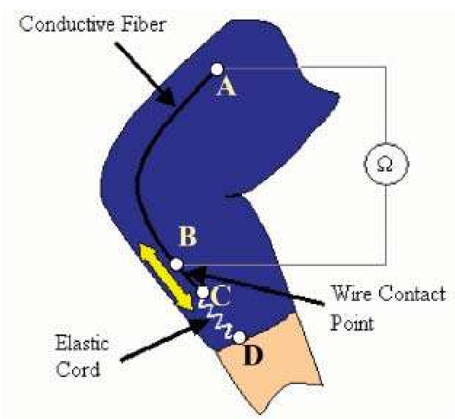


Fig. 51 Joint monitoring sensor; the joint monitoring sensor; Left: Schematic view of the sensor design; one thread is running lengthwise across a single-axis knee joint; Right: Prototype of the sensing garment; pants with conductive sensors for lower body monitoring

In Fig. 51 the single conductive fibre sensor integrated into the pant is shown. At point A, one end of the conductive fibre is attached to the nonconductive, form-fitting garment. At point B, along the conductive fibre, a wire contact point is stitched permanently into the nonconductive fabric allowing the conductive fibre to slide freely back and forwards. A coupled elastic cord keeps the other end (point C) of the conductive fibre in tension, which is permanently attached to the remote side of the joint, point D. Stretching in this coupled material will consequently always occur in the elastic cord, CD, and not in the conductive fibre, AC. The elastic cord will change length upon the movement of the joint having the result of the coupled conductive fibre to freely sliding past the stationary wire contact point at B. The length of the conductive fibre between the points A and B will change due to the rotation of the joint. However, the electrical contact with the stationary wire is constantly maintained. Thus, it is possible to measure the resistance continuously across these two points A and B and to linearly relate it to the length [117].

Pressure sensor fabrics are capable to provide information on pressure field distribution and its temporal variation when integrated in underwear or in a wheelchair. Thus, they can be used to detect when the user has been seated in a certain position for to long and can prevent decubitus. A research group at the University of Bologna in Italy is working on a concept for a pressure-sensitive fabric.

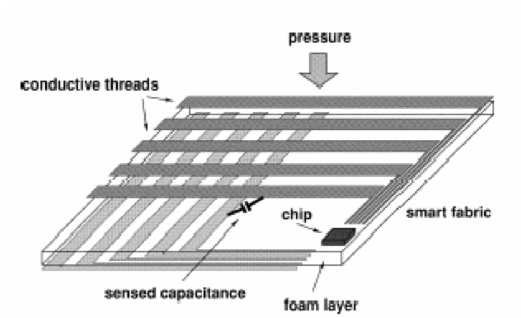


Fig. 52 Concept of pressure sensitive fabric [118]

The system is based on a chip that can be placed in the corner of a pressure-sensitive fabric and can produce a digitally processed image. In order to map the pressure that is applied over the fabric surface, the capacitance variation between rows and columns of conductive fibres, wrapped around a synthetic foam layer (insulator), is detected [118].

The Bolton University has developed and commercialised a thermal monitoring blanket used for measure the temperature of the sleeper and warn of major changes.

Researchers at the Georgia Tech are developing a garment that is capable of identifying the location of bullet holes using a mesh network consisting of conductive and fibre-optic yarns.

A shirt with integrated breathing rate sensors, a shock/fall sensor, temperature sensor and electrodes for electrocardiogram has been developed within the French project VTAMN (Vetement de Tele-Assistance Medicale Nomade). The breath rate sensing is performed by sinusoidal-like conductors integrated into a textile band, whereas a shock/fall identification is enabled by an electronic monitoring of the three-component acceleration of the body [119].

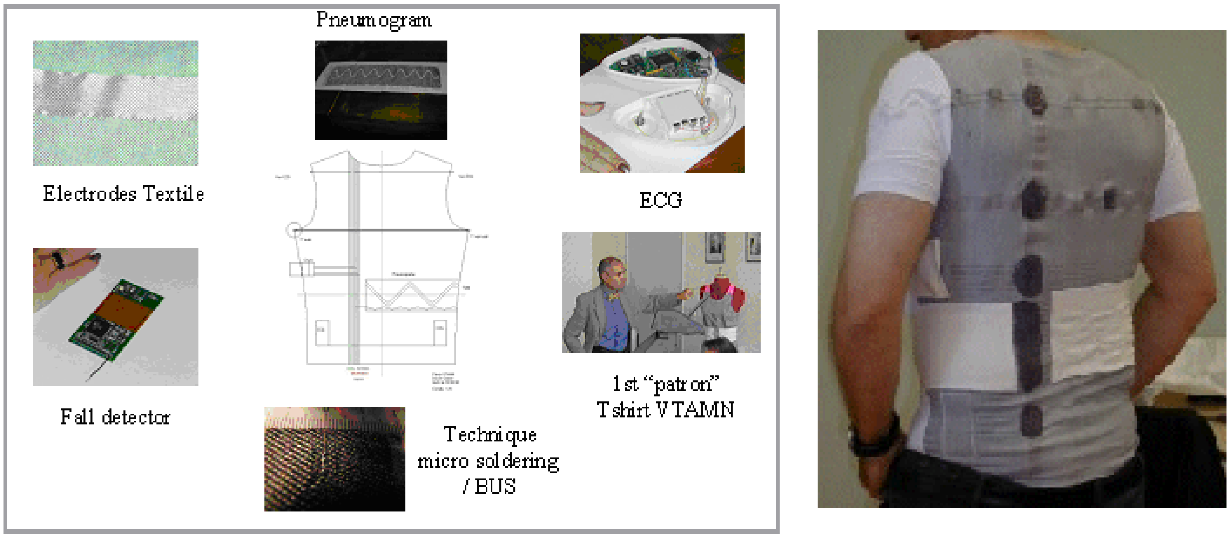


Fig. 53 Embedded electrodes and pneumogram [119]

There is, next to the Intellitex suit, a monitoring system commercialised on the market to prevent S.I.D.S.-Sudden Infant Death Syndrome (Crib death), the Mamagoose. It is a washable pyjama suit with detached electrodes with which heart and respiration rate can be measured.
However, this system is an example for a biomedical device for babies and small children which are relatively cumbersome resulting from a merge of existing tools and sensors on regular clothes and do not use textile structures to carry out measurements of physiological parameters.

The project Scentient Beings explores a living dress as a sensitive smart second skin. It uses multi-sensorial clothing which can deliver fragrance and medication. The idea to use cloth as a new, emotional skin came up by Jenny Tillotson, researcher at the Central Saint Martins School of Art & Design. She researched how scent influences the health and well-being and created a smart dress and sensitive shoes.
The smart dress, which is illustrated in Fig. 54, is based on how scents are being produced and recognised. It mimics the body's circulation system, the senses and scent glands. The system can for instance be used to register the body's state of health or to produce a refreshing deodorant when the wearer is sweating.

Fig. 54 The smart second skin [120]

The Sensitive Shoes are capable to administer an elaborate foot reflex massage by stimulating various pressure points. The ball of the foot touches the solar plexus point, the centre of emotional energy, adding a healing effect to the wearer's walk. Fig. 55 shows the Sensitive Shoes.

Fig. 55 The Sensitive Shoes [120]

The sole shape is customised to the wearer's foot. A battery, a micro switch LED and a battery holder are integrated into the front heel made out of an acrylic tube. The reflexology points are positioned above the acrylic tube [120].

The MIT spin-off company VectraSense also announced a computerized shoe by the end of the year 2004, named 'verb for shoe'.

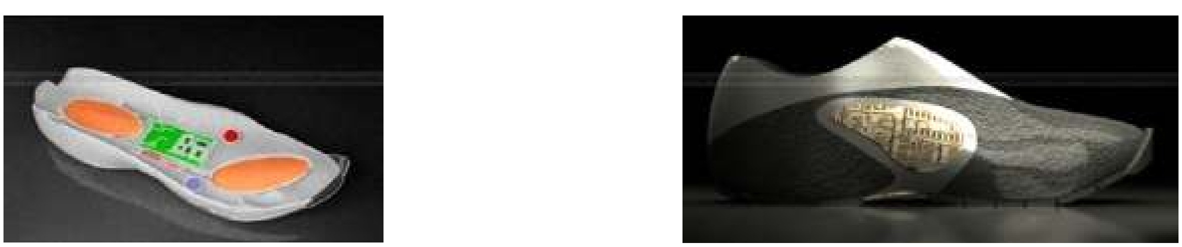


Fig. 56 Prototype of Verb for Shoes by VectraSense [121]

The shoe is capable to sense the activity level and can adjust according to the wearer's movements. The shoe can be wireless linked to a computer or other shoes of the same type. This is performed through an embedded computer in the sole that learns individual movement patterns and adjusts the shoe accordingly. This computer also allows for wireless data storage and information sharing [121].

Alexandra Fede designed and produced a dress that massages the wearer periodically, the so-called JoyDress. She introduced a prototype at the Avantex International Innovation Forum and Symposium in Frankfurt in 2002 where she won the prize for innovation in fashion engineering.

Fig. 57 JoyDress prototype [122]

The fabric, illustrated in Fig. 54, contains a series of vibrapads, which are energized by en electronic control unit that enables timing and strength to be pre-planned. The prototype dress has the vibrating pads sewn on the fabric [122].

Lisa Stead, also working at the Central Saint Martins School of Art & Design, aims also to connect fashion aesthetics with materials science and electronics in order to provide reactive emotional aesthetics and interactive personalisation for the wearer. Hence, she designed the Emotional Wardrobe, a collection of worn and unworn garments that represent and stimulate emotional response. The worn garment responds to the wearer via body sensors, translating an inferred change in emotional state with a change in the garment aesthetics. LEDs create various patterns of colour, which glow from behind contours in the dress. The rhythmic patterns associated with music and emotion and could be used to improve self-awareness of moods or enhance and explore social interaction and self-expression. This concept could also encourage interaction between the wearer and society. Therefore she used for instance sensors that measure body signals such as galvanic skin response, which are transferred wirelessly from the dress to the AffectiveWare platform. The platform contains personal 'emotional' data from the wearer, collected from a series of emotional testing exercises. The data base analyses the readings by matching them against the held information and selects an emotion and a corresponding garment display program. This command is send wirelessly back to the dress to trigger the light display [123].

The group of unworn garments 'live' around the house. They suggest that clothing left unworn could assume an emotive function by reacting to human presence. By representing human characteristics, fears and fantasies, they seek to provoke paradoxical emotions in the viewer. The collection comprises a dress that can be seen in Fig. 58, a scarf and a jacket. The dress ‘Desiree’ comprises electroluminescent 'sequins' that flirts with the viewer. When it senses the presence of a human it shimmers, the signals becoming more excited as the person draw nearer, imitating the human gaze during the ritual of flirting.

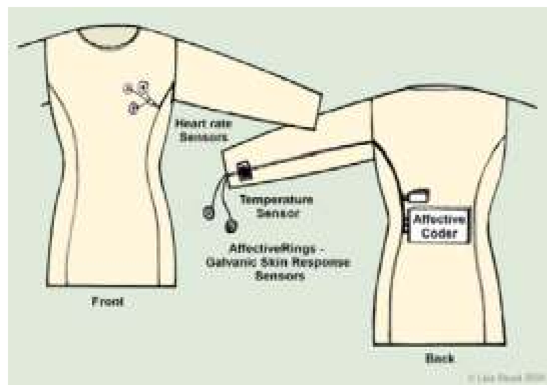


Fig. 58 Dress ‘Desiree’ out of the Emotional Wardrobe collection by Lisa Stead [124]

The scarf ‘Pikme’ works accordingly. It uses electroluminescent wires woven within a tactile knit and motion sensors to activate a response. As soon as a person approaches the scarf, the signals become more intensive. The jacket ‘Icaris’, a feathered jacket, uses thermochromic inks and conductive heating materials with timers to initiate the colour change in the feathers [124, 125].

CuteCircuit veers towards similar products as Lisa Stead. The group of Wearable Technology developed several different prototypes of smart dresses or shirts among which is the KineticDress. The dress reacts to the wearer’s activity and mood. This is achieved by embedding sensors into the textile that follow closely the body of the wearer. The sensors are able to capture the wearer’s movements and interaction with others and display this data through the electroluminescent embroidery that covers the external skirt section of the dress. Depending on the amount and speed of the wearer’s movement the electroluminescent embroidery changes pattern, displaying the wearer’s mood to the audience. The algorithmic program that controls the KineticDress is designed to follow the pace of the wearer: a still pose, when sitting alone shows a black dress, when the wearer starts moving and interacting with others the dress slowly lights up with a blue-circles pattern that is moving [126].

Fig. 59 The KineticDress by CuteCircuit [126]

Additionally, Philips Design prototyped two garments with incorporated electronics that express the emotions of the wearer. Bubelle, the "blushing dress" comprises two layers; the inner one is equipped with sensors that respond to changes in the wearer's emotions and projects them onto the outer textile. It behaves differently depending on who is wearing it. The other prototype is Frison, a body suit that reacts to being blown on by igniting a private constellation of tiny LEDs. Both measure skin signals and change light emission through biometric sensing technology [127].

Fig. 60 Prototypes of emotional clothing, Bubelle and Frison, produced by Philips Design [127]

A researcher of the MIT team, Maggie Orth, established the company International Fashion Machines (IFM) that is specialised in electronic textiles and textile design. They presented the Firefly dress in 1997. It is a lighting electronic dress with fabric circuitry, power distribution plane and sensors. It embellishes the wearer's motion with an ever-changing display of light. Its first part is a skirt, handmade from two layers of conducting organza (one supplying power and the other ground) separated by a layer of nylon netting. Light-emitting diodes (LEDs) with fuzzy conductive Velcro ends for electrical contacts are placed throughout the netting. When both ends of an LED brush against the power and ground planes, the circuit is complete and the LED lights. The bodice (with a conductive front panel) and the necklace form a second dynamic element. The necklace is a simple analogue computer, powered when any of its conducting tassels brush against a plane of conducting organza sewn to the front of the bodice. Each tassel has its own resistor network and provides a different colour bias to the red, green, and blue LEDs on the face of the necklace. It is exhibited at the National Textile Museum in Washington D.C. [34].

Fig. 61 Firefly Dress

2.1.4.3.1 Patents published

The first patents on electronic textiles were assigned in the late 60's, namely a woven electrical connector with wires and dielectric threads in warp and weft direction and a woven high-frequency transition line consisting of electrically cables woven in. They find applications in circuitry and in transmitting high-frequency electrical signals, respectively (US patents 3414666 and 3447120).

In 2003, Alan Magill published a patent (US patent 2003/0212319) in which he described a health monitoring garment, especially for electrophysiological cardiac and respiratory monitoring. The garment employs a means of conducting electricity from the surface of the skin, through the fibres of a fabric to another fabric which is removable attached to it. This removable fabric contains a microprocessor, telemetry and a power source.

A woven electronic textile is claimed in the US patent 2004/0009729. The woven fabric contains electrically conductive yarns in warp and weft direction. The conductive yarns comprise an elongate substrate including at least one electrical conductor that provides an electrical contact to the electronic devices.

In US patent 2004/0092186 a textile electronic connection system is claimed. The system comprises a textile ribbon with integrated transmission lines running lengthwise in the ribbon. A fastener is used to connect ribbons and thus the transmission lines to each other and to allow a quick connection and disconnection.

The University of Manchester Institute of Science and Technology in Manchester, U.K., developed a knitted transducer for monitoring vital signs of the wearer. The knitted resistive strain gauge comprises a single knitted layer of a conductive electromeric yarn and a non-conductive elastomeric base yarn. The non-conductive yarn is used for the base knitted structure in which the conductive yarn is laid in course direction in a predefined e.g. rectangular shape. An increase in resistance will occur due to stretching of the conductive yarn. The transduction zone is connected to the transducer device by using conductive fibres in the first and last courses of the transduction zone (patent WO 2004100784).

Philip Leonard patented a textile thread with incorporated electronic elements in US patent 2004/0115430. The threads can be processed into a textile assembly so that the threads can form an intercommunicating system used for instance in computer, transmitter and receiver, and radio systems.

A Finnish consortium patented a sensor to be placed on the skin that can be integrated in a garment and has a contact layer in contact with the skin containing conductive fibres for receiving signals (US patent 2004/0138546).

Philips patented a wearable body-fat sensor under US 6718200. The sensor is made of a fabric having an electrode and sensors. They developed for instance a pair of shoes with a weight-measuring sensor, a conductive textile and an impedance measuring circuit. The electronic components are coupled so that the body-fat composition of a person can be measured based on the data received from the weight sensor and the impedance measuring circuit.

2.1.5 Applications in the interior textile sector

There is also a lot of interest in integrating electronics with interior textiles. Although there are no examples or products on the market by now, there are many activities going on in the research stage,

especially in carpets. In this case a textile-based mechanism is used to respond to an external influence, producing a reaction in terms of appearance or a radio signal.
In the following, we subdivided the research projects and the available products according to their performance as for the applications in the clothing sector.

2.1.5.1 Electronic textiles for communication, information and entertainment

The "Interactive Tablecloth", invented by International Fashion Machines and Philips, is probably the first inventions for electronic interior textiles and was presented in 1999. A power circuit, woven into the washable linen tablecloth, provides inductive cable-free power to the electric appliances on the table. This research is triggered by the fact that textile is an excellent product for the creation of ambient intelligence. Equipped with suitable electronics, it can sense the environment, respond to the mood of the inhabitant and connect to other devices in the room and as such react to the desires of its inhabitants. This was first expressed by Philips "This is our vision of 'Ambient Intelligence': people living easily in digital environments in which the electronics are sensitive to people's needs, personalized to their requirements, anticipatory of their behaviour and responsive to their presence".

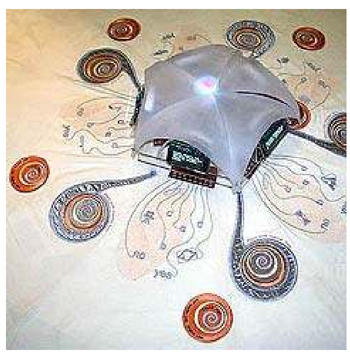


Fig. 62 Embroidered tablecloth [34]

The electronic tablecloth is a sensor surface that allows users to interact with a computer and with each other in the context of a social function. Attendees identified themselves to the system by setting their assigned "coaster tags" on the swirling pattern, above which are embroidered the words "Place your coaster here." The coaster is in turn a capacitively coupled radio frequency identification device (RFID) tag, and is read by the tag reader in the tablecloth when the user sets it on the swirling pattern and touches the fabric electrode on top of the coaster. The computer then enters a dialog with the user through the appropriate fluorescent display and keypad. Five keypads and five capacitive tag readers are embroidered to the tablecloth [34].

Another example in the field electronic interior textiles is the “Thinking carpet” developed by the German company Vorwerk Teppichwerkein co-operation with Infineon. The carpet is a current development with integrated heat and pressure sensors. In this case, sensors act as touch detectors and light-emitting diodes (LEDs) as display elements. However, these do not appear to have a textile element, they are woven into the carpet structure by the use of wires. A prototype of the “Thinking carpet” was presented at the international Orgatec trade fair in Cologne /Germany in 2004 [58].

The IT+Textiles research programme of the Interactive Institute in Sweden (already mentioned in 2.1.4.1), funded by VINNOVA, the Swedish Agency for Innovation Systems, intends to explore the potential of design in the field computational technology and textiles. For this purpose, attention is paid to technical possibilities of these new materials. In the scope of the programme ‘The Energy Curtain: Energy Awareness’ was created. The Energy Curtain is a window shade woven from a combination of textile solar-collection and light-emitting materials. During the day, the shade can be drawn to the extent that people choose to collect sunlight and, during the evening, the collected energy is released so that pattern glows and thus gives light. The first prototype of the curtain consists of two layers, an inner and an outer layer, which are sewn together at the edges and horizontal seams secure the entire span of the curtain.
The inner layer, which faces the inside of a room, has a cotton plain weave ground structure. Into this structure optical fibres are inserted. The ends of the fibres are connected to white LED lights, which are hidden together with the cables and other electronic parts in between the inner and the outer layer of the curtain. The lighting effect of the inner layer is a result of the light from the LEDs conducted through the optical fibres. In order to amplify the light emitted from the optical fibres, a reflective or a fluorescent yarn is inserted into the weaving structure underneath each fibre. Thus, an effect of increased light reflection is caused.

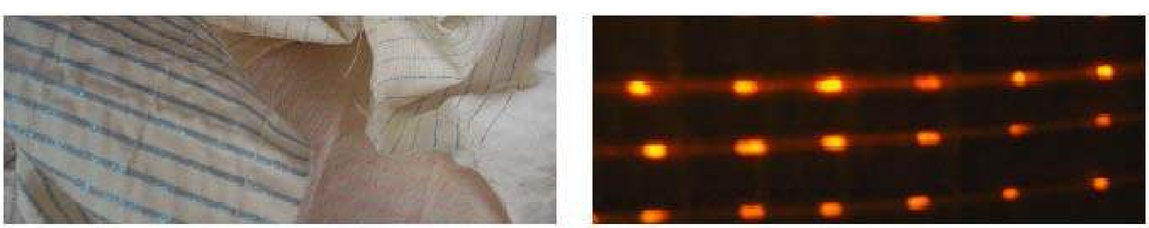


Fig. 63 Inner layer of the energy curtain with integrated reflective and afterglow materials

The outer fabric layer that faces the window glass is made out of a cotton weave construction. As the structure consists of long floats, solar cells can be inserted. They are each soldered to a wire that conveys the electricity collected from the sunlight away for storage. So far in the prototype construction, an extra wire is needed to connect the solar cells to each other. However, this wire will be replaced by a stainless steel fibre in future models [8, 72].

One of the first concepts that emerged within the IT+Textile programme was the ‘Interactive Pillows’. These pillows are a pair, so that the two persons of a loving couple have one each. If one lover hugs his/her pillow, the other pillow will light up and become warm. The pillow being hugged will do the same. In order to communicate, the pillows are connected via internet, a mobile phone network or by other wireless devices. The principle is based on a switch consisting of a piece of foam rubber sandwiched between two layers of aluminium foil. The foam rubber has tiny holes in it, so that the aluminium foils contact each other when the foam is compressed. For short distances, the communication between the pillows is based on radio frequency. The radio modules work as a virtual serial cable. A small Basic X BX24 is hidden within each pillow and operates by interpreting data from the switch, communicating with the other pillow and turning on the electroluminescent wire. A Darlington driver circuit provides enough current for the electroluminescent circuits to be activated. To ensure the communication over greater distances, two additional base stations have been constructed, which convey the serial data to a computer. The computer in turn can send the information via TCP/IP protocol to another computer.

Fig. 64 Interactive pillow [72]

The pillows are targeting for instance separated parents not living full-time with their children, or people who travel frequently, or even couples having long-distance relationships [8, 72].

Another pillow designed for entertainment is the iPillow^{TM} by iPod, which serves as a portable mp3 loudspeaker. The pillow speaker contains two built-in speakers, each at the end of the pillow, which run by batteries. The mp3 player is plugged into the pillow and a zippered mesh bag holds the player in place.

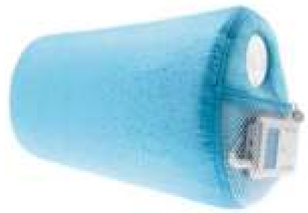


Fig. 65 iPillow™ [128]

However, the functional element in the pillow still remains an external and rigid electronic device. The pillow can be ordered via internet for US $ 75 [128].

A researcher of the MIT team, Maggie Orth, established the company International Fashion Machines (IFM) that is specialised in electronic textiles and textile design. The team has developed and is now commercialising a soft and fuzzy light switch POM POM.

Fig. 66 Light switch POM POM by IFM [129]

The switch is made fully out of stain-resistant textiles and is capable to dim and adjust light level in any room [129].

2.1.5.2 Electronic textiles for thermal control

This section scarcely bears any prototypes or products.

One of the rare to find products are electroconductive textile heaters. The American company Thermosoft has developed them and now markets them under the tradename FiberThermics®.

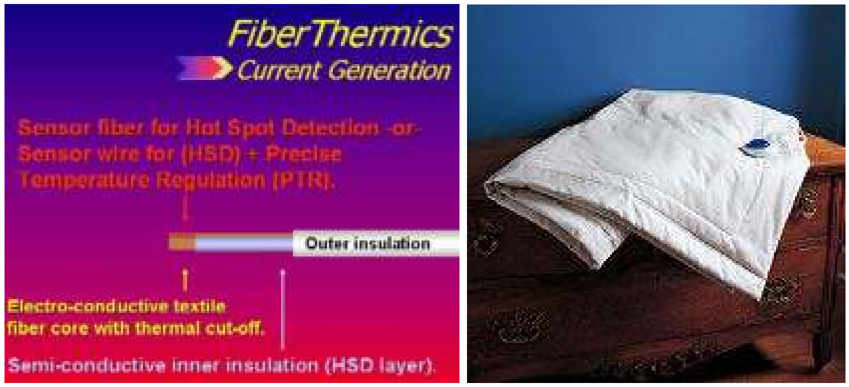


Fig. 67 FiberThermics® by Thermosoft [130]

The picture shows the principle of the technology. It has been incorporated in blankets to conduct heat evenly throughout the blanket. The outer material is a fleece that covers a polyester fibrefill. Heat is activated by a solid-state electronic control with multiple settings. Next to the blankets which can be bought for 130 US$, also mattress pads, mattresses and sleeping backs are commercially available [130].

2.1.5.3 Electronic textiles for health, wellness, motion, fitness or mood

Together with the Fraunhofer-Institute for Algorithms and Scientific Computing and the companies Suess Medizin-Technik and the Telematik-Center TMD, the German company ITP GmbH developed a telematic patient surveillance system based on a textile sensoric bed cover. The two-layered textile bed cover consists of several systems to register the parameters measured by integrated textile sensors. Different textile sensors have been constructed in order to measure several parameters, such as surface pressure, temperature and humidity. In the left picture below, the carrying layer with six pressure sensors and one humidity sensor is shown. The picture in the middle depicts the structure of the textile pressure sensor, while the right picture illustrates the textile humidity sensor.

Fig. 68 Textile sensors used in the bed cover [131]

The textile pressure sensor was developed by ITP, in total 12 pressure sensors are embedded in the cover and work independently from each other. The humidity sensor was developed by the TITV in Greiz /Germany. It is capable to detect the relative humidity within the bed cover. As it is used as a measure for incontinence, it is located in the centre of the cover near the surface. The signals are transferred to a plug that is also part of the bed cover and controls and analyses the measured signals [131].

The Center for Future Health at the University of Rochester has established the Smart Medical Research Laboratory. The Centre's overall goal is to develop an integrated Personal Health System, so all technologies needed to guarantee health are integrated and work seamlessly. This technology will allow consumers, in the privacy of their own homes, to maintain health, detect the onset of disease, and manage disease. The data collection modules in the home will start with the measurement of traditional vital signs (blood pressure, pulse, respiration) and work to include measurement of 'new vital signs', such as gait, behaviour patterns, sleep patterns, general exercise, rehabilitation exercises, and more.

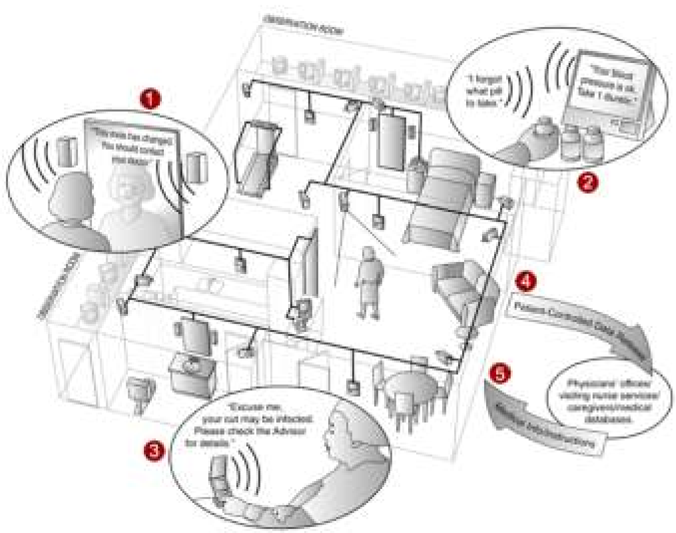


Fig. 69 The Smart Medical Research Laboratory [132]

This five-room house, visualised in the drawing above, is outfitted with infrared sensors, computers, biosensors, and video cameras for use by research teams to work with research subjects as they test concepts and prototype products.

Researchers observe and interact with subjects from two discreet observation rooms integrated into the home. These research teams address the technical, informational, and human issues that will form the basis for affordable health care products that can be easily used by people with varying abilities [132].

2.1.5.4 Patents published

2.1.6 Applications in the technical textile sector

Technical textiles are a fairly fragmented domain with 3 important areas: protective textiles, transport textiles (automotive, railway…) and textiles for construction. The technicality of the products is very high as they are expected to meet very high performance requirements. Because they are used in many different applications they combine functional properties with structural properties.

In the technical textile sector smart textiles are used for resistive heating in car seats and composites. In the following two examples are given.
The British company Terram is producing spun bond nonwoven geotextiles with built-in conductors and radiofrequency transducers for use under railway tracks, called PW 5. These are designed to show the strain being experienced by geotextiles [58]. They compose of a mixture of polypropylene and polyethylene with detectable metallic strips. Each conductive strip must contrast with essentially non-conductive material surrounding it [133].
Woven and knitted meshes, either of carbon fibre or carbonised polyacrylonitrile (PAN), incorporating electrodes attached to the vehicle's power supply, are used in vehicles to provide heat to a car seat squab. The meshes are laminated to or between conventional fabric layers. Thus, there is a trend visible from wire-based systems to fibre based systems. However, due to current prices of textile based heating systems, the application of such is still restricted to top-end application, such as aircrafts, racing yachts and Formula 1 racing cars. The British company Gorix can be exemplarily pointed out as a licenser of PAN-based woven meshed technology.
The Gorix PAN mesh is further used in an airbag deployment sensor; the mesh combines heating functions with a pre-warning system based on filed interference (Daimler-Chrysler).

Further, pressure sensors are applied in the interior of automotives. For instance, the ElekTex® fabric touchpad by Eleksen is utilised by the supplier of seating and interior systems Johnson Controls in its controls for car interiors [38].

Additionally, Eleksen Ltd. designs and manufactures the peripherals for Microsoft's Origami Ultra-Mobile PCs, which were presented at the CeBit exhibition in Hannover /Germany in March 2006.

Fig. 70 A prototype ElekTex® keyboard sleeve for Microsoft's Ultra-Portable computer [134]

The peripheral designs include ElekTex® keyboards, which are either connected to the PC by a short-range wireless signal (the Bluetooth standard) or which use a universal serial bus (USB) port. The touchpad provides an interface technology for development of dynamic and feature-rich peripherals and can be used, for example, to enable typing on tablet PC cases, provide portable typing interfaces for leading mobile devices and extend the usability of mobile PCs with media and data entry controls [134].

Research is currently conducted by Konarka Technologies Inc. and the Ecole Polytechnique Fédéral de Lausanne (EPFL), aiming at the development of photovoltaic fabrics, based on nanotechnology. The production of a photovoltaic fibre, able to produce electric energy from the sunlight, has already been demonstrated. The company Konarka is specialised in plastics that convert light to energy and hence in the co-operation with the Swiss school they incorporated a light-activated power plastic into nylon, so the nylon becomes photovoltaic. However, strength, thickness and electrical performance of the fibre need to be optimised in textiles in order to use as reinforcement in concrete and masonry [135].

Photonic Inc. is active in the field of buildings. They developed a system capable to characterise different structural behaviours in real time. The system is textile integrated.

Appearance changing textiles, like luminescent textiles, also use at least partly electronics to get functionalised. For the production of luminescent textile structures, researchers at the TITV Greiz used a woven double comb structure with electrodes woven in on both sides. The whole structure is coated with an electroluminescent printing paste, which is activated to light by high-frequency voltages [81, 82, 83, 84].

The German Gesellschaft für Intelligente Textile Produkte, ITP, is specialised in producing heating fabrics. Their product line ranges from heating woven structures, over heating nonwoven structures to heating knitted textile structures. Basically, they are using silvered coated Nylon fibres and silvered coated Copper wires. Further, they are developing electroluminescent fabrics, products with integrated textile sensors for gas, temperature, humidity and biomedical information, and fabrics with integrated GPS and GSM [136].

Environmental sensing can detect enemies or potential biochemical threats, such as a woven conductive fabric with embedded button size microphones that detect the sound of remote objects such as approaching vehicles.
Researchers at Virginia Tech developed such a large-scale acoustic beamingforming textile. Woven prototypes are embedded with a communicating network of sensors and computing devices and can continuously run for significant periods of time on a standard nine volt battery [137].

2.1.6.1 Patents published

The IEE International Electronics & Engineering S.A. protected a seat sensor constructed from a spacer fabric (WO 03/093067).

The Siemens AG holds a patent for the production of a fibre with an integrated electronic component. The fibre can be incorporated into a woven structure. They used as a fibre core conductive polymers and coated them by conventional chemical fibres (WO 02/095839).

2.2 *Colour change materials*

2.2.1 Description

This chapter deals with textile structures treated with dyestuff that change colour for either functional or purely aesthetic reasons, in response to some external stimulus. These external stimuli might be for instance acids, alkalis, sunlight, water, mechanical loading and electrical power. The colour changing effect is based on physical and chemical changes in dyestuff molecules and can be either temporary or permanent. In literature these dyestuffs are referred to as smart dyestuffs. Although smart dyestuffs are not yet widely used due to poor resistance to visible light, heat, other external influences and costs, they have the potential to be used to produce smart textile materials. In the following, different types of smart dyestuffs are presented and in which way and extend they are applied on textiles.

In general, forms of colour changing material are produced in an encapsulated form as microencapsulation helps to protect these sensitive chemicals from the environment [138].

2.2.2 Technology

Thermochromism

Microencapsulated thermochromic systems pioneered by the ink industry constitute the active element that received fibre and fabric finish embodiments. The systems comprise a colourless electron-donating chromatic organic compound, an electron acceptor, and a reaction medium generally made up of one or two components. Above the medium's melting point, one of its two components solvates the electron donor and the system is colourless. As temperature drops to the medium's solidification point, solvation ceases, and the electron donor turns to the electron acceptor, which produces a coloured addition compound. These processes are all reversible. The chemical structures of the electron donor and acceptors determine the colours. The reaction medium components, on the other end, control the temperatures at which the colour appears and disappears, as well as the sharpness of these transitions and the colour intensities. Incorporation of ordinary dyestuffs or pigments increases the number of colour combination options [139].

Thermochromic dyes

Thermochromic liquid crystals are commonly used to visually display temperature changes. The crystals are capable of displaying different colours at different temperatures, and with this ability have found a number of niche utilities. Fabrics treated with thermochromic dye change from being a colourful to a colourless product at the time of activation and, if applied with other pigments then effects such as violet becoming red can be achieved. Additionally, products are available that will not be reversible.

In the following, we explain what is meant by the term “liquid crystals”.

The three common states of matter, solid, liquid and gas, are different because the molecules in each state have a different degree of order.

In the (crystalline) solid state there exists a rigid arrangement of molecules which stay in a fixed position and orientation with a small amount of variation from molecular vibration.

In the liquid phase the molecules have no fixed position or orientation and are free to move in a random fashion, so the liquid state has less order than the solid state. The intermolecular attractive forces that keep a solid together are now only strong enough to keep the liquid molecules fairly close together. A liquid can therefore be easily deformed [3].

Fig. 71 Liquid phase

In the gas state the random motion of the molecules has increased to overcome the intermolecular forces and the molecules eventually spread out to fill any container that holds them.

The positional and orientational order is greatest in the solid state and least in the gaseous state.

A liquid crystalline phase occurs in some substances in a temperature region between the solid and the liquid state. In this state the substance possesses some properties of both liquids and solids. A liquid crystal is a fluid like a liquid but is anisotropic[4] in its optical and electro-magnetic characteristics, like a solid [3].

Fig. 72 Liquid Crystal

Liquid crystals can be divided in two categories:

---

[4] An isotropic liquid has no orientational order. In an anisotropic material, the properties depend on the direction in which they are measured.

thermotropic liquid crystal molecules exhibit temperature dependent liquid crystal behaviour, the transition to liquid crystal is accomplished by a change of temperature

lyotropic liquid crystals are materials in which the liquid crystalline properties are induced by the presence of a solvent, with mesophases[5] depending on solvent concentration, as well as temperature.

The main phases of liquid crystals are nematics, chiral nematics, smectics and chiral smectics.

Nematics

By decreasing the temperature from the isotropic phase, in which the molecules are randomly positioned and oriented, to the nematic phase, the material gains an amount of orientational order but no positional order. This orientational order makes it possible to define an average direction of the molecules, called the director n [3].

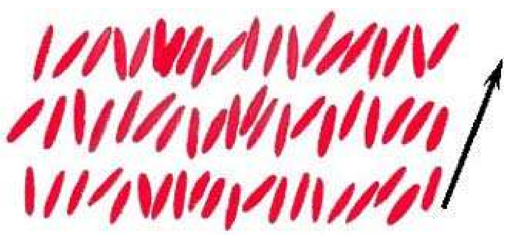


Fig. 73 The director n

Chiral nematic (cholesteric)

In this phase the molecules prefer to lie next to each other in a slightly skewed orientation. This induces a helical director configuration in which the director rotates through the material. The liquid crystals consist of rod-like molecules, which take the form of the steps of a microscopically small spiral staircase.

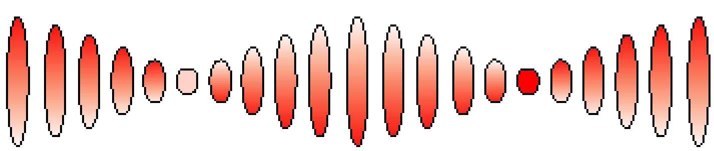


Fig. 74 Chiral nematic phase

An important characteristic of the chiral nematic phase is the pitch p. It is defined as the distance it takes for the director to rotate one full turn in the helix. A by-product of the helical structure of the

[5] Equilibrium liquid crystalline phases formed with order less than three dimensional (like crystals) and mobility less than that of an isotropic liquid. Parallel orientation of the longitudinal molecular axes is common to all mesophases (long-range orientational order)

chiral nematic phase is its ability to selectively reflect light of wavelengths equal to the pitch length, so that a colour will be reflected when the pitch is equal to the corresponding wavelength of light in the visible spectrum. When the chiral nematic phase is cooled down, the helix has the tendency to unwind. This means that the length of the pitch increases and another wavelength will be reflected. When the temperature continues to decrease and the smectic phase is not reached yet, the colour will pass through the infrared. When the temperature rises again, all changes are reversible. The effect of temperature can best be explained by comparing the spiral staircase with a spring. Temperature changes cause the spring to contract or to stretch. A 'spring' in stretched position will reflect another light than a 'spring' in contracted position and hence it has another colour.
It is this class of liquid crystals that is used in the textile industry. Using this variety of liquid crystals, it is possible to achieve significant changes in appearance over narrow temperature ranges (5-15°C) and to detect small variations in temperature (<1°C) [3].

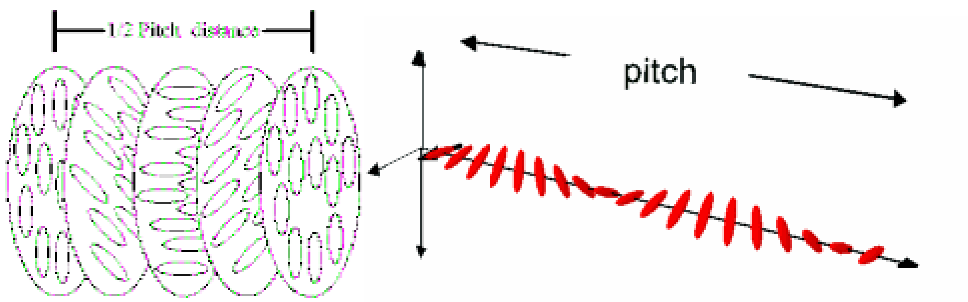


Fig. 75 The pitch

Smectics
At certain temperatures, generally below the nematic phase, the liquid crystal material may gain an amount of positional order. When this happens the liquid crystal forms into smectic phase where the molecules, although still forming a fluid, prefer to lie on average in layers.

Fig. 76 Smectic phase

Since these liquid crystals are in a mesophase, they must be enclosed in microcapsules in order to preserve their thermochromic behaviour. The cover of the capsules consists of gelatine, cross-linked with an aldehyde, which is insoluble in water and protects the content against other solvents and

softeners. These are said to be able to destroy the thermochromic properties. The microcapsules have a diameter between 8 and 15µm. They are applied on the textile substrate by means of silkscreen printing or transfer printing. The ink consists of small capsules in an aqueous binding resin. Since the thermochromism involves reflected light, the effects are best seen against a dark background, which soaks up the light transmitted by the liquid crystal. Only those wavelengths that are reflected by the liquid crystals are observed, and not those that are reflected by the substrate. All the colours, which are not reflected by the print layer, will be absorbed. The temperature at which the colour change should start can be adapted and varies between – 30°C and + 70°C. The temperature at which the colour change occurs can be set accurately to 1°C.
While the changes in colour may be striking and relatively sensitive to temperature, opportunities to take advantage of this technology for textile coloration are limited by the necessity of using dark substrates as well as the requirement that the liquid crystal systems must be microencapsulated [3].

The American company C.T.I. commercialises thermochromic textile screen inks under the tradename DynaColor™. The inks are available in various colours and activation temperatures. The colour change is reversible, so that the original colour will be restored upon cooling.

Thermochromic pigments

In 1988, Toray Industries Inc. developed a multicolour fabric Sway® on the basis of thermochromic organic pigments. This fabric enabled 64 colour hues in temperature intervals of 5°C in the temperature range -40°C and +80°C. They used the technology of microencapsulation of four thermochromic pigments, which were capable of changing colour from white into pink, blue into black, yellow into blue, and pink into grey. Depending on the end use, colour changes were designed to occur between 11-19°C for ski wear and 13-22°C for women's clothing [140].
In the late 1980ties and early 1990ties, the Generra Sportswear Company, which manufactured t-shirts with numerous colour change choices, bought the right from the Japanese Matsui-Shikiso chemical company to print cotton fabrics with thermochromic organic pigments with negative thermochromism. This process was commercialised under Hypercolour®.
Today, organic thermochromic pigments are mostly used for embroidery on apparel and for thermal printing.

Photochromism

The photochromic microcapsule reacts on contact with ultraviolet rays so a typical end use has been towelling and beach wear in the textile sector. These products are extremely active in the range of 200-320nm, which is the harmful portion of UV rays. By absorption of light the chemical structure is changed, creating the appearance of colour. However, if the light is intercepted, the textile goods will resume their original chemical structure and the colour will disappear-making the process fully reversible [141].

$$A(\lambda_1) \underset{\text{deactivation}}{\overset{\text{activation}}{\rightleftarrows}} B(\lambda_2)$$

There are different kinds of chemical processes which are responsible for the transition from form A to form B:

- a variation in the oxidation condition of a metal;
- trans-cis isomerisation;
- a homolytic or heterolytic breaking of the chemical bond

These reactions obviously have to be reversible in order to be catalogued as a photochrome reaction. If not, an ordinary photochrome reaction takes place.

Photo-chromic dyes

A very important natural photo-chromic dye with reversible colour changeability is rhodopsin, which is present in the retina of the eye. Rhodopsin is activated by light and induces nerve stimuli, which are transmitted to the brain where they provide the perception of colours. Due to extraordinary stability to photo degradation, rhodopsin is a potential photoswitchable biomaterial which is suitable for various applications.

Photochromic dyes are less used than thermochromic dyes due to poor stability.

- Colour pigments that change in response to temperature and light conditions are utilized for camouflage purposes [142].
- Photochromic dyes:
  used for optical memories and switches
  filters

First fabrics with photochromic dyes appeared in the 1980ties. The Japanese producer Kanebo Ltd. used microencapsulated spiropyrans, which were printed on textile materials. Under the influence of UV rays with wavelength 350-400nm, the dyes reversibly changed from light blue to dark blue. As spiropyrans are unstable, they were replaced by more stable spirooxazines in the end of the 1980ties.

At this time Toray Industries Inc. developed the process of coating fabrics with photochromic dyes. The fabric, known under the tradename Sway UV®, was able to turn blue or violet under the influence of UV rays with wavelength 350-380 nm. Within 30 seconds after UV radiation, the colour of the fabric disappeared. Sway UV® was used in T-shirts, polo shirts and jumpers.

C.T.I. also commercialised photochromic textile screen inks under DynaColor™. The inks are off-white when not exposed to UV radiation and gain colour as soon as they are exposed to UV light. They claim that their ink is ideal for t-shirts and other apparel.

Electro-chromic dyes

Electro-chromic dyes and switches are used nowadays in combination with conductive fibres or polymers for fashion applications to result in colour-changing fabrics.

Researchers at the department Fiber and Polymer Science at Clemson University, U.S., designed fibres that can quickly change their colour, hue, depth of shade or optical transparency by application of an electrical or magnetic field in 2001. They figured out that the visible radiation absorption and the colour of electro- and magneto active oligomeric molecules can be changed by varying the electrical or magnetic field. The research group made two approaches. On the one hand they modified the surface of electrically conductive polymers as polyanilline, polypyrrole, polythiophene and polythiophene with thiols. On the other hand, they attached molecular devices to the surfaces of conductive polymers. However, research does not seem to go on [143].

Another possible chameleon technology uses microscopic capsules, embedded in a fabric, that change colour when exposed to electricity. However, challenge to use this in real life environment is the power source [144].

2.2.3 Applications in the clothing sector

2.2.3.1 Research projects and products

Thermochromic dyes

In the beginning of the 1990s garments with thermochromic materials were presented on a fashion show to celebrate the 150th anniversary of the Royal Society of Chemistry in London. Tight-fitting garments were shown that are black in colour when hanging in the wardrobe. But, when wearing them, they shimmer in rainbow colours. At this time, the chemicals company Merck, UK, modified the materials so that they alter hue at different temperatures. Thermochromic pigments were launched on the market under the brand name Licritherm by Merck.

The American company Color Change Corporation145 sells Thermochromic Leuco Dye. The LD materials are coloured in their cool state and translucent in their warm state. For LD clearing points below 34°C, it takes 2-4°C to change to clear. These dyes are micro-encapsulated with an average particle size of 5 microns.

A research group at XS Labs succeeded to create an information pattern in a dynamic textile by using the embroidery technique. The embroidered stitching material was a heat conducting material, which was placed beneath a thermochromic textile. So, they presented an apron for a PDA to express wearing and tearing. The apron has two separated fabric layers, one at the bottom with heating threads and one above with the thermochromic fabric. The two fabric layers contact each other depending on the movements of the wearer.

Other chromic material

Recently, the firm Procter & Gamble announced their intention to launch an intelligent slip on the market. The aim is to notify the female wearer when ovulation is coming or when she will start to menstruate.

To determine the ovulation, a layer of silicones is used covered with a thin plastic film. The silicones react to hormonal changes that are characteristic for the ovulation period and expand a little. The small thickening modifies the refraction of the light, resulting in a violet dot on a golden background.

To determine the menstruation period, two indicators are necessary. In the first place, a resin is used which turns blue at the presence of the smallest trace of blood. The second product is an acid which turns red at a pH between 4 and 7. These two indicators together give a purple colour, approximately four hours before the start of the menstruation.

The U.S. Army Soldier Center in Natrick is doing research work on camouflage clothing by examining two different concepts. Under one concept, soldiers would choose from a database of existing patterns, such as South American Jungle, that would be replicated on the garment. Other camouflage researchers at the Tokyo University are examining ways to create clothes with the ability to take digital images of the surrounding environment and duplicate them then on the clothes. This is referred to as "Predator" effect [144].

2.2.3.2 Patents published

In US patent 20050074639 the company Unilever patents a method producing a hair covering which comprises a woven or non woven substrate comprising synthetic or natural materials, which are impregnated, or coated, or both, with a thermochromic dye. The hair covering of the invention may contain two or more thermochromic dyes, one which changes colour at a threshold temperature, and the second, which changes colour at a still higher temperature. Colour change by the first dye may indicate that a desired threshold temperature has been reached. Colour change by the second dye may indicate that the hair has been brought to too high a temperature.

2.2.4 Applications in the interior textile sector

2.2.4.1 Research projects and products

Chromical materials, also called Chameleon fibres, are used in the field of interior textiles to make patterns appear and disappear.

Thermochromic

Scientists at XS Labs have developed Shimmering Flower that functions as a woven animated display, constructed with conductive yarns and thermochromic inks together with custom electronics components. The textile is woven on a Jacquard loom, which allows the creation of beautiful and complex imagery. The flower image was created with a custom drawing software. The colours and pattern of the weaving change very slowly, reminding the viewer of the nature of natural time and change.

Fig. 77 Shimmering Flower display [92]

Thermochromical screenprint paste can be used on textiles. The property of the material is a colour change when the material is heated up to around 37°C. Thus, the fabric may be heated up by hand or breath. When the heating source is removed, the fabric changes slowly back to its original colour.
In the frame of the project ‘Fabrication’ experiments with thermochromical paint containing mixed pigments were carried out, resulting in different colours and intensities.
In order to control when the colour change should take place, heat elements were integrated into the textiles by different ways. One possibility is that different fabrics in layers are sandwiched together with heat elements in between and the thermochromic paint on the top layer. A second way to integrate the heat element is to print on carbon fabrics. A colour change will appear when electricity is turned on. Another possibility is to make a weave with conductive wires.

International Fashion Machines produced electro-textile wall panels by using the so-called Electric Plaid^{TM}, a woven fabric that exploits reflective colouring. This fabric contains interwoven stainless steel yarns, painted with thermochromic inks, which are connected to drive electronics. The flexible wall hangers can then be programmed to change colour in response to heat from the conducting wires.

Fig. 78 Electric PlaidTM

Within the scope of the Swedish programme IT+Textiles, two fabrics, called 'Tic' and 'Tac' designed for tea and coffee breaks, have been developed. The two fabrics, each wrapping a piece of furniture, are connected to each other via internet. Positioning a hot cup on fabric 'Tic' activates patterns hidden in the textile surface of 'Tic', as well as in 'Tac'. The working principle is as follows. The two fabrics 'Tic' and 'Tac' are thermochromic woven structures. Underneath them heating elements are laid out in a nine square Tic-Tac-Toe grid. When a hot object, like a cup of tea or coffee, is placed on the grid, the heating element heats up and the colour of the textile changes beneath the cup. A sensor beneath the textile senses the change in temperature and sends the information via internet to the other textile. The corresponding heating element underneath the other fabric is heated up and the pattern gets visible on the fabric surface. So, this technique can be used to play the game 'Tic-Tac-Toe' with persons sitting not with you on one table, but sitting on another table that is wrapped with the corresponding piece of fabric.

The prototype was realised as two pieces of furniture combining together seats and side tables. In the following pictures, the design of the furniture covered by the 'Tac' fabric is presented on the left picture. While this piece of furniture comprises a table and two seats, the piece of furniture designed for the 'Tic' fabric consists of one seat and a table. It is shown in the back of the right picture.

Fig. 79 Furniture design [8]

The hardware, consisting of a plastic sheet with laser-cut heater wiring, nine temperature sensors, a controller unit and a laptop, is hidden inside the two furniture pieces. When the temperature is raised above the threshold value of the temperature value, the software detects that a cup has been placed on the fabric [8].

Photochromic

A team at the Interactive Institute in Sweden is working on a project named 'Using Color-Changing Textiles as a Computer Graphics Display'. The researchers used a fabric made out of photochromical threads as a display which can be written over and over again. A computer controlled UV-lamp was utilized as a writing tool.

The Swedish project 'Fabrication' at the Interactive Institute explores how aesthetic decoration and information can work together. Therefore they are creating fabrics that change patterns from time to time by combining textile materials with dynamic properties, such as chromic, electroluminescent and conductive materials. For instance, the group designed an 'Information curtain' which works on the basis of photochromical treated threads and the curtain changes colour from white to coloured when the sun rises [72, 146].

Fig. 80 Dynamic textile materials within the project Fabrication

Other chromic material

The thesis project 'Fashion Victims' is an initiation of designers from the Interaction Design Institute Ivrea in Italy. The idea is to denounce social problems, as electronic pollution, in fashion by changing colour patterns in the fabric. If the wearer nears for instance a cell phone or a wireless network, he/she will be warned about this pollution by a pattern that slowly spreads over the fabric. The intensity and frequency of the electromagnetic radiation are reflected in the colour and density of the pattern appearing on the clothes.

Fig. 81 Fashion Victim [147]

They presented their work on the e-fare in Amsterdam in 2003. Since then, it seems as the project has not been preceded any more.

2.2.4.2 Patents published

2.2.5 Applications in the technical textile sector

2.2.5.1 Research projects and products

Benjamin Miller and colleagues of the University of Rochester, US, have developed a sensor that generates an easy recognisable array of colours that signify dangerous or antibiotic-resistant strains. So far, the device produces only a very small colour change, which is not detectable with the naked eye.

Most bacteria are either Gram-positive or Gram-negative. A dye called crystal violet stains Gram-positive bacteria blue-violet and Gram-negative bacteria red. This staining procedure was discovered in 1884 by the Danish biologist Christian Joachim Gram and is still used today to distinguish the two cell types. Miller's team hope to replace the cumbersome staining procedure with a simple process that registers the difference instantly and in situ. Therefore they will use silicon-based light-emitting devices. When Gram-negative bacteria stick to the surface of porous silicon, the colour of the emitted light slightly changes. The researchers make the silicon attract Gram-negative, but not Gram-positive bacteria, by coating it with specially designed molecules that hook chemicals groups only present on Gram-negative microbes.

Eventually this may lead to the development of smart bandages that could soon alert doctors to the presence of certain bacteria in a wound by glowing different colours.

Photochromic yarn SolarActive™ International, Inc. (USA)

2.2.5.2 *Patents published*

Toray Industries, Inc., published a patent for the production of a photochromic spiro-oxazine compound that is valuable as a photochromic printing material for clothing and decorative articles under US 4784474 in 1988.

In US 6 749 935 B2 a temperature-sensitive colour-changeable composite fibre produced by the Japanese company The Pilot Ink Co., Ltd, is described. The sheath-core-type structures are imposed by constraints on spinning conditions set by the thermal sensitivity of microcapsules. The sheath is made of a high-melting fibre-forming polymer (e.g. polyester or polyamide), and the core consists of a dispersion of microcapsules (5 to 20 µm) with epoxy/amine resin walls in a low melting matrix (e.g., polyolefin, polyamide, or polyester). Due to that sensitivity, the sheath must cover at least 80 percent of the fibre's surface and constitute 25 to 90 percent of the fibre's weight.

The patent is based on another patent applied by Pilot Ink from 1977, US patent 4028118. In this patent the production of a thermochromatic material exhibiting a reversible metachromatism within a temperature range from -40°C to 80°C is described. The material can be processed into microcapsules or into thermochromic printing inks.

2.3 Optical fibres

2.3.1 Description

A material that is not primarily associated with textiles is glass. However, fabrics comprising glass fibres are used for interior textiles as they are capable to reflect and filter light and additionally they resist mould/ funghis and moths. But, disadvantageously, they have the tendency to irritate the skin, a property that makes it difficult to apply them in fashion [5].

Fibres of glass are often referred to as optical fibres, usually about 120µm in diameter, which are used to carry signals in the form of pulses of light over distances up to 50 km without the need for repeaters. These signals may code voice communications or computer data.

Interest in the use of light as a carrier for information grew in the 1960's with the advent of laser as a source of coherent light. Initially, the transmission distances were very short, but as manufacturing techniques for very pure glass arrived in 1970, it became feasible to use optical fibres as a practical transmission medium. At the same time developments in semi-conductor light sources and detectors meant that by 1980 world wide installation of fibre optic communication systems had been achieved.

Fields of application:

Telecommunication

Optical fibres are now the standard point to point cable link between telephone substations.

Local Area Networks (LAN's)

Multimode fibre is commonly used as the "backbone" to carry signals between the hubs of LAN's from where copper coaxial cable takes the data to the desktop. Fibre links to the desktop, however, are also common.

Cable TV

As mentioned above domestic cable TV networks use optical fibre because of its very low power consumption.

CCTV

Closed circuit television security systems use optical fibre because of its inherent security, as well as the other advantages mentioned above.

Optical Fibre Sensors

Many advances have been made in recent years in the use of Optical Fibres as sensors. Gas concentration, chemical concentration, pressure, temperature, and rate of rotation can all be sensed using optical fibre. Much work in this field is being done at the University of Strathclyde [3].

2.3.2 Technology

An optical fibre is a cylindrical dielectric waveguide made of low-loss materials such as silica glass. It has a central core, in which the light is guided, embedded in an outer cladding of slightly lower refractive index. Light rays incident on the core-cladding boundary at angles greater than the critical angle undergo total internal reflection and are guided through the core without refraction. Rays of greater inclination to the fibre axis lose part of their power into the cladding at each reflection and are not guided.

There are three main kinds of fibre optics, the most simple being the ‘step index’ where the light is bounced along the length of the fibre from one side to the other. Two materials with different densities are needed, the less dense being used as coating. In this method, the light travels in zig-zag motion and thus transmission of information can take some time. Another way of producing fibre optics involves the ‘graded index’ fibre which also relies on materials with different densities. The variation occurs in the centre of the fibre causing the light to bounce, but in a smoother and more gradual curve. The sharpest and most direct transmission of light travelling in a straight line is achieved by applying a synthetic fibre possessing a very narrow inner core, almost in the width of the actual path of light. The Japanese company Mitsubishi Rayon was one of the first companies that were active in developing plastic fibre optics for illumination in the 1990ties [5].

Photonic crystal fibres

Photonic crystal fibres (PCFs), which are optical fibres that employ a microstructured arrangement of low-index material in a background material of higher refractive index, were first demonstrated in 1996. The background material is often undoped silica and the low index region is typically provided by air voids running along the length of the fibre.

PCFs may be divided into two categories, high index guiding fibers and low index guiding fibres. Similar to conventional fibres, high index guiding fibres are guiding light in a solid core by the Modified Total Internal Reflection (M-TIR) principle. The total internal reflection is caused by the lower effective index in the microstructured air-filled region.

Low index guiding fibres guide light by the photonic bandgap (PBG) effect. The light is confined to the low index core as the PBG effect makes propagation in the microstructured cladding region impossible.

The strong wavelength dependency of the effective refractive index and the inherently large design flexibility of the PCFs allow for a whole new range of novel properties. Such properties include endlessly single-moded fibres, extremely nonlinear fibres and fibres with anomalous dispersion in the visible wavelength region.

M-TIR is analogous to total internal reflection known from standard optical fibres. It relies on a high index core region, typically pure silica, surrounded by a lower effective index provided by the microstructured region. The effective index of such a fibre can, in the simple case, be approximated by a standard step index fibre, with a high index core and a low index cladding. However, the refractive index of the microstructured cladding in PCFs exhibits a wavelength dependency very different from pure silica - an effect which allows PCFs to be designed with a complete new set of properties not possible with standard technology. As an example, the strong wavelength dependence of the refractive index allows design of endlessly single-moded fibres, where only a single mode is supported regardless of optical wavelength. Furthermore, it is possible to alter the dispersion properties of the fibres, thereby making it possible to design fibres with an anomalous dispersion at visible wavelengths.

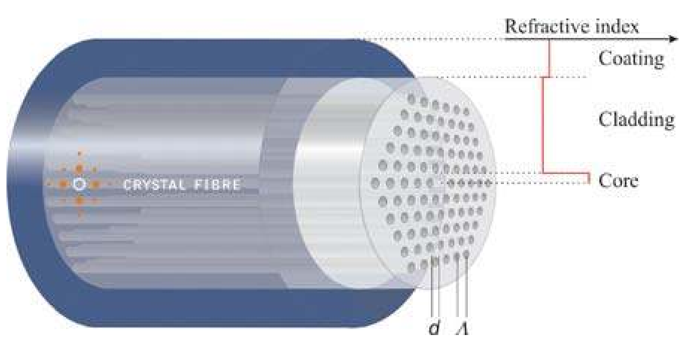


Fig. 82 Crystal Fibre [148]

More complex index structures can also be constructed by utilising arrangements of holes of different size in various periodic or nonperiodic structures. In addition, highly asymmetric core fibres can be fabricated thereby creating fibres with very high level of birefringence.
The technology also makes it possible to create highly nonlinear fibres which can be used for e.g. super continuum generation [148].

A research team from the Massachusetts Institute of Technology (MIT) is working on the design, production and characterisation of optoelectronic fibres consisting of metallic, semiconductive and insulating materials. Basically, optoelectronics encompasses the study, design and manufacture of hardware devices that convert electrical signals into photon signals and vice versa. Any device that operates as an electrical-to-optical or optical-to-electrical transducer is considered an optoelectronic device [149].
In order to result in highly uniform fibres with well-controlled geometries and good optical properties, they used a fibre-drawing technique from a preform. This preform is made up by a low melting temperature crystalline conductor (Sn), amorphous semiconductors (As-Se-Te-Sn and As_2Se_3) and a high glass transition temperature polymeric insulator (polyetherimide and polyethersulphone). It is heated up in a furnace and drawn into a fibre. A single fibre can be regarded as an optoelectronic device, but by modification it can adapt more functionality. Therefore, the researchers developed a fibre structure that is capable for dual electron-photon transport. This is achieved by a hollow air core fibre surrounded by a mirror layer, within which the light is confined. The fibres' clad contains an array of Sn metal strands that give an ohmic response at the same time. The scientists also succeeded in developing a light sensitive fibre. The working principle can be described as follows: Sn metal electrodes in the fibre core contact a photoconductive chalcogenide cylinder which produces a current upon illumination under bias conditions. As these fibres are flexible, they can be processed into a woven structure, which then has the ability to identify the location of illumination. Possible application areas represent fabrics embedded into computer screens or projectors. Thus, instead of using a mousse for communication with the computer, a light beam can be utilised because the screen can detect the location where it was hit [150, 151].

2.3.3 Applications in the clothing sector

2.3.3.1 Research projects and products

Optical fibres are currently used in textile structures for different application areas, such as telecommunication, illumination, medical products and sensor technology.

At the AVANTEX 2002, a research team from Georgia Tech presented a smart shirt, called the Georgia Tech Wearable Motherboard that makes use of optical fibres to locate the exact position of a bullet's impact. The Wearable Motherboard™ is probably the first intelligent suit that can be used for medical purposes. The basic shirt includes an optical wiring structure that can be equipped with conventional sensors to measure different body parameters.

Currently, optical fibres are used to create textile-based displays, so-called Optical fibre flexible display (OFFD). For this purpose optical fibres as well as conventional fibres make up a woven fabric structure. A small electronic device, integrated into the textile system, controls the LEDs that illuminate groups of fibres. Each group provides light to one pixel (given area) on the matrix. A special control of the LEDs enables various patterns to be displayed in both, dynamic and static manner. The fact that it posses a very thin size and a ultra light weight makes the structure interesting.

In general, optical display textiles can be created on the one hand by existing or conventional textile structures, into which optical fibres are inserted. On the other hand they can be produced by newly developed textile materials. To the first group belong the works of the research group of Vladan Koncar and of the research of Eric Deflin for France Telecom, as well as the products of the company Luminex. Their projects will be described briefly in the following.

A research group around Vladan Koncar in France is working on a woven OFFD using Poly (methyl methacrylate) (PMMA) fibres as weft threads and silk as warps. Silk was chosen to result in good flexibility, fine titration and an improved capacity to diffuse and reflect the light emitted by the optical fibres for better legibility of information. They also tested different finishing methods, e.g. coating, to ensure the grid stability and flame resistance and to enable optimal light emission intensity and contrast. The screen for fabric displays comprises a number of surface units or pixels, which are directly formed on the optical fibres. The process consists of generating micro-perforations that reach into the core of the fibre. The remainder of the fibre, which did not receive any specific processing, conveys the light without being visible on the surface. Generally, two different processes can be used to perforate the fibres, either a mechanical treatment by the projection of microparticles with different velocities on the optical fibre's cladding, or a chemical treatment by using different solvents. There are three different methods to light ON and OFF static patterns on the fabric, like texts, logos and scanned pictures. The first method uses a basic fabric. A stencil key delimits the lightening zone. The picture remains static with a high resolution. In the second method, the zone to be lit is formed during weaving on a Jacquard loom before being processed. The remaining, inactive fabric is composed of the floating fibres on the back of the fabric. A third method uses a two-layer adapted basic-velour fabric that makes optical fibres as visible as possible. Before being woven, the fibres are chemically processed, enabling the specific dynamic lighting zones to be created. Further, the researchers modified these techniques and developed a matrix that enables basic information to be displayed in a static and dynamic way. A variety of light sources can be used for the structure. The choice mainly depends on the number of fibres connected to each source and the level of power consumption. The LED technology in this case is the preferred one, as many effects can be generated on the displays. The first OFFD was displayed on a jacket. With its function to be seen for security and publicity it has a great potential to be used for fire fighting and police applications. However, besides for clothing purposes, it might also be used in car interiors to display information to navigate drivers [152, 153].

Communication between garment and wearer has also been realised by France Telecom with a textile communication device (OFFD). Glass fibres form a flexible screen which is produced by weaving. Each plastic fibre-optic thread is illuminated by tiny LEDs that are fixed along the edge of the display panel and controlled by a microchip. An electronic component is integrated into the material and controls the LEDS, which illuminate groups of glass fibres independent of one another. These light and dark patches essentially act as pixels for the display screen. A jacket and backpack have been produced as prototypes [114, 154].

The US company Luminex designs and manufacturers lighting devices by different technologies.
The so-called UniGlo(R) technology uses optical fibre mounted on a back reflector to create lighting panels. A computer controlled etching process ensures uniform light distribution.
Another technology uses optical fibre woven into a cloth to create layers and is then built up into a panel or other lighting device. Computer controlled looms create variable micro bends in the optical fibre as it is woven into a cloth. In this way, it is ensured that the light is emitted uniformly along the length of backlighting panel. The working principle is illustrated in the following picture [155, 156]:

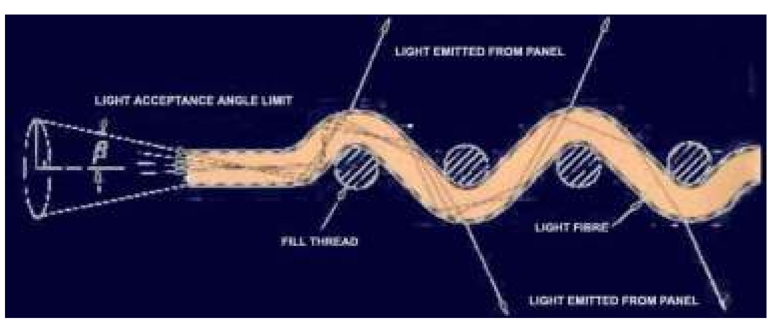


Fig. 83 Working principle of light emission [156]

The fabric layers are then laminated to form a panel.

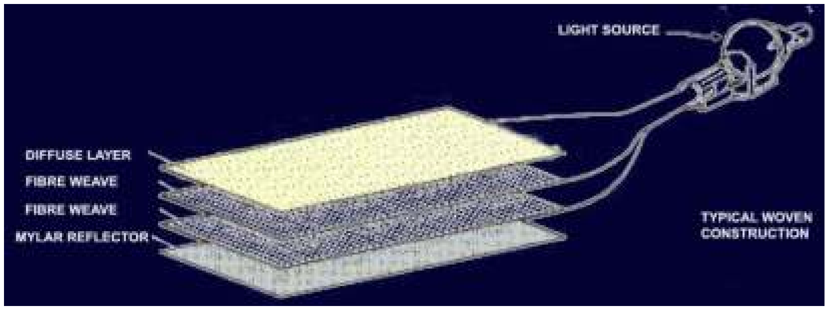


Fig. 84 Panel consisting of fabric layers [156]

To the second group described above, namely newly developed textile materials, belong chameleonic fibres, photoadaptive fibres and the products of the company VISSON. Chameleonic fibres have been discussed in chapter 2.2.

Scientists at Auburn University research on photoadaptive fibres for textile materials. By definition, photoadaptive fibres experience photoinduced reversible optical and heat reflectivity changes. Photoadaptive systems are very attractive since they experience reversible changes in their physical and chemicals properties in response to illumination. The research group develops photoadaptive fibres where metal particles are built by exposure to high intensity of visible light, but decay once the photon intensity decreases to ambient light levels. For this purpose polymeric films that are optically transparent and water-insoluble were made by crosslinking poly (viny alcohol) with dimethylsulfoxide in the presence of poly(acrylic acid).

Swelling the polymeric materials with solutions of Ag+ and AuCl4 - ions allowed uniform incorporation of the metal ions into the polymer matrices. The high optical quality of these films enabled direct detection of photo-generated metal particles utilising UV-Visible spectroscopy. Speed of metal particle formation was optimised by systematic variations of the preparation conditions. Ag particles of nanometre size were detected within seconds of illumination and particle growth took place via metal deposition on existing particles. Generation of Au particles was about ten times slower and occurred through a chain reaction. In both cases the metal crystallites formed only upon exposure with high intensity artificial light or sun light, but not under ambient light. The fast photochemical metallization occurring exclusively under high photon flux is one of the desired properties of the materials that are being developed.

Areas of potential applications of the polymeric fibres include reflection of infrared radiation, 3D storage of optical data and shielding of electromagnetic radiation or resistive heating elements [157].

The company VISSON in co-operation with Philips Research Laboratories utilizes conductive wires, which are coated with light-emitting layer. This layer is very thin and made out of electroluminescent material. The woven structure forms an x-matrix out of wires. At each crossing point, the light-emitting layer starts to illuminate when applying electricity and therefore a pixel is generated.

The Italian-made fabric Luminex® contains coloured light emitting diodes and is commercialised by the Luminex SpA. A tiny light source distributes light throughout the fabric of the whole polymethylmethacrylate fabric, which has a light conductive fibre woven in. Out of this fabric, tailored made clothes are produced, for example sparkling cocktail dresses or costumes for opera singers. The fibres are powered by tiny rechargeable batteries that can be turned on and off by the wearer via a hidden switch [158].

The company Grado° zero espace uses plastic optical fibres (POF), which consist of an inner acrylic core coated with a thin cladding of a fluorinated polymer. Since the refractive index of the outer cladding is lower than the core, light entering one end of a fibre reflects along the interior core material at the interface of the core and cladding. Light passes through the length of the fibre in a zigzag path on its way to the other end.

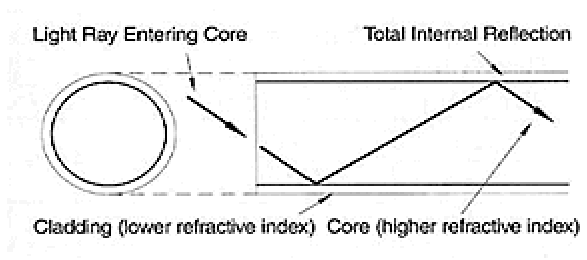


Fig. 85 Plastic optical fibre [159]

POF is available in three grades, based on optical transmission value. There are, in order of increasing light transmission efficiency, commercial, industrial and optical grades. Heat resistant grades can withstand much higher operating temperatures than the commercial, industrial and optical grades, but have a higher optical attenuation.

Plastic optical fibres have advantages over glass optical fibres in cost, weight, durability, and flexibility [159].

Fig. 86 Jacket ‘Luciferas’ with incorporated POF by Corpo Nove [159]

Hussein Chalayan designed an airplane dress that changes shape by remote control. The dress is made using glass fibres.

Fig. 87 Glass fibre dress by Chalayan [160]

The Finnish Clothing+ Oy developed the concept of a Reima Robotec overall, researched the integration of the fibre and electronics into a children's overall and is now producing the electronics for Reima Oy. The Robotec overalls combine visibility with entertainment. The garment has an optic fibre sown into the shoulder, and is very easy to operate. In order to switch the light on and off, the child needs to wave the right sleeve in front of the badge on the chest. The luminous fibre is fun for the children and provides an added safety feature in lightless conditions where traditional reflectors do not work. The overalls entered the market in the autumn of 2004, and they are a part of the well-known Reimatec line of waterproof, windproof and breathable clothes.

Fig. 88 Reima Robotec overall [161]

The U.S. company Photonics, Inc. developed a vest with integrated optical fibres and electronic wires for sensing environmental changes such as temperature and chemicals. The fabrics they use range from woven and non-woven to knitted structures designed for medical and military applications

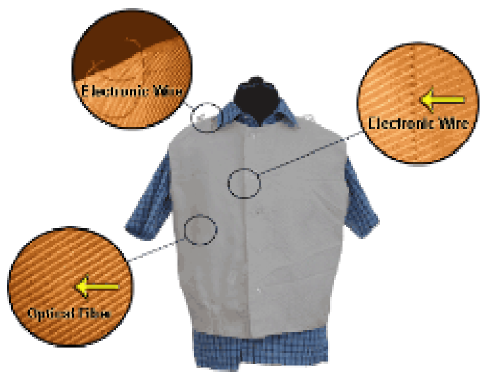


Fig. 89 Textile with embedded optical fibre and electronic wire [162]

They are also developing stress and strain sensors from various materials, like metals and polymers, which have embedded optical fibres. An example is illustrated below.

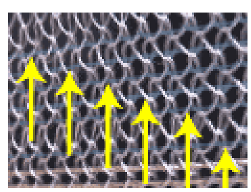


Fig. 90 Textile with six embedded optical fibres [162]

In the picture, it gets visible that the optical fibres are inserted in warp direction of a warp knitted construction.

2.3.3.2 Patents published

2.3.4 Applications in the interior textile sector

2.3.4.1 Research projects and products

The Romanian designer Andrea Apavaloaei, member of the international organisation INDEX that aims at creation of new designs that improve lives of many people, created a concept of synergic aggregation of textile and optical fibres. The concept foresees the combination of sensorial and emotional properties together with the aesthetic function of a textile. Apavaloaei plans to integrate these functions into a couch, a carpet and a tapestry. In order to result in relaxing, controlled thermal comfort, ambient light, massage and controlled relative humidity, she wants to combine different fibres and integrate them into the textiles. So far, the concepts have not been realised [163].

Fig. 91 Communicating couch, carpet and tapestry [163]

In the area of bright optical display textiles, Philips Research laboratories and Eindhoven University of Technology developed a special open sandwich technique with which it is possible to deposit a layer of liquid crystal onto a single underlying sheet. With this invention, wallpapers and curtains at home could change colour by the touch of a button, or TV screens and plastic LCDs sewn into fabric displaying text messages can be create. Liquid crystals are peculiar liquids as their molecules spontaneously line up. Passing a voltage across the molecules switches their alignment, blocking the transmission of light. Thus, a display might change colour from light to dark. The special LCD paint is made by mixing liquid crystal with molecules that link together into a rigid polymer when exposed to ultraviolet light. Special about the paintable LCD is that they use only a single substrate, as opposed to the traditional two-plate. The LCD fabrication can be described as follows.

A mixture of four components (a liquid crystal, two monomers - which can be photopolymerised at different wavelengths of light - and a photoinitiator) is applied as a thin film to a substrate. This glass substrate is patterned with an array of interdigitated electrode pairs (each pair provides an in-plane electric field that will control an individual 'pixel' of liquid crystal) and a polyimide orientation layer. The monomers are then polymerised in a two-step process.

First, the film is exposed through a mask to light of 400 nm wavelengths. This causes one of the monomers to undergo controlled phase separation and polymerization to create a grid of rigid struts oriented perpendicular to the plane of the film. These form the walls of individual square cells containing liquid crystal. The mask is removed, and the entire surface of the film is then exposed to 340-nm ultra-violet light. The second polymerisable component now undergoes phase separation and polymerization, this time forming a thin layer that caps the liquid-crystal-containing cells. During this second photopolymerisation step, the two polymers crosslink with each other, mechanically coupling the polymer topcoat with the substrate via the struts. Thus, individual closed cells of liquid crystal are formed, and each can be switched on and off using the underlying electrodes. Finally, the structure is coated with polarizer films and the result is a fully functioning LCD created on a single substrate.

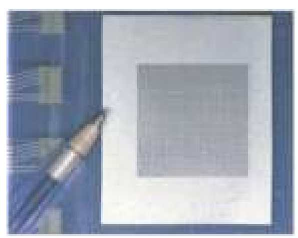


Fig. 92 One layer LCD [164]

This method of LCD construction improves on the versatility - display thickness and total area - and cost effectiveness of conventional two-substrate LCD production, and also provides a significant step towards the realisation of 'display-on-anything' technology [164, 165, 166].

Through the increasing implementation of electronics in cars, the wiring and the electrical circuits are also increasing, for example by safety devices and multimedia devices descend. Due to this development, also the weight and the cost of a car are increasing. Thus, fibre optic systems represent an attractive alternative to copper wires based technologies as they offer light weight, a higher information rate compared to other conductive media of comparable size, are not affected by electromagnetic interferences and lower costs.

Philips Research and the textile institute TITV Greiz have developed an interconnecting substrate made entirely of fabric which they presented at the Internationale Funkausstellung (IFA) 2005 in

Berlin. On the fabric, researchers have placed passive matrices of compact RGB LED packages. The pixelated luminaries with relatively large distance between RGB pixels have been embedded in everyday objects like cushions and floor mats.

The photonic textile can also be made interactive by incorporating sensors, like pressure or orientation sensors, and communication devices into it.

Fig. 93 Photonic textile by Phillips [167]

The picture shows the photonic textile. As the fabric covering the tiny light source naturally diffuses light, each pixel seems bigger than it actually is [167].

2.3.4.2 Patents published

2.3.5 Applications in the technical textile sector

2.3.5.1 Research projects and products

In the technical textile sector, optical fibres are often used as sensors to exploit the Bragg Effect.

At the Hong Kong Polytechnic University, a research group has developed several applications using optical fibres to measure strain and temperature in composite structures [168, 169, 170, 171]. Fibre optic Bragg grating sensors are attracting considerable interest for other sensing applications, like pressure, chemicals and biological factors [172].There is a great interest in the multiplexed sensing of smart structures and materials, particularly for the real-time evaluation of physical parameters at critical monitoring points. Most of the sensing applications of Fibre Bragg Grating (FBG) sensors focus on their reflection spectra, which depend on the relation between the Bragg wavelength and their physical quantities.

Further, a research group at the University of Maribor is working on fibre-optic chemical sensors. In this case, optical fibres act as remote sensors and can detect chemical contaminants. Light is generated by a light source and is passed through the optical fibre. When the light returns through the fibre, it is captured by a photo detector [173].

The Canadian company TACTEX Controls, Inc., commercialises a pressure sensing optical fibres based material capable in detecting pressure on its whole surface, called Kinotex® derived from "kinaesthetic textiles". The sensor systems and components appear like thin sheets of a material based on urethane or silicone cellular elastomers. Within the material, several pressure sensors, called taxels, are installed, whose density and performance characteristics are adjusting to the requirements of the product. Each taxel is consists of a tiny light source and a tiny detector imbedded in a thin cellular elastomer. As pressure is applied to the elastomer in the region of the taxel, the cell size distribution is altered along with the bulk optical scattering properties of the material in that area. The light detector measures the change in scattered light intensity at the taxel, and interprets this as a change in pressure. Optical fibres laminated into the structure are used as the "nervous system", to deliver transmitted light to the location of the taxels, and to deliver received light back from the taxel. In Tactex products, the light source is typically a light emitting diode (LED) connected to a bundle of fibres, and the light detector is usually a photodiode or an array of detectors connected to a second set of fibres. A microcontroller or DSP is used that converts the signals from the detectors to digital signals, conditions those signals, and computes the required pressure information or decision data using a set of algorithms implemented in firmware. The fabric is applied as computer input device, medical device and devices in automotives [174].

The University of Sydney comprises an Optical Fibre Technology Centre, which was founded on silica fibre fabrication. Thus, two major research fields at the centre are Silica Photonic Crystal Fibres and Microstructured Polymer Optical Fibres (mPOF). Nowadays, they expanded their research activities also to Fluoride Glass Optical Fibres [175].

The Geodetect system by Polyfelt® Geosynthetics is a geotextile-based monitoring system. It consists of a high strength textile, equipped with optical sensory fibres linked to a monitoring device and a PC. The system is developed for the measurement of strain, allowing measuring the deformation and absorbing behaviour of concrete reinforcements.

Fig. 94 wallsystem equipped with Geodetect

(1) Leromur concrete cinder blocks (2) reinforced geotextile (3) Geodetect-strips (4) weatherproofed cable (5) mobile measuring device [176]

The Geodetect fabric is used to monitor the deformation and absorbing behaviour of a bridge construction in Saint-Saturnin in France. Geodetect delivers data during the construction period and after completion of the installed wallsystem. The construction started in 2004 [176].

2.3.5.2 Patents published

The University of Stuttgart and the German Institutes for Textile and Fibre Research Denkendorf patented a fibre comprising a glassfibre core surrounded by semiconductor layers (WO 02/37577). The fibre can be further processed into a textile structure and can be, for instance, used for the production of a textile switch.

The company Tactex Controls, Inc., issued patents to protect its place as a designer and manufacturer of sensing products and to secure its innovations in the medical products field:

US 6715359 'Pressure sensitive surface'

A position sensor comprises a substrate having an array of pressure sensors and a membrane overlying the substrate. The membrane includes physical parameters which vary with position. The membrane may include discontinuous regions and protrusions which affect the way in which forces on the membrane are distributed to the substrate. A pressure sensor may also include a controller for receiving pressure information from the substrate, with a signal processor being programmed to localize the depressed region or regions of the substrate.

US 6788295 Touch pad using a non-electrical deformable pressure sensor

A touch pad for controlling electronic equipment includes a deformable touch surface and a compressible pad body in contact with the touch surface. The compressible body is formed from a material which scatters or diffuses light within the material. Multiple sources of light or other wave energy are directed into the interior of the substrate to form multiple illuminated cells inside the pad body. Each illuminated cell forms an integrated cavity within the pad body. A detector in communication with the compressible material detects light intensity within the integrated cavity. A processor receives signals from the detector and converts the signals into useable information relating to the position of regions of compression of the pad.

2.4 Phase change materials and Microencapsulation

The introduction of adaptive phase change materials initiated the use of passive smart materials, which were introduced in chapter 1.2. These materials possess the capability to improve the thermal comfort for someone exposed to extreme temperatures when they are integrated into the garment. The following subchapters give an overview on the state of the art of these materials including technological aspects as well as their applications and products in our aforementioned three textile areas, clothing, interior and technical textiles.

2.4.1 Description

The technology of microencapsulation has originated both from the paper and the pharmaceutical industries. The encapsulation process was discovered and developed by Barrett K. Green of the National Cash Register Corporation (NCR) in the 1940's and 1950's when his company needed a product that would give multiple paper copies without carbon paper. The new printing system was triggered by including a colourless sue-base in gelatine microcapsules (coated back, CB) and coating the second sheet of paper (coated front, CF) with acidic clay, which could react with the dye-base to produce a colour.
Large efforts in microencapsulation research were done by the pharmaceutical industry in the 70's and 80's. Microencapsulation was an ideal tool to formulate very unstable compounds or to regulate their release. In the last years a growing number of applications of microcapsules on textiles have emerged.

Micro-encapsulation is a technique enclosing certain substances in a solid, liquid or gaseous state in microcapsules (small spheres with a diameter of a few micrometers). A microcapsule consists of a core, containing the product of interest and a shell that either permanently or temporarily protects the core. The shell prevents the active substance from getting mixed with the textile material. Widely used shell materials are gelatine, starches, cellulose derivatives, polyactides, polyethylenglycols, polyvinyl alcohols, acrylates, fats and waxes.

The aim is either to progressively release the substance in the microcapsules in order to exercise a certain function. In this case, perfumes, medicines, depilatories are processed in the textile.

Or else, the substance remains in the capsules exercising its active function from inside; in this case, PCMs (Phase Change Materials) are incorporated. The substance in the microcapsules is activated by body heat or by movement.

The substances in the microcapsules will become active under the influence of an environmental stimulus and in this way they give the textile an ‘intelligent’ character.

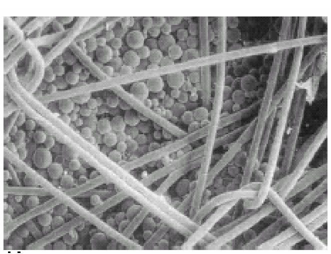
There are four release mechanisms to deliver the content of the microcapsule.

The oldest and most common mechanism is by simple fracture of the shell under the influence of a mechanical stress.

A second possibility is degradation of the shell. This degradation can be caused by dissolution, a chemical or an enzymatic breakdown of the shell. When the needed environmental conditions are set, the content of the microcapsule will be released. The deliverance can be perfectly controlled.

The two last release mechanisms are caused by the breaking of the shell upon swelling of the core. The encapsulated products are in a dried form and they will start to swell when they are brought in contact with the suitable product. The shell must allow the diffusion of this product into the core. Products that decompose while encapsulated can swell by a change in osmotic pressure within the capsule.

The potential of encapsulated phase change materials was first recognised when the US National Aeronautics and Space Administration (NASA) tried to find a technology to manage the thermal properties of garments, in particular for the use in space suits. In 1987, Triangle Research and Development Corporation of Rayleigh, US, whilst working for NASA, encapsulated phase change materials with the hope of reducing the impact of extreme variations in temperature encountered by astronauts during their mission in space. For further development the work was licensed to Outlast Technologies, US, to exploit the technology initially in fabric coatings, which are commercially available.



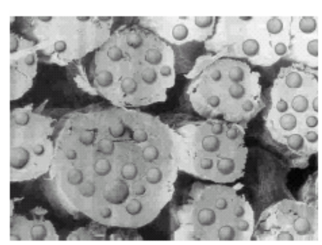


Fig. 95 PCM microcapsules coated on the surface of fabric and embedded within fibre

As a partner of Outlast, Accordis, formerly Courtaulds Fibres, together with Ciba developed an in-fibre variant of the Outlast microcapsules, which are incorporated by 5-10% in an acrylic fibre. This is achieved by using the late injection technology [177, 178, 179].

PCM capsules are now particularly applied to outdoor wear and in the household in blankets, duvets, mattresses and pillowcases. As well as being designed to combat cold, PCM encapsulated in textiles can help to combat overheating.

2.4.2 Technology

Phase Change Materials (PCM) change their state of matter at a certain temperature: from liquid to solid and vice versa. When the temperature rises, the excess heat is stored. When the temperature falls, the previously stored heat is released again.

When a PCM changes from a solid into a liquid state, one can distinguish between three phases during this process:

1. activation energy is supplied
2. this energy is absorbed and used to break the molecular bonds in the solid structure. The material's temperature remains constant until the phase transformation is completed.
3. the substance becomes liquid and the materials temperature starts to increase

Phase change materials mostly find their application as thermal control/regulation materials due to high latent heat absorption and release which occurs upon phase changing without changing, or only little, in temperature.

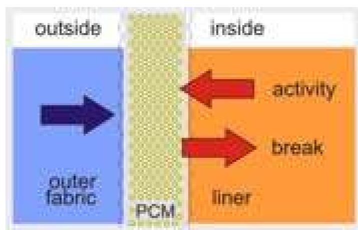
In the textile sector, usually combinations of different paraffin waxes are used. These are hydrocarbons with different chain lengths and thus different melting and crystallization points. With changing the proportionate amount of each paraffin type, the melting and crystallization can be altered. In table 2 different paraffin waxes with their crystallisation and melting points, as well as their latent heat fusion are presented.

Phase change material	Crystallisation point (°C)	Melting point (°C)	Latent heat of fusion (cal/gm)
licosane	30.6	36.1	59
octadecane	25.4	28.2	58
heptadecane	21.5	22.5	51

hexadecane	16.2	18.5	57

Table 2 Different paraffin waxes used in microcapsules

However, in general, the changing of the phase occurs within a temperature range in the vicinity of the body temperature. Therefore, the main function of the PCM will be to minimise the heat flow between the human body and the outside environment thus maintaining the skin temperature relatively constant and at a level considered to be comfortable.
In order to prevent the substances in the liquid state from flooding, it is necessary to capture them in a microcapsule, which is resistant against mechanical action, temperature and different chemicals.
Microcapsules are integrated either into an acryl fibre (during spinning) and produced by Accordis, a coating or foam [3].



Source: Merck

Fig. 96 Working principle of PCM

The American Society for Testing and Materials (ASTM) developed an approved standard test procedure to measure the amount of latent energy in textile materials, the first "Test Method for Steady State and Dynamic Thermal Performance in Textile Materials" (ASTM D7024). The method was developed with the help of Outlast® Technologies, Inc., and the Colorado State University.

A study carried out by researchers of the EMPA in Switzerland showed that the heat conduction of the microcapsules containing paraffin wax is better in the liquid state of the wax than in the solid state.

2.4.3 Applications in the clothing sector

PCM technology was originally developed in the 60's for use in NASA space suits. With the successful introduction of micro-encapsulated PCM (mPCM), this technology became available to the consumer and industrial markets.

2.4.3.1 Research projects and products

Outlast® has so far also been used for sports and outdoor clothing. Outlast® exploits the fundamental physical laws of thermodynamics. Microcapsules incorporated into a fabric react to the exterior temperature. The PCM liquefies when heated and the surplus heat energy is stored. At cold exterior temperatures, the PCM solidifies and releases the stored energy [114].

Several products using Outlast® have already made their way to the active wear marketplace. Some examples are listed below.

- In the middle of the year 2004, the Dockers® brand introduced a new line of Thermal Adapt™ Khaki´s using Smart Fabric Technology™ by Outlast® on the market
- Tempo Shain Corporation from U.S. licensed Outlast® technology for boot and shoe liners.
- Bula, Inc. uses Outlast® in winter headgear, hats and caps for hunting and outdoor sports.
- Ploucquet GmbH&Company from Germany also licensed the technology.
- Grandoe Corporation developed Outlast® fabrics for the use in a variety of men´s and women´s ski gloves.

The supplier list also includes brands including Bugatti, Burton, Gordini, New Balance, Obermayer and Rukka.

Schoeller Textil USA Inc. also uses phase change materials in Thermasorb®, which are micro-PCM capsules processed in powder form in Confortemp® foam.

With Comfortemp® the Carl Freudenberg KG, Germany, has commercialised a PCM incorporated into a nonwoven that is used in apparels.

With Comfortemp® inside the liner and insole of the wearer's shoe, cold can be overcome. In the winter, the mPCM forms an effective barrier against the cold by releasing stored up heat inside the shoe keeping the foot comfortably warm. In warm conditions, the mPCM absorbs the excess heat inside the shoe which contributes to less sweat and more comfort.

Schoeller®-PCM™

Respirex International Ltd. offers a phase change material in blocks incorporated into a flame retardant insulated vest for use by firefighters. It is non-flammable and it can be recharged in the refrigerator.

Further, all kinds of fragrances can be applied onto textiles, to enhance a garment, promote a product or to mask a manufacturing malodour.

Other possible products that can be micro-encapsulated are: moisturisers, essential oils, vitamins, deodorants and even insect repellents.
Moisturisers, for instance, have been incorporated by micro-encapsulating on stockings in order to improve the comfort and prevent drying out of the skin. Such panties are commercialised by the French underwear company DIM [180].

Skintex® from Cognis is another product that can be applied to clothes for skincare. Based on slow release microcapsules, Skintex® uses active ingredients that have a real effect on wellbeing, such as moisturising, cooling, energising, relaxing and mosquito repelling.
The microcapsules are embedded into the fabric. These are filled with high-grade ingredients and, over time, they are slowly released onto the skin. A protective layer of chitosan protects each capsule, saving its contents from warmth, drying out and the cold, and giving it durability against the wear and tear of day-to-day life. At the same time, chitosan has skin-caring attributes. It helps to protect the skin from dehydration.
The ingredients are released through two mechanisms. Firstly, there is the light friction the wearer creates when wearing clothes fitted with the capsules. Secondly, the chitosan layer is slowly reduced over time through the wearer's body's own enzymes - activating the ingredients and enabling them to move from the fabric onto the skin.
According to the company, every fabric, be it a natural or synthetic material, can be fitted with Skintex® [181].

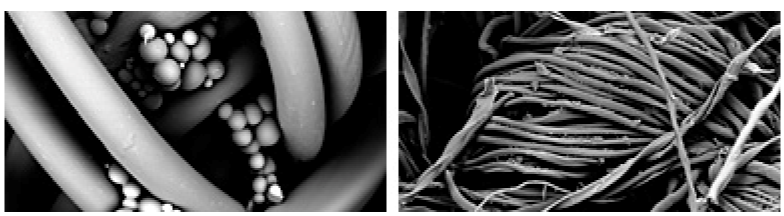


Fig. 97 Skintex® on polyester (left picture) and Skintex® on cotton 5right picture) (Source: Cognis)

Further, Neyret, a French clothing company, developed fragrant lingerie.

Olivier Lapidus is the first haute couture designer to use the technique of micro-encapsulation to create 'perfumed' fabrics for evening wear. The perfume is wash-resistant and dry-clean resistant and the fabrics release their fragrance gradually, during wearing.

2.4.3.2 Patents published

The Secretary of State of Defence in Britain claims the production of a thermally insulating textile adapted to provide a variable degree of thermal insulation dependent on ambient temperature. The textile construction is composed of a laminate of two fabric layers having an interposed bulking layer onto which shape memory polymers in a repeated pattern are arranged. Thus, the bulk layer can vary the air gap between the two fabric layers depending upon a predetermined temperature (US 6312784 B2).

In US patent 6989471 from 2006 The Procter & Gamble company claims the invention of a hygienic absorbent article such as diapers; adult incontinence articles or feminine protection articles. This article comprises two layers with an absorbent core and a phase change material in between. The PCM is capable of releasing or absorbing heat when needed and is activated by the wearer, caregiver or environmental conditions between the article and the wearer.

Malden Mills published a patent (US 6723967) in 2004 in which they claim heating or warming textile articles with phase change components. The heating textile, for instance in form of a jacket, consists of a fabric with electrical resistance heating elements that generate heat upon application of electrical power, e.g. from a battery mounted to the fabric. The PCM is also included into the fabric and is formulated to change phase in the temperature range of use, to cyclically absorb and release latent heat. Is it maybe the Polartec fleece?

In US patent 6759476 a flexible thermal control composite is claimed. The composite comprises a polymer and an endothermic agent. The endothermic agent is dispersed, distributed and suspended in the polymer. Then it is cured to form a Polymer Containing an Endothermic Agent (PCEA)[6]. Thereafter they were extruded and spun into PCEA fibres, which can then be processed into textile structures. In general, the PCEA composite finds versatile applications, including protective clothing, winter clothing, diving suits, but also furniture, walls, car interiors etc..

2.4.4 Applications in the interior textile sector

2.4.4.1 Research projects and products

In Britain, scientists have developed an acrylic fibre by incorporating microcapsules containing phase change materials. These fibres have been used for producing lightweight all-season blankets.

[6] PCEAs are capable of thermal control through their ability to absorb and store heat or to absorb and release it

At the fair ‘Heimtextil 2006’, the German bed-linen manufacturers, Waldenburger Bettwaren GmbH introduced their new brand ‘Comfort-line by Walburga’, a heat regulating bedlinen. A fine mesh, which comprises a balanced mixture of polyester microfibres and cotton, is lined on one side with a flexible ‘Climarelle’ temperature-regulating fleece. This fleece contains millions of microscopic little PCM capsules whose job it is to regulate the temperature.

Fig. 98 Bed fleece of the Comfort-line by Wallburga [182]

2.4.4.2 Patents published

2.4.5 Applications in the technical textile sector

2.4.5.1 Research projects and products

The Belgian company Devan chemicals is specialised in micro encapsulation technology in textiles. The microcapsules may contain fragrances, moisturisers, vitamins or essential oils in microscopic spheres. Typically, the sizes of the microcapsules range between 3 to 8µm. The release of the capsule’s content is triggered either by gentle rubbing of a coated area or by wearing a capsule treated garment.

Fig. 99 Microcapsule [183]

A team of researchers at the University of Illinois, USA, has recently developed a synthetic material that can heal itself [184]. The idea was inspired by biological systems in which damage triggers an automatic healing response. The material consists of a micro-encapsulated healing agent and a special catalyst embedded in a structural composite matrix. When the material cracks, the microcapsules rupture and release the healing agent into the damaged region through capillary action. As the healing agent contacts the embedded catalyst, polymerisation is initiated which then bonds the crack face closed.

In recent fracture tests, the self-healed composite recovered as much as 75% of their original strength. As microcracks are the precursors to structural failure, the ability to heal them will enable structures that last longer and require less maintenance.

The currently used spheres, measure about 100µm in diameter. Larger spheres could weaken the composite matrix.

A research group at the Thüringisches Institut für Textil- und Kunstoff-Forschung e.V. (TITK) developed PCM-Lyocell fibres. They added microencapsulated paraffin's to the spinning dope before the spinning process. The researchers see possible application fields next to temperature regulating clothes, also in blankets used for rescue missions and in the field of construction for the climate control of rooms by integrating PCM-fibres in on-wall or wallpaper [185].

2.4.5.2 Patents published

In 1988, Triangle Research and Development Corporation published a patent (US patent 4756958) concerning the production of a fibre with integrated microspheres filled with phase changing materials with thermal controlling properties. The fibres can be woven in order to produce a fabric possessing enhanced thermal storage properties.

2.5 Shape memory materials

2.5.1 Description

Shape memory materials are materials that can revert from their current shape to a previously held shape, usually due to the action of heat. In addition, they show a highly elastic behaviour in a certain temperature range. Shape memory materials are applied in textiles in form of alloys, polymers or gels.

Alloys

The Swedish physicist Arne Oelander discovered an interesting phenomenon while he was working with an alloy of gold and cadmium in 1932. The Au-Cd alloy could be deformed in its cold state and

returned to its original state when heated. Metals that possess this property are referred to as shape memory alloys (SMAs) [12].
According to Smartlab Shape Memory Alloys can be defined as "a unique class of metal alloys that can recover apparent permanent strains when they are heated above a certain temperature. The SMAs have two stable phases - the high-temperature phase, called austenite and the low-temperature phase, called martensite" [186].
The phase in which the alloy is situated depends upon the temperature and the pressure exercised on the object.
Shape memory alloys, such as nickel-titanium NiTi, have been developed to provide increased protection against sources of heat, even extreme heat. A shape memory alloy possesses different properties below and above the temperature at which it is activated. Below this temperature, the alloy is easily deformed. At the activation temperature, the alloy exerts a force to return to a previously adopted shape and becomes much stiffer. The temperature of activation can be chosen by altering the ratio of nickel to titanium in the alloy.
For explanation of the working principle, we consider a NiTi-alloy, whose structures are illustrated in the following drawing.

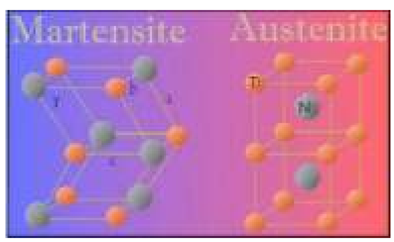


Fig. 100 Martensite and austenite structure [186]

The martensite and the austenite structure are clearly distinct. The a, b and c sides in the martensite grid all have different lengths. When pressure is exercised on the grid, these lengths will adapt themselves to compensate the pressure. The angle γ can also change as a function of the pressure exercised. Thanks to these properties, a shape memory alloy in the martensite structure can easily be transformed. Care should be taken, however, that the pressure exercised is not too big, as once the bonds are broken, the material will not be able to fully regain its original shape.
A thermal cycle looks as follows. The dividing line between martensite and austenite is determined by pressure and temperature. The straight lines on the graph below represent the limits of these transitions.

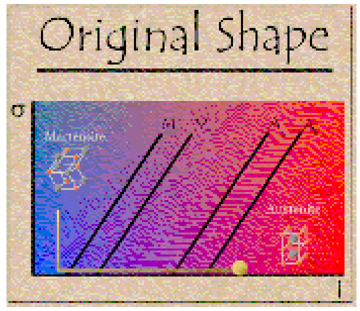


Fig. 101 Ms beginning martensite - Mf end martensite. As beginning austenite Af end austenite Transition from martensite to austenite grid [186]

When the alloy is formed, it consists of a 100% austenite grid until it is cooled down and becomes 100% martensite once the alloy falls below the Mf temperature. During this cooling process, the shape of the material has not changed. When arrived in the martensite phase, the material can easily be transformed, thanks to the variability of the parameters *a, b, c* and γ. When the material is released after this transformation, it will not return to its original shape because the temperature is below Mf. However, if one heats up the material, it will regain its original shape once the temperature As is attained. This recovery cycle comes to an end once A_f is reached.

If the memory alloy is faced with counteraction during this cycle, it can generate great forces. This phenomenon can be used to make actuators.

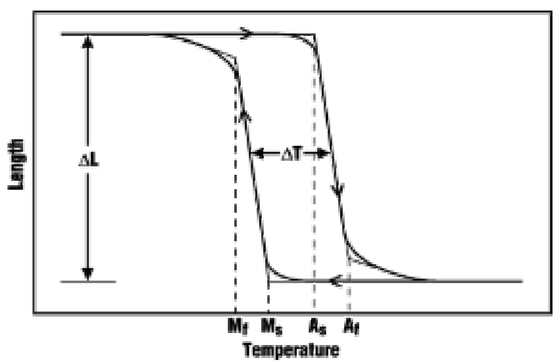


Fig. 102 Hysteresis curve by displaying length versus temperature

Above the transition temperature, in the austensitic stage, the SMA shows a superelastic behaviour. The elasticity can be 20 times the elasticity of conventional materials. The impressive amount of 'elastic' strain observed in SMAs forces the material to spring back immediately to its original shape if an applied stress is removed [187].

A big variety of metal alloys present the properties of shape memory alloys. However, there is only a limited number commercially important. The most frequent shape memory alloy is a NiTi-alloy, known as Nitinol. This specific alloy has very good electric and mechanical properties and a high resistance against corrosion. Moreover, Nitinol has the quality of inducing the transformation by means of electric energy. When sufficient electric power is transmitted through the wire, the generated warmth will produce the transformation. Usually, a shape memory alloy is chosen whose transformation temperature lies far above room temperature. By changing the rate of Ni and Ti, one can increase or decrease the transformation temperature. The available transition temperatures vary between –100 and + 100°C.

NiTi-alloys usually occur in the form of wires, making them suitable to be processed in a textile material.

Because of their biocompatibility, NiTi-alloys are also applied in the medical world. They are put to use in surgical tools as well as in permanent implants.

BioMetal is the trade name of nickel-titanium fibres produced by Toki, a Japanese company. The fibres are capable to remember a certain length, which means when a force is applied on the fibre during heating it contracts. When it cools down again, it elongates. The fibres can be used for instance as electrothermal driven actuators.

Further, the American company Dynalloy Inc. commercialises a shape memory alloy actuator wire made of nickel-titanium under the trade name Flexinol®. Its ability to flex and shorten is electrically driven. The alloy wire can be applied variously; in the field of textiles applications include light fibre switches and light fibre gates (automotive industry) [188].

Cuprous-zinc alloys are capable of a two-way activation and therefore can produce the reversible variation needed for protection from changeable weather conditions. They will also react to temperature changes brought about by variations in physical activity levels.

Polymers

Shape memory polymers are defined as polymeric materials with the ability to sense and respond to external stimuli in a predetermined shape.

Shape memory polymers were first developed in France (CdF Chimie Company) and commercialised by Nippon Zeon Co. in Japan in 1984.

Polymers such as polynorbornylene, transpolyisoprene, styrene-butadiene copolymer, polyethylene, polyester copolymerised with others and block polyurethanes have been discovered to have shape memory properties. A variety of about twenty polymers were developed with shape memory effects.

Shape recovery due to the shape memory of polymers may be triggered by heat, light, electricity and other stimuli.

Shape memory polymers possess some characteristics that make them attractive to use in textiles, such as light weight, corrosion resistant, formability and low cost. SMPs are available for example in form of pellets. They can easily be compounded and formed by extrusion or injection moulding.

Recently developed memory polymers belong to the group of polyurethanes. They are thermoplastic polymers having their glass transition temperature at a range of – 30°C till 100°C. Mitsubishi Heavy Industries commercialises these polymers in the form of hydrophilic vapour-transmitting membranes.

There are several advantages of SMPs compared to SMAs, such as easy processability, comparatively low production costs, biocompatibility, substantially easier shaping procedure and high shape stability. A disadvantage of SMP in comparison to SMA is the much lower recovery force.

Compared with other types of shape memory materials, such as alloys, literature for understanding the characteristics and the detailed mechanisms responsible for the properties of shape memory polymers are still very fragmented and restricted. The Hong Kong Polytechnic University is doing investigations into their detailed characteristics.

A. Block copolymers

Shape memory polymers are block copolymers consisting of two segments: a hard and a soft segment. The soft segments should be large enough to allow a considerable free rotation when the temperature changes and to result in the recovery of the deformations previously exerted on the structure.

The hard segments include the urethane bond and chain lengtheners[7]. They are present in a sufficient quantity to be able to form a continuous crystalline phase[8], the fixed phase. The soft segments, consisting of polyether or polyester dioles, form the glass phase[9] or the reversible phase. During the first formation of an object from a shape memory polymer via a thermoplastic process, both phases are in the melted position. The extrusion temperature of the films lies between 170 and 200 °C. When the object is cooled down to a temperature where both phases are in the solid state, the definite form of the object is obtained. Next, the object is re-heated to a temperature at which only the glass phase turns soft. Now, it is possible to transform the object under pressure. The object is cooled down again in this temporary form. A second heating under negligible pressure results into a recovery of the permanent shape.

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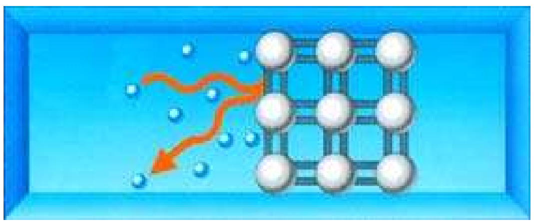
[7] **chain lengtheners** : chemicals which can react with the end groups of two or more polymer chains resulting into a longer polymer.

[8] **continuous crystalline phase**: in certain parts of a polymer, the atoms are arranged in such a way that it is possible to assume a disposition in a crystal lattice;

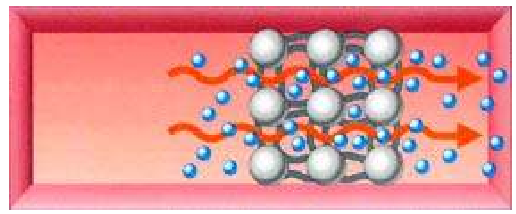
[9] **glass phase** : parts of the polymer where no crystallisation can occur, can have two positions. A hard, brittle position below a certain temperature and a viscous, rubbery position above this temperature. The temperature at which this transition occurs, is called the glass transition temperature, the rubbery state is the glass phase.

B. Thermal vibrations

Shape memory polymers can also be used to make a moisture permeable membrane. In this case, the polymer membrane reacts by inducing thermal vibrations. Micro-Brownian movements of the amorphous polymeric soft segments occur when the temperature rises above a predetermined activation temperature. Due to these movements, micropores appear in the polymer membrane. Water vapour molecules (with an average diameter of 3.5 Å) and body heat can escape through these pores.



Molecular structure below the activation temperature [189]



Molecular structure above the activation temperature [189]

Fig. 103 Molecular structure

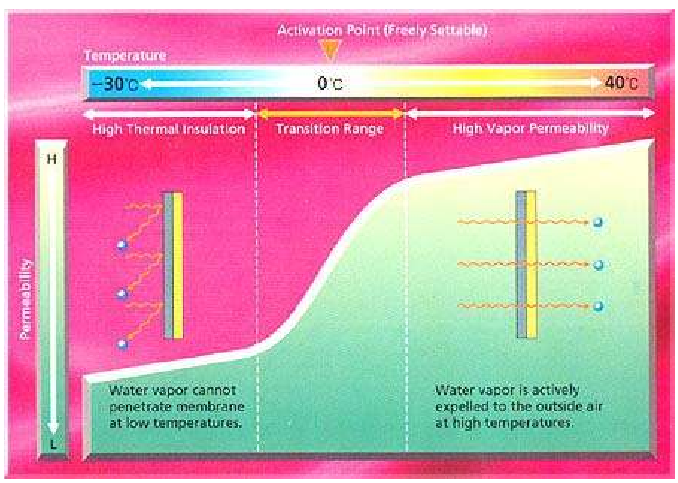


Fig. 104 Activation scheme [189]

Gels

Encapsulated Bi-Gels absorb liquid at differing rates according to temperature which causes them to bend. This offers possibilities for their use as actuators in a variable insulation system. Exploratory work using polyacrylamide and poly-N-isopropylacrylamide did not produce the envisaged robust actuator behaviour.

Workers at the company S.Mizushima of Mizushima Silk Industry Ltd. succeeded in developing a shape-memory silk yarn. The silk yarn is chemically treated by dipping in a solution of hydrolyzed fibroin, keratin and collagen, dried, crimped, dipped again in water and thermo-set in the wet state under high pressure at 110°C for ten minutes, yielding shape-memory silk. As the twisted structure is stored in the memory, the silk yarn reversibly recovers its curled shape by steaming after it has been untwisted and uncurled. The silk yarn can be applied in various textile products, like outer garments, tights and knitted yarns [140].

2.5.2 Applications in the clothing sector

2.5.2.1 Research projects and products

Alloys

In practice, a shape memory alloy is usually in the shape of a spring. The melting point of this alloy lies around 1340°C, which makes it extremely suitable for protective clothing. The Ni-Ti relation is chosen in such a way that the springs are flat in unheated condition, in other words at room temperature. Due to the low shift modulus, they can easily be opened. Thus, at increasing temperatures the springs will open up. This results into a considerable increase of the shift modulus, which makes it difficult for them to close. The springs only have a one-way function: when cooling down, they will not regain their original shape. When the springs are used in heat-resistant clothing, the garment cannot be used again once it is being exposed to the heat.

The pioneering UK Defense Clothing & Textiles Agency (DCTA R&TG) in this field created an intelligent suit suitable for protective clothing for firefighters at the end of the nineties. It consists of two separate layers, in which cotton bands are introduced in order to incorporate the springs. The springs are only fixed at the outside layer, so that they are minimally obstructed when expanding. The springs used are conic and have a 25mm diameter. Air is a good insulator. Under the influence of the transformed springs, both textile layers will move away from each other as a result of which an insulating air layer is formed between them.

A doll wearing the garment is exposed for 8seconds to a propane burner, emitting an 80kW/m² flux of warmth. Because of the heat, the springs open up and create an insulating air layer between both textile layers.

The results of this test set-up were very satisfactory. For comparison, at the backside of the doll, where no springs were attached, burns in the second and the third degree were found.

The inner layer used: a Proban® - cotton woven

The outer layer used: a Kermel[10] - viscose weft knit

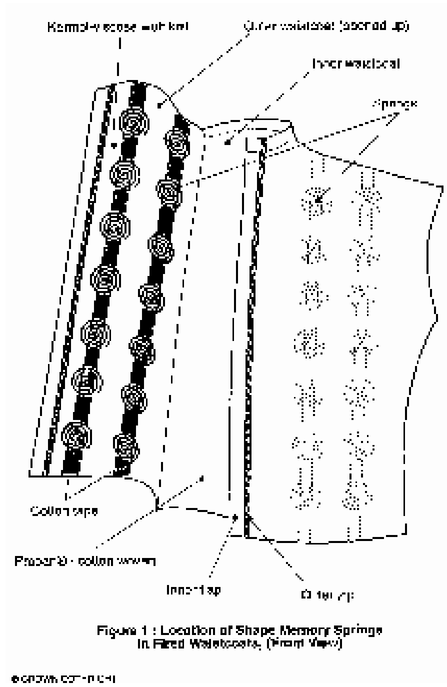


Fig. 105 Waistcoat with incorporated springs made of a memory alloy

Additionally, Nitinol alloys were also be used to design superelastic bra-wires. In common metal the limit of elasticity is about 2%. A superelastic Ni-Ti wire has elasticity as high as 6%. This means that a Ni-Ti wire can support a larger amount of strain with complete recovery on unloading. The support wire can locally deform t adjust to any given shape, without stiffening. This results in a higher comfort, when used in a bra. The superelastic wire combines the comfort of a nylon wire and gives the wanted support of a steel wire.

Grado° zero espace has commercialised a wrinkle free shirt called 'Oricalco' out of Nitinol fabrics. The 'Thermal Shape Memory Alloy' is characterised by its extraordinary ability to recover any shape, pre-programmed, upon heating. Until today this light weight alloy with about 50% Titanium inside has been used in advanced sectors like space and recently in medical applications. Through the Technology Transfer Programme of the ESA, D'Appolonia has transferred this knowledge in traditional sectors.

In this framework Corpo Nove, through their R&D spin-off Grado Zero Espace, have used Thermal Shape Memory metals as a fabric for the manufacturing of a shirt on with long sleeves which was

[10] **KERMEL** is a high-technological fibre developed in the 60s by Rhône Poulenc. It is an aramid fibre, belonging to the polyamids and the polyimids. The fibre is thermostable and not-inflammable, which makes it very useful for all sorts of protective clothing (for firemen, police officers, personnel in petrol refineries and chemical companies).

made out of this fabric. The sleeves fabric could be programmed to shorten immediately as the room temperature became a few degrees hotter. The fabric can be screwed up into a hard ball, pleated and creased then just by a flux of hot air (even a hairdryer) pop back automatically to its former shape.

Fig. 106 Crease resistant shirt [159]

Further, Haggar Clothing (USA) launched a men's shirt and trouser line called ForeverNew™ by the end of the year 2004 [190]. They promised that the colour of the clothes will not fade, the textile will not shrink; will stay without wrinkles and stains.

Polymers

Shape memory polymers can be applied in thermal-insulating (against heat as well as against extreme colds) clothing. Therefore polymers are used that have an actuation temperature within the clothing temperature environment.

The thermal-insulating effect is mainly obtained by incorporating an air layer between the different textile layers. The idea is to apply an adaptable polymer film between two layers of textile. When the temperature at the outside textile layer decreases, this is passed through to the adjacent shape memory polymer layer, which changes into another form, resulting in a broader air gap between the two textile layers.

This can be realised when the shape memory polymer takes a non-flat shape during cooling and when the polymer layer is sufficiently resistant against the forces influencing the textile material. Moreover, the polymer film has to be able to undergo different transformation cycles.

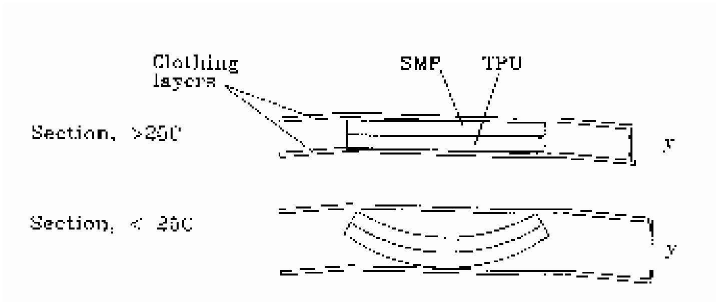


Fig. 107 Memory polymer film between two textile layers (Source: Techtextil Symposium 1999)

A prototype was made using a bi-material laminated film consisting of a layer of shape memory polymer (with a glass transition temperature of 25°C) film and a layer of a compatible elastomeric film. When the temperature drops below 25°C the shape memory layer will shrink linearly by some 3 % and become rigid, creating an out-of-plane deformation. It is anticipated that the deformed laminated films will provide reversible enhanced thermal insulation in response to cold.
When using a shape memory polymer with a glass transition temperature in the region of 55°C a laminate could be formed to protect against heat.

A few remarkable achievements have been made in water vapour permeable materials where, through the use of shape memory polymers, a water vapour permeation rate is achieved controlled by the difference in relative humidity and temperature. Casual and sportswear clothing have been developed which keep the wearer warm in cold season and cool in hot season. Examples can be found in the subsequent paragraphs.

Mitsubishi Heavy Industries introduced the polyurethane membrane ‘DiAPLEX-The intelligent material’ to the outer wear market, which is waterproofed, windproofed and breathable. Its functionality is based on the principle of thermal vibrations. The shape memory polymer can be attached in form of a laminate to a variety of fabrics, being capable to adapt to the surrounding environmental conditions.

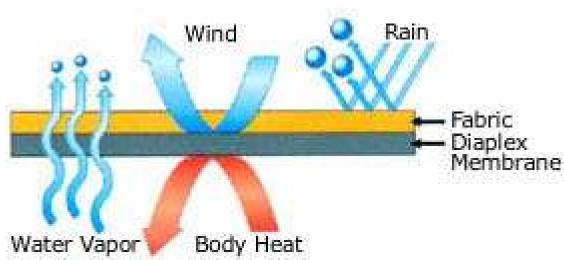


Fig. 108 Cross-section of a fabric with a DiAPLEX membrane [189]

Toray Industries and Marmot Mountain Works® also introduced a polyurethane polymer film MemBrain® laminated between adjacent layers of clothing, thus resulting in a waterproof and breathable fabric. When the temperature of the outer layer of clothing has fallen sufficiently, the polyurethane film responds so that the air gap between the layers of clothing becomes broader. This broadening is achieved if, on cooling, the film develops an out-of-plane deformation, which must be strong enough to resist the weight of the clothing and the forces induced by the movements of the wearer. The deformation must be capable of reversal if the outer layer of clothing subsequently becomes warmer.

Another application of shape memory polymers is the production of form regulating clothes. Australian scientists at University of Wollongong have invented a smart bra that will change its properties in response to breast movement, giving better support to active women. The bra tightens and loosens its own straps, or stiffens and relaxes its cups, to restrict breast movement, preventing pain and sag. The bra is made of a fabric with a special coating that makes it contract when the strain on it passes a pre-set level. Scientists at Wollongong University say the brazier automatically provides women extra support during strenuous activity such as exercise.
Other smart fabrics being developed by the team include a knee sleeve that tells athletes whether they have landed properly and a cloth for the US military with built-in solar energy cells and batteries. The team is also working with doctors at Sydney's Royal North Shore Hospital on a glove for people with hand injuries that uses electric signals to help patients clench their hands and pick things up.

In protective clothing, shape memory polyurethanes have been proposed to shield against heat, although these ideas have, to our knowledge, never reached the market.

Finishings

MiracleCare, developed by the Japanese company Toyobo, is a long-standing vapour phase shape-memory finishing process for cotton and other cellulosic materials.

Nano-Tex licenses a nanotechnology treatment applied by pad in fabric form or by dipping the finished garment. This is a permanent method of minimising wrinkles, while also offering softness and breathability. The crease removal is achieved by a mixture of heat and moisture [191]. Eddie Bauer used this technology in a khaki trousers collection.

2.5.2.2 Patents published

The Japanese company Mitsubishi Jukogyo succeeded to produce fibres from shape memory polymers. The polymer is a polyurethane elastomer with a glass transition temperature of about 40°C. Yarn is either produced by spinning of pure fibres or by mixing with other fibres. The yarns are then being woven. The fabric gets a certain shape at a temperature lower than the glass transition temperature. Heating the fabric beyond that temperature, it obtains another shape. In that shape, it is cooled down its glass transition temperature. When the woven is reheated beyond the glass transition temperature, it will regain its original shape (US 5128197).

Philips invented a pocket, suitable for incorporation in garments or luggage, which prevents any items held in the pockets from falling out inadvertently. For this purpose they used a shape memory alloy that contracts and thus performs a closing action of the pocket opening when it is heated (US 6834797).

Further, Philips utilizes shape memory alloys for tactile feedback devices. The devices consist of an elastic body to which a shape memory alloy is attached. When applying power to the system, the shape memory alloy assumes a shape that causes a tactile feedback to the user (Us 2003/0181116).

2.5.3 Applications in the interior textile sector

2.5.3.1 Research projects and products

Gels

Matresses: The patented Lever Support System is an exclusive technology developed and tested by Strobel Technologies

2.5.3.2 Patents published

2.5.4 Applications in the technical textile sector

2.5.4.1 Research projects and products

Alloys

Shape memory alloys are used in different surgical implants including stents. For example they are used in the field of orthodontics, where enabling braces are inserted more easily before tightening *in situ*.

Polymers

Study is now on the way to apply FRP (fibre reinforced plastics) in which shape memory polymers are used as matrix resin to the inflatable structure in space. This program, initiated by Mitsubishi Heavy Industries, aims at compact folding of the FRP moulded to final shape to transport to the space before expanding it to the original shape in space [192].

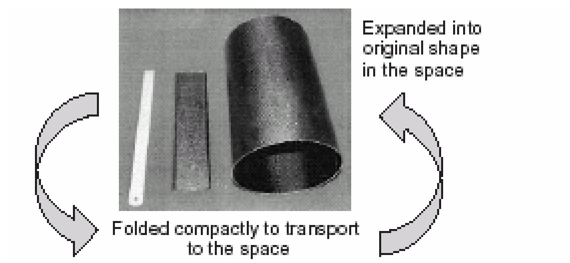


Fig. 109 Inflatable space material [192]

C.R.Bard (U.S.) and mnemoScience GmbH (Germany) are co-operating in the field of shape memory polymers for surgical use, for example yarn based sutures (polyurethane) that change form in the body.

Scientists working at MnemoScience GmbH developed a ´shape-shifting´ plastic that can be fashioned into novel medical devices such as sutures that allow an optimized tightening of the knot. The plastic is composed of two components with different thermal characteristics, oligo(ε-caprolactone)diol and crystallisable oligo(ρ-dioxane)diol. The multiblockcopolymer features two blockbuilding segments, a hard and a switching segment, which are linked together in linear chains. The plastic can be stretched or strunched into temporary forms up to four times larger or smaller than its permanent shape. The plastic is automatically transformed into this permanent shape when exposed to a suitable external stimulus, such as increase in temperature. As the material is biodegradable, it can dissolve after the wound is healed and is harmlessly absorbed by the body.

Additionammy, shape memory polymers can enable a slow release of drugs to be applied to the stents surface in order to prevent cell build up *in situ*.

2.5.4.2 Patents published

Kimberly-Clark uses humidity sensitive shape memory materials to develop hygiene products that become more compact and hence more effective when moisture is sensed, improving the comfort level. The shape memory materials can be in the form of films, fibres, filaments, strands, non-wovens, and pre-moulded elements (US 6 627 673).

2.6 *Stimuli sensitive polymers*

2.6.1 Description

This chapter describes the current innovations and commercialisations in fabrics that change their responses to external stimuli or environmental changes such as temperature, humidity, pH, light, electrical field, chemicals, ionic strength or stress. The responses excite changes, for instance, in shape, structure, surface characteristics, solubility, formation of an intricate molecular self-assembly or a sol-to-gel transition.

These polymers can be processed in fibres, or can be applied on the fibre surface in order to obtain specific properties.

2.6.2 Applications in the clothing sector

2.6.2.1 Research projects and products

Taking for instance humidity as a stimulus, the wicking performance of a fabric can vary according to the humidity level. A research group at the Centre of Biomimetics at University of Reading, UK, tries to imitate the opening and closing of pine cones. When cones are hanging on the tree, they are firm and closed. However, when they ripen and fall to the ground, they open in order to release the seeds. This works because the scales of the cone consist of layers of two materials that react differently to humidity. When the cone desiccates, the scales will bend, because one of its sides will expand more than the other.

In co-operation with the London College of Fashion they are researching the material, which they think could be in everyday use by people within a few years. The smart garments will consist of a top layer of tiny spikes of water-absorbent material, possibly wool. When the wearer of the clothing gets hot and sweats, the tiny spikes in the material will react to the moisture and automatically open up, so that air from the outside can get through the material to cool the wearer. When the wearer stops sweating and the skin dries, the fins will close down again to stop air getting in. The lower layer will be of material that is not porous so that rain can never get through from the outside, whether the spikes are open or closed [193, 194].

Fig. 110 Flap opening in the textile structure [195]

The project has been chosen as one of eight to represent United Kingdom science at Expo 2005 in Japan.

Fig. 111 ....Temperature regulating jacket exhibited at EXPO 2005

Another example of fabrics that change their performance in response to moisture is textiles coated with a polyurethane film. The company Baxenden Chemicals has developed a hydrophilic polyurethane coating for textiles that becomes more breathable, the more moisture is build up inside the clothing. In general, a solid, hydrophilic polyurethane coating constantly adapts to surrounding conditions of water vapour pressure. Their resistance values decrease with the amount of water contained in the polymer. In extreme cases, when liquid water is in contact with the polymer surface, hydrophilic polyurethanes reversibly absorb up to three water molecules per ethylene oxide unit and may become swollen. In this state water vapour transport through the molecular network is enhanced and the diffusion coefficient increases [58].

Researchers at the Indian Institute of Technology succeeded in developing a smart breathable cotton fabric coating which responds to changes in ambient temperature. They used a temperature sensitive copolymer-poly (N-tert-butylacrylamide-ran-acrylamide). The coating on the fabric shows a retained temperature-sensitive swelling behaviour and a transition in the temperature range of 15-40°C. Below 15°C, the coating swells by 800% while above 40°C it deswells to a swelling percentage of less than 50% (on the basis of dry weight). The response was found to be reversible and stable to repeated cycles of transition [196].

2.6.2.2 Patents published

The company International Flavors & Fragrances patented the method of making a fragrance containing fibre in US 6517759.

2.6.3 Applications in the interior textile sector

2.6.3.1 Research projects and products

2.6.3.2 Patents published

2.6.4 Applications in the technical textile sector

2.6.4.1 Research projects and products

In 1950, two researchers (W. Kuhn and A. Katchalsky) developed fibres being able to contract under the influence of a pH change. However, a disadvantage was the slow reaction time of the polymer: the change lasted for some minutes. Through the years, other fibres have been developed having much shorter reactions: from a few seconds (De Rossi 1987) to a few tenths of seconds (Suzuki 1989). These fibres also have a high tensile strength.

The degree of contraction and the developed forces equal those of a human muscle.

At the University of New Mexico, U.S., research is going on into the development of artificial muscles. To this end, a polyacrylonitrile fibre, ORLON[11] is used. A few years ago, researchers discovered that PAN fibres are able to contract when the degree of acidity in the surroundings changes. In two tenths of a second, they can shrink 20%, this is almost as fast as a human muscle. Depending on the degree of acidity, PAN fibres can contract to half or a tenth of their original length. Moreover, the fibres are strong: they can bear up to 4 kg/cm^2, which is more than a human muscle.

A big disadvantage of these PAN muscles is the need of a chemical activator. The possibilities would become more extensive if one would succeed in having the artificial muscles functioning with electricity for example [3].

Superabsorbent polymers are produced by polymerising acrylic acid to become crosslinked sodium poly-acrylate. The carboxylic groups of the absorbent polymer are solvated when brought into contact with a water based liquid. As a result, the groups partially dissociate into negatively charged carboxylic ions. In this state, the polymer chain contains a large number of similarly charged ionic groups which repel each other. The polymer coils become more bulky and thus extend their propensity to absorb

[11] ORLON is an acrylic fibre produced by the company Du Pont

increasing quantities of the aqueous liquid. This process would normally lead to a complete solution of the polymer. However, due to the crosslinking between the polymer chains of the absorbent polymer, only the formation of a gel takes place, precluding its solution. The water is strongly bonded by means of hydrogen bonds in the gel.
Superabsorbent polymers can swell up to hundreds of times their own weight in aqueous media. Their swelling behaviour is characterised mainly by the amount of water they absorb and the rate of absorption.

At the North Carolina State University, U.S., a project is going on (since 2001) to develop stimuli-sensitive polymers. To this end, the molecular and physicochemical principles accompanying the changes of these polymers will be studied. The aim is to extrude fibres completely made of stimuli-sensitive polymers. One starts from fibres based on polyacrylic acid, carboxymethyl cellulose and chitosan and one proceeds according to the wet spinning process.

Drug delivery systems

Textile materials in drug delivery systems are a topic of increasing interest and research in the last years. As textile materials are characterised by their open permeable structure and large surface area, they are applied in *in-* and *ex-vivo* drug delivery systems. Research is going on in the field of textile slow release systems like fibres bearing cyclodextrins, ion-exchange fibres, microparticles and nanofibres containing drugs produced by electrospinning.

Fibres bearing cyclodextrins

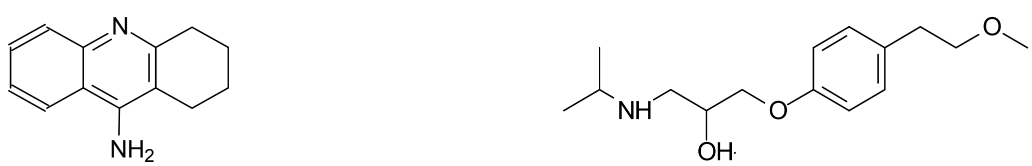
Cyclodextrins are able to form complexes with a variety of long chain aliphatic or aromatic molecules like drugs, detergents and fragrances, for example. The group of drugs that can be bonded to cyclodextrins is quite large, because the complex formation is largely independent of the chemical properties of the drug molecule. Thus different types of drugs have been investigated, varying from neutral to ionic and from basic to acidic. Van der Waal's forces play a significant role in the formation of a drug-cyclodextrin complex. Both, the complexation as well as the decomplexation, namely the release of the drug from the cyclodextrin, are equilibrium processes. Cyclodextrins can be fixed either permanently or non-permanently to the surface of a fibre. Grafting of cyclodextrins on textiles turned out to be very promising. Different types of cyclodextrins have already been grafted on textile fibres like cotton, Tencell, wool, polyester and polypropylene.

Ion-exchange fibres

Besides in wastewater purification, uranium enrichment from seawater, ion-exchange fibres are also applied in textile drug delivery systems. With characteristics like a fast ion-exchange rate and a high

separation capacity, ion-exchange fibres present more attractiveness for use than other ion-exchange materials.
Ion-exchange fibres have either a positive or a negative electric charge, which is compensated by mobile counter-ions of opposite charge. The principle of ion-exchange is based on electroneutral condition. Ion-exchange generally is a diffusion process, sensible to concentration gradients. Many drugs are charged at physiological pH, therefore they can act as mobile counter-ion, and this allows them to be used as drug delivery systems.
An example of an already commercialised ion-exchange fibre suitable for drug delivery is given by Smopex® fibres from SmopTech Co. in Turku/Finland.

Another possibility to obtain ion-exchange fibres is to graft ion-exchange groups to cotton, flax, cellulose, wool, polyethylene, polystyrene, polyacrylonitrile, polyamide and carbon fibres. *In*- and *ex-vivo* ion-exchange drug delivery systems have been developed. *In-vivo* the drugs can be released by ions present in body fluids, whereas in *ex-vivo* applications the concentration of ions needed for the exchange is determined by excretion through the skin. A research team in Finland at the Helsinki University of Technology is working on ion-exchange fibres in transdermal iontophoresis. The aim of the study is to develop a controlled drug delivery vehicle for trans-dermal iontophoresis using fibrous ion-exchangers as a drug reservoir. For this purpose, positively charged model drugs; tacrine, metoprolol (figure below), nadolol and propranalol are loaded into the ion-exchange groups of the fibre and then released using a salt solution, containing counter-ion to the drug, and weak current, iontophoresis [197].



Tacrine Metoprolol

Fig. 112 ....Chemical structures of Tacrine and Metoprolol

Researchers from the University of Belgrade developed cation-exchange fibres based on PAN with the carboxylic group as functional group.

Further, the Thüringisches Institut für Textil- und Kunststoff-Forschung e.V. (TITK) is researching on ion-exchange fibres on cellulosic basis. They developed a special process, the ALCERU® technology, to dissolve cellulose directly without any chemical modification for producing textile fibres in a subsequent spinning process. The possible homogeneous integration of organic or inorganic additives allows the production of several functional cellulose-materials, among them an ion-exchange fibre. With the same process, they succeeded to develop a PCM fibre (see chapter 2.4.5.1) [198].

Hollow fibres, microencapsulated fibres, microparticles and nanofibres

A group at the University of Tehran Medical Sciences investigates hollow fibres drug delivery systems in which the fibre wall is a permeable membrane. The fibre itself is filled with a liquid drug or a drug solution. Therefore there is still a distinct separation in fibres and drugs.

Another method to incorporate drugs into fibres is to suspend or dissolve a drug into a polymer solution used to produce fibres. A research group in Baltimore, U.S., works on producing drug-loaded Chitosan-alginate fibres from interfacial polyelectrolyte complexation. The drug, namely dexamethasone, can be trapped into the fibres as the two polyelectrolytes formed a complex at the solution interface and were mechanically drawn into a fibre. These fibres are supposed to have high encapsulation efficiency and sustained release of charged molecules. In this case the driving force for drug release is diffusion [199].

Another technology to produce textile structures containing drugs is electrospinning, which is very promising. In general, the smaller the dimensions of the drug and the coating material required to encapsulate the drug, the better the drug to be absorbed by the human body. Drug delivery with polymer nanofibres is based on the principle the dissolution rate of a particular drug increases with increasing surface area of both the drug and its carrier.

A joint research group of different departments of the Commonwealth University in Richmond, U.S., produced electrospun fibre mats out of poly(lactic acid) (PLA), poly(ethylene-co-vinyl acetate) (PEVA) and from a 50:50 blend of the two, containing an antibiotic. They found out that electrospun PEVA and blended mats gave a smooth drug release over five days [200].

Electrospun poly(L-lactic acid) fibre mats are further examined by a research group at the Chinese Academy of Sciences. They try to improve the drug release by reducing the diameter of the fibre with the help of anionic, cationic and non-ionic surfactants. They further studied the encapsulation of lipophilic and hydrophilic drugs inside the fibre mats and their release kinetics [201, 202].

Another team researches on heparin incorporated into electrospun PCL fibre mats for controlled drug release for vascular injuries.

Lonwave (hollow, PES+ceramic micro-particles) from KURARAY is an infrared radiating fibre.

2.6.4.2 Patents published

2.7 Piezoelectric materials

2.7.1 Description

The word ‘piezo’ is derived from the Greek word for pressure. In 1880, Jacques and Pierre Curie discovered that pressure, applied to a quartz crystal, creates an electrical charge in the crystal; they called this phenomenon the piezo effect. Later they also verified that an electrical field applied to the crystal would lead to a deformation of the material. This effect is referred to as the inverse piezo effect. Piezoelectric materials can be used to convert electrical energy into mechanical energy and vice versa. After the discovery it took several decades to utilize the piezoelectric phenomenon. The first commercial applications were ultrasonic submarine detectors developed during World War I and in the 1940’s scientists discovered that barium titanate ceramics could be made piezoelectric in an electric field.

Pressure sensors to provide information on pressure field distribution and thus enabling to monitor seating or standing positions of the wearer over time can be based on piezoelectric and piezoresistive substrates, but they are difficult to integrate into elastic fabrics because mechanical stresses, like impact and compression, can seriously damage the sensors. Works and projects on pressure sensors are already reported on the chapter conductive materials.

However, we would like to mention the fabric strain sensor developed at the University of Pisa at this point to explain the sensing function. The sensing function of the textile material is realised in two different ways:

1. yarn coated with polypyrrole
2. yarn coated with carbon loaded rubber

Polypyrrole is a π-electron conjugated conducting polymer that combines good properties of elasticity with mechanical and thermal transduction. Lycra fabric is PPy-coated using a slightly modified method developed by Milliken Research Corporation. In this way a fabric sensor is developed (US patent 4,803,096).

The sensors based on carbon filled rubber (CFR) are realized either by directly printing the carbon/rubber mixture onto fabrics or by weaving CFR coated fibres.

Due to the piëzoresistive properties of the used materials, there is a relationship between an imposed strain and the resistance of the material. In this way a wearable sensing system is developed to measure biomechanical signals such as respiration, heartbeat and body movement.

Researcher in the US developed an in-shoe multisensory data acquisition system that monitors temperature, pressure and humidity [203].

2.7.2 Technology

2.7.3 Applications in the clothing sector

2.7.3.1 Research projects and products

The British Company QinetiQ has inserted a small ceramic piezoelectric device in the heel of a shoe. The pressure and flexing of the foot during walking is converted into a small amount of electricity [204].

2.7.3.2 Patents published

2.7.4 Applications in the interior textile sector

2.7.4.1 Research projects and products

2.7.4.2 Patents published

2.7.5 Applications in the technical textile sector

2.7.5.1 Research projects and products

Developments are taken place in the use of auxetic fabrics or yarns as carriers for drugs or other agents that would be released under pressure (e.g.swelling) of the wound.

2.7.5.2 Patents published

2.8 Others

2.8.1 Applications in the clothing sector

2.8.1.1 Research projects and products

Climate control

The vAIRis membrane jacket, a joint project of the companies Sympatex Technologies and Ploucquet, and the Eidgenoessische Material- und Pruefgesellschaft (EMPA; Confederate Materials and Testing Association), is equipped with integrated variable heat insulation. The beating heart of this membrane jacket is a micropump, which is responsible for filling three down-filled chambers with air or emptying the air out of it. It has an input or output of 4 l/min at a weight of only 25 g and runs on a 6 V battery [114].

Another example for such a climate control jacket is offered by the company W.L. Gore Associates. The introduced Gore Airvantage into the market. Air is blown into an airtight insulation layer that breathes, as soon as the wearer wants to be warmer. Bugatti and Escada have integrated this technology into their collections.

The Italian company Grado° zero espace is marketing under the brandname Corpe Nove clothing ranging from a jacket incorporating Aerogel and sold under the Hugo Boss label; and items, containing the fluff and seed fibres from poplar trees. 'Feelgood clothing' is being made from SeaCell, derived from algae.

For the first time this extraordinary material, from the latest generation of thermal insulators, has been taken outside its usual sphere of use in the aerospace sector and used as a fabric coating. Liquid Ceramic's main features are its resistance to heat and to UVA and UVB rays. It also makes the material it is applied to much more resistant to abrasion. The fact that this ceramic is liquid also makes it possible to maintain an incredible lightness and flexibility which do not alter the characteristics of the material it is coated onto.

Fig. 113 The jacket produced by Corpo Nove. The liquid ceramic is used on the internal surface of the garment [101]

Alyce Santoro created the so-called Sonic Fabric^{TM}, a cloth woven from 50% prerecorded audiocassette tape and 50% cotton and which is audible. The sounds on the cassette tape in the weave can be heard when drawing a tape head over its surface. The Sonic Fabric^{TM} was inspired by the use of small strands of cassette tape used as wind indicators and by Tibetan prayer flags inscribed with wind-activated blessings.

So far, a dress, messenger bags and Tibetan prayer flags have been developed. The two latter products can be ordered for US $125 and US $150, respectively [205].

Fig. 114 Sonic Fabric™, dress, flags and bag made out of the fabric

To exploit new technologies fully, however, a multidisciplinary approach is required involving networks and a dialogue between researchers, manufacturers, applications specialists and marketing professionals. Innovators are responding to the challenges with a plethora of developments.

Researchers at the Centre of Biomimetics at University of Reading are carrying out research to mimic Penguin down feathers to create a variable thickness active thermal insulation structure for clothing used in extreme conditions. The Penguin down feather is a good insulator because of its structure: It possesses a shaft of circular cross section (barb) and perpendicular fibres (barbules). The goal of developing thinner, more efficient insulation fabrics and a penguin pelt has got a temperature gradient in the order of 80°C across a thickness that's no more than 2cm. Synthetic alternatives provide a lower insulation value per unit weight because the y do not consist of the natural feathers' barbules.

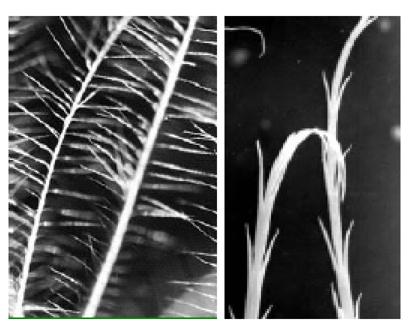


Fig. 115 Penguin down feather [206]

Currently, there is no commercial product available

Recently, the firm Procter & Gamble announced their intention to launch an intelligent slip on the market. The aim is to notify the female wearer when ovulation is coming or when she will start to menstruate.

To determine the ovulation, a layer of silicones is used covered with a thin plastic film. The silicones react to hormonal changes that are characteristic for the ovulation period and expand a little. The small thickening modifies the refraction of the light, resulting in a violet dot on a golden background.

To determine the menstruation period, two indicators are necessary. In the first place, a resin is used which turns blue at the presence of the smallest trace of blood. The second product is an acid which turns red at a pH between 4 and 7. These two indicators together give a purple colour, approximately four hours before the start of the menstruation.

Benjamin Miller and colleagues of the University of Rochester, New York State, US, have developed a sensor that generates an easy recognizable array of colours that signify dangerous or antibiotic-resistant strains. So far, the device produces only a very small colour change, which is not detectable with the naked eye.

Most bacteria are either Gram-positive or Gram-negative. A dye called crystal violet stains Gram-positive bacteria blue-violet and Gram-negative bacteria red. This staining procedure was discovered in 1884 by the Danish biologist Christian Joachim Gram and is still used today to distinguish the two cell types. Miller's team hope to replace the cumbersome staining procedure with a simple process that registers the difference instantly and in situ. Therefore they will use silicon-based light-emitting devices. When Gram-negative bacteria stick to the surface of porous silicon, the colour of the light emitted changes slightly. the researchers make the silicon attract Gram-negative, but not Gram-positive bacteria, by coating it with specially designed molecules that hook chemicals groups only present on Gram-negative microbes.

Eventually this may lead to the development of smart bandages that could soon alert doctors to the presence of certain bacteria in a wound by glowing different colours.

2.8.1.2 Patents published

2.8.2 Applications in the interior textile sector

2.8.2.1 Research projects and products

Textile with sonic properties is also object of research in the framework of the Swedish programme IT+Textiles of the Interactive Institute. The project 'Mute' is based on the idea of sound-absorbent textile surfaces in public, office, school or daycare settings. In this case the textile changes its spatial form as a response to certain conditions. In order produce a textile that has different acoustic properties depending on its state, changes in its surface are necessary. For this purpose a model of textile blocks sliding in and out between in each other was created. It uses tiny pneumatic cylinders and a compressor. Thus, the fabric changes its acoustic properties by stretching, as with stretching the fabric its ability to dampen the sound is reduced. So far, this project is mainly conceptual, but it will progress [8].

2.8.2.2 Patents published

2.8.3 Applications in the technical textile sector

2.8.3.1 Research projects and products

A further examples of the use of ceramics in textiles is Masonic N from Kanebo, which is a Nylon filament with ceramic microparticles incorporated.

Auxetic materials

By definition, an auxetic (or negative Poisson's ratio) material expands in all directions when pulled in only one, giving therefore a deformation kinematics opposite to that of 'conventional' materials.

They are developed for sutures, although they are demanding strength and expansion. Commercialised products are far away.

They are also used for arterial prostheses (where any extensive blood pressure results in a firming of the arterial wall) and artery dilators (where tension can be applied to expand auxetic sheats laterally) W.L.Gore has commercialised a PTFE (GoreTex PTFE) that is used in arterial sheats.

The German curtain and decorative textile manufacturer ADO International marketed a fabric that can split up harmful substances, like nicotine or formaldehyde, into their harmless elements carbon dioxide and water vapour. The so-called ActiBreeze textile is based on a photocatalytic reaction. When light incidences on the curtain, an into-the-fibre-integrated medium sends electrical impulses, which split up the harmful substances.

UV protection can be achieved in textiles by ceramic molecules that split harmful light rays. Encapsulating ceramic fibres into polyester yarn to develop clothes that regulate body temperature and offer UV protection. (EnkaSun) [142].

A researcher team from the UK and Russia succeeded in extracting individual graphite crystals, which were used to produce the thinnest possible fabric, a grapheme. This new material may lead to computers made from a single molecule [207].

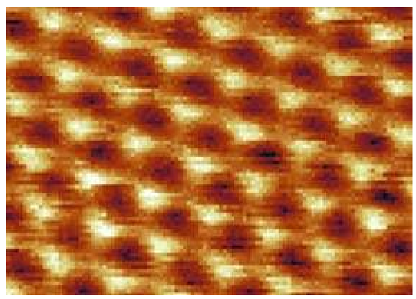


Fig. 116 Graphene - first example of single atom thick fabric

2.8.3.2 Patents published

2.9 European projects within Framework Programmes 5 & 6

The Framework Programme for Research, Technological Development and Demonstration is the main research policy instrument of the European Union.

In this report we take Framework Programmes 5 and 6 into account. The fifth framework programme (FP 5) lasting 4 years, from 1998 – 2002. FP5 was conceived to help solve problems and respond to major socio-economic challenges the EU is facing. It focuses on a number of objectives and areas combining technological, industrial, economic, social and cultural aspects. For this purpose it had a multi-theme structure consisting of four Thematic Programmes [208].

The Sixth Framework Programme (FP6) defines the European Union's strategic priorities for the period of 2002-2006. FP6 comprises seven Thematic Priorities covering a series of well-defined research objectives and five cross-cutting activities responding to common themes across all research areas like international cooperation, SME-specific actions or research for policy support. A further programme part is dedicated to Structuring of the European Research Area (ERA), a policy concept aiming to overcome research fragmentation in Europe, comparable to the concept of the European Single Market [209].

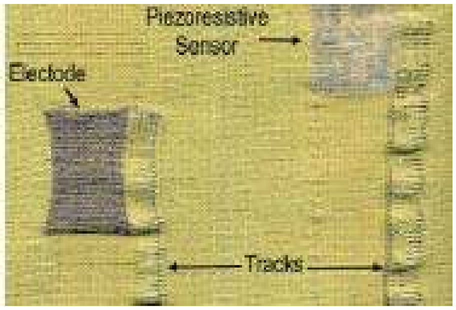
Regarding EC co-financed projects in the field of textiles and clothing, it can be pointed out that they contribute to the improvement of health monitoring based on textiles and garments according to a predefined scheme: it starts with "physiological parameter-oriented projects" (e.g. WEALTHY, MyHeart, MERMOTH and OFSETH) relying on textile-embedded sensors, it adds biosensing (e.g. BIOTEX), and extends in the combination of the sensed signals (e.g. PROETEX) and beyond [210].

2.9.1 European projects within FP5

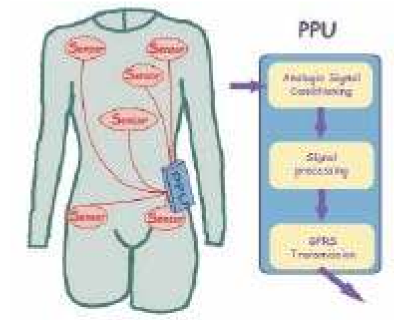
2.9.1.1 WEALTHY

WEALTHY is an IST project for 2½ years started on 1st of September, 2002. In the scope of the project smart materials in fibre and yarn form endowed with a wide range of electro physical properties (conducting, piezoresistive, etc.) are being integrated and used as basic elements to implement wearable system for collecting physiological data [211].

The system WEALTHY is a comfortable health monitoring system which is based on a wearable interface with integrated fabric sensors, advanced signal processing techniques and modern telecommunication systems. The system was developed by a consortium of the University of Pisa, Smartex srl, Centre Suisse d' Electronique et de Microtechnique, Atkosoft S.A., Institut National des Sciences Appliquees de Lyon, Istituto Scientifico H San Raffaele, Centre de recherces du service de Sante des Armees, Messe Frankfurt Exhibition GmbH and Centre National de la recherché Scientifique. The system comprises wearable and wireless instruments garments with integrated strain sensors based on piëzoresisitive material as well as fabric electrodes made of metal based fibres. The piëzoresisitive material consist of Lycra® fabric coated with carbon loaded rubber and a woven commercial electroconductive yarn. The metal based fibres for the fabric electrodes comprises of two stainless steel fibres twisted around a viscose textile yarn. Also, connections have been made out of textiles, using the circular knitting technique.



Part of the WEALTHY interface



Overall WEALTHY function 212

Fig. 117 Fabric interface and overall monitoring function of the WEALTHY garment

The system can monitor physiological variables, such as respiration, electrocardiogram, activity, pressure and temperature. A miniaturised short-range wireless system has been integrated into the garment which transfers signals to the WEALTHY box/PCs, PDA and mobile phones. The garment interface is connected with the PPU, where local processing as well as communication with the network is performed [212].

2.9.2 European projects within FP6

2.9.2.1 WearIT@work

The WearIT@work - Empowering the mobile worker by wearable computing - project is a 4½ years lasting IST (Information Society Technologies) Integrated project with the highest EC funding of textile relating projects so far. The EC contributed 14.297.149 € to the project whose total cost amount to 23.683.309 €. The project started on 1st of June 2004. It aims to prove the applicability of computer systems integrated to clothes, the so-called wearables, in various industrial environments. These novel computer systems will support their users or groups of users in an unobtrusive way e.g. wearing them as a computer-belt. This will allow them to perform their primary task without distracting their attention enabling computer applications in novel fields. The project will result in four pilot applications. In the first 18 months “Show Cases” are to be realised and evaluated. Based on the experiences gained there “System Prototypes” are to be developed, which will be the basis of the final “Industrial Pilots” in the four dedicated fields: Emergency Rescue; Healthcare; Maintenance and Production [213].

2.9.2.2 My Heart

The MyHeart project is a 3¾ year lasting IST Integrated Project, started on 31st of December 2003, whose goal is to gain knowledge on a citizen's actual health status by continuous monitoring of vital signs. The consortium consists of 33 different partners from 11 countries. It integrates system solutions into functional clothes with integrated textile sensors. The combination of functional clothes and integrated electronics capable of processing them on-body can be defined as intelligent biomedical clothing. The processing consists of making diagnoses, detecting trends and reacting to them. Together with feedback devices, able to interact with the user as well as with professional services, the MyHeart system is formed.

This system is suitable for supporting citizens to fight major CVD risk factors and help to avoid heart attack, other acute events by personalized guidelines and giving feedback. It provides the necessary motivation to adopt the new life styles [214].

In order to sense different body parameters, scientists at the Wearable Computing Laboratory at the ETH in Zurich developed together with the company Sefar Inc. a System-on-Textiles, which is a woven fabric with thin insulated copper fibres, as shown in Fig. 118.

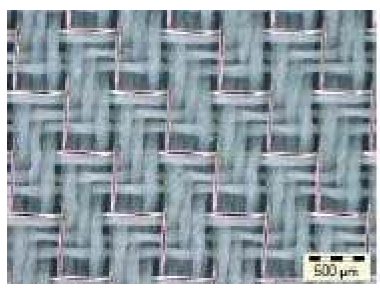


Fig. 118 Conductive Textile: System-on-Textiles [215]

In order to create an arbitrary conductor path within the textile, single copper wires must be connected at crossing points. This connection forms a textile via, the fundamental building block for a connecting structure in fabrics. As there is a linear dependency of temperature of the copper wires and their electrical resistance, the fabric is capable to measure temperature. Due to the usage of the wires as warp and weft material, a grid like structure is formed which enables to locate the hot spot by measuring the resistances of warps and wefts.

For the purpose of sensing pressure, the researchers developed a pressure sensor mat made out of a spacer fabric with embroidered electrically conductive patch arrays on both sides. With this system, the sitting posture can be detected. Each opposing patch pair in the array forms a plate capacitor whose capacity changes with compression force on the spacer fabric.

Finally, a prototype T-shirt with textile and rigid off-the-shelf sensors was developed [215].

Within the scope of the European MyHeart project, researchers at the Wearable Computing Laboratory are working on an automatic dietary monitoring system. At the conference UbiComp in Japan in 2005, they presented their first results. They demonstrated that sounds from the user's mouth can be used to detect that he/she is eating and even different kinds of food can be recognized by analysing the chewing sound. So far, the sounds are acquired with a microphone located inside the ear. However, in future they want to investigate other components of a dietary system, among them are a collar electrode for the detection of swallowing motions [216].

2.9.2.3 MERMOTH

MERMOTH is a European Commission co-financed research projects that contributes to medical remote monitoring of clothes. Nine partners from different European countries worked together for three years from 2003 to 2006 to develop a comfortable, wearable monitoring unit, which will be based on a wearable interface. The objectives of the project are one the one hand to design a combined textile / hardware and software architecture for a family of wearable clothes which provide continuous ambulatory monitoring of patients in academic research and the clinical trials of drugs and on the other hand to build prototype sets of garments which address the two applications market with different compromises between power / distribution and consumption, user friendliness, relevance of the collected data and cost of ownership [217].

2.9.2.4 Flexifunbar

Flexifunbar is an integrated project in the sixth framework of the European Commission in the scope of the thematic call "Nanotechnologies and nanosciences, knowledge-based multifunctional materials, new production processes and devices" (NMP). Partners from industry and academic organisations and institutions from different European countries join the project to develop hybrid multi-barrier-effects materials, based on multi layer complex structures and functionalisation of micro- and nanostructures. The development of such materials covers various application fields, such as transportation, home and building and health. The project started on October 1st, 2004 and will last for four years [218].

2.9.2.5 Avalon

Avalon - Multifunctional textile structures driving new production and organizational paradigms by textile SME interoperation Across high-added-VALue sectOrs for knowledge-based product/service creation – is another 4 year lasting project within the 6th framework programme NMP of the European

Commission. 31 partners from 10 European countries work on the cross-sectoral development of hybrid textile structures integrating multifunctional shape memory alloys (SMAs) and the related processing techniques as well as design, simulation and organisational methodologies. They will enable the integration of such textile structures into novel high performance products in the fields of smart wearable systems and textile reinforcements for technical applications [219].

2.9.2.6 Biotex

The BIOTEX project is a STREP project (Specific Targeted Research or Innovation Project) part of the 6th framework programme of the European Commission and a joint call between NMP and IST (Information Society Technologies). The overall goal of the project is to create a garment that monitors biochemical parameters. For this purpose, the project aims first at developing patches, adapted to different targeted body fluids, such as blood and sweat, and biological species, where the textile itself is the sensor. The technology will then be extended to the entire garment. The project can be seen as an extension of the two former projects WEALHTY and MyHeart, in which physiological parameters, like ECG, temperature, movement and respiration, were monitored. Eight partners from industry and research organisation joined the 2.5 year lasting project [220].

2.9.2.7 Acteco

Acteco (acronym for "Eco Efficient activation for hyper functional surfaces") is an integrated project within the priority NMP of the FP6 of the European Commission with duration of 4 years. Partners, representing industry and research organisations, from 8 European countries aim at developing plasma technology for functionalising surfaces for textiles, biomedical and food applications. For this, the technology will be further developed with the help of end-users so that problems, like the consumption of large amount of water and solvents, with which the industry is struggling for many years can be solved [221].

2.9.2.8 ProeTEX

ProeTEX – Advanced e-textiles for firefighters and civilian victims- is a 6th Framework IST Integrated Project involving 23 partners from industry and research. The 4 years project will develop a full system for firefighters and civil protection workers plus a limited system for injured civilians. Hence, the focus of the project is made on textile-based micro-nano technologies within a communicating framework. Textile and fibre based integrated smart wearables for emergency disaster intervention personnel with a goal of improving their safety, coordination and efficiency and additional systems for injured civilians aimed at optimising their survival management are developed. For this purpose a wearable interface for monitoring the operator‘s health status and surrounding environment potential risk sources, giving him/her useful real time information and/or alarms, as well as allowing data transmission between the operator and the central unit, will be created.

2.9.2.9 Stella

Stella – Stretchable Electronics for Large Area Applications is an IST project that has started on February 1st with duration of 4 years. Eleven partners from different European countries aim at developing integrated electronics in stretchable parts and products with stretchable conductors for use in healthcare, wellness and functional clothes. For this purpose the consortium modifies existing elastomers and non wovens substrates and develops conductor patterning and interconnection methods [222].

2.9.2.10 OFSETH

The OFSETH project – Optical fibre sensors embedded into technical Textile for Healthcare monitoring consists of a consortium composed of 11 partners from textile, optics and medical fields and 5 EU countries that started working together at March 1st, 2006 for 3.5 years. The aim of OFSETH is the integration of optical fibres related technologies into functional textiles to extend the capabilities of wearable solutions for health monitoring. They use two main technologies, one based on Fibre Bragg Grating sensors and the other one based on Near Infrared Spectrometry. These technologies can permit to assess various parameters such as cardiac, respiratory rates and oximetry that will be investigated here but also pH or glucose concentration. In general, target applications are based on wearable static sensors to monitor cardiac and respiratory activity as well as oximetry, and wearable mobile sensors to demonstrate the wearability of FBG and fibre NIRS monitoring [223].

2.9.2.11 Lidwine

Lidwine is a four year lasting NMP project within the 6th framework programme of the European Commission. 21 partners from industry, research units and medical centres will work together on the integrated project dedicated to SME’s. The project focuses on the development of multifunctional medical textiles to prevent and treat decubitus wounds. Target applications include an antibacterial textile for wound care, integrated with medication depots including an active circulation support bandage. Therefore, active (controlled contractive cuff) and passive (textiles with integrated electrodes) system will be developed and applied. Further, drug capsules with an enzyme-based on/off switch for release will be developed.

2.9.2.12 Contex-T

Contex-T is a European project dedicated to geotextiles. Within the scope of the project intelligent kinetic, scissor-like, structures are designed that serve as membranes for roof constructions.

2.9.2.13 Inteltex

Inteltex is like Lidwine an integrated project of the European Commission with a 50% participation of SMEs. The overall objective of the INTELTEX project is to develop a new approach to obtain intelligent multi-reactive textiles integrating nano-filler based Conductive Polymer Composite (CPC)-fibres. The consortium will work on various scientific and technical activities, ranging from CPC synthesis, the control of carbon nanotube dispersion in polymers to fabrication of CPC fibres and textiles. In a subsequent step, the developed materials will be used in specific applications including protective clothing, anti-theft devices and textiles for buildings and health.

2.9.2.14 Polytect

The project is an integrated research project for SME partially funded by the European Community. The consortium of the Polytect project is working on polyfunctional technical textiles against natural hazards. The project aims at the development of multifunctional textile structures for application in construction for the retrofitting of masonry structures and earthworks [224].

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