1

The future of smart-textiles development: new enabling technologies, commercialization and market trends

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Abstract: Smart-textiles development is entering a new era that is characterized by the convergence of different disciplines, such as electronics and polymer sciences. This chapter begins by reviewing the challenges in smart-textiles development and illustrating current trade-offs. Then, the chapter gives an overview of recent technological breakthroughs and shows how new enabling technologies from different disciplines help to overcome technological barriers. Finally, the chapter describes new approaches to the commercialization of smart textiles and reveals potential topics that will shape the future of smart textiles.

Key words: enabling technologies, trends in development, commercialization.

1.1 Introduction

A textile is a fascinating material. In various fabrication steps, millions of separate fibres are interlaced and modified and finally form a complicated structure with rather unpredictable properties. The resulting fibrous structures are highly inhomogeneous (electrical engineers might even say imprecise and chaotic) and therefore difficult to model. Knowing how to adjust textile process parameters in order to achieve a specific desired material behaviour is sometimes rather an art than science. However, the special structure of textiles is what makes them unique. No other material has this kind of drapability, lightness and porosity combined with robustness, strength and, last but not least, low manufacturing costs. A long time ago, textile producers discovered that textiles could provide more than just aesthetic and decorative features. The book *Extreme Textiles* shows amazing examples of recently developed high-performance textiles (McQuaid, 2005):

- textile containers that lift a weight of 12 tons;
- gloves that cannot be cut with knives or even razor wire;
- airbags that protect a space rover when landing on the surface of a foreign planet;
- racing cars (as well as boats, bicycles, etc.) that are made of carbon-fibre-reinforced polymers, that are lightweight, and can therefore achieve extremely high speeds.

If textiles can achieve such high-tech functionality, it is only logical to think about making them smart. The new research field of smart textiles arose about 15 years ago and initially focused on aerospace and military applications. After several years, researchers realized that smart functions in textiles also are attractive to civil and commercial products. However, the euphoria was dampened by a lack of success in the market. Now, smart-textiles research is finding new perspectives and directions. This chapter describes recent technological breakthroughs and analyses trends in smart-textiles development.

1.2 The technological trade-off between smartness and integration

1.2.1 Smartness of objects

The goal of every smart object is to make the lives of humans easier, safer and more comfortable. The smartness of an object refers to its ability to react to external stimuli. However, a clear definition is not easy as there are different levels of smartness. If an object property changes according to different environmental influences, this does not automatically make the object smart. After all, several mechanical, thermal, or electrical properties change depending, for example, on the surrounding climate. Smartness starts when the reaction of the object properties is not linear to the ambient changes and when this non-linearity brings benefits to the user. In the textile area, phase change materials are often called smart as they store heat in a hot environment and release heat when it gets cold. In contrast to 'normal' materials, smart materials change a specific property, like shape or aggregate state, rapidly and significantly. Smart materials are often called designed materials as their property changes can be tuned during fabrication. Common examples are:

- piezoelectric materials that can change shape when a voltage is applied;
- chromogenic materials that can change colour in response to electrical, optical or thermal stimuli;
- shape memory materials that can react with large deformations on temperature changes.

However, in such smart materials, the cause-and-effect relation is very simple: just one variable external stimulus is taken into account, and the reaction is always the same, regardless of any user needs.

A higher level of smartness can be achieved with electronic technology. In electronics, the non-linear behaviour of so-called 'active' electrical components like transistors is used to build programmable machines. These machines carry out logical operations and deliver a goal-oriented output, depending on multiple input parameters. Researchers have been improving the performance of computers and making them increasingly smarter. These advances have developed into the research field of artificial intelligence. In this area, smartness tries to imitate the human brain and involves planning, learning, reasoning and knowledge. This decision-making and problem-solving type of smartness can be called intelligence. ‘An intelligent agent is a system that perceives its environment and takes actions that maximize its chances of success’ (Russell and Norvig, 2003).

This enormous range of smartness often leads to confusion and controversy when the term ‘smart textiles’ is used. Certainly, for different applications, different levels of smartness are required. However, as a matter of principle, electronics is the only available technology that allows the generation of a goal-oriented output from multiple input parameters as well as user control. In addition, even the above-mentioned smart materials often do not function without electronics, as an electrical stimulus is required (e.g. to control piezoelectric actors). That means, no matter what level of smartness is envisioned, textiles have to learn from electronics. Textile technologies and materials sciences have to be combined with principles used in electrical engineering and measurement technology. For this reason, some experts prefer the term electronic textiles or e-textiles instead of smart textiles. However, this term is limiting as it excludes any kind of non-electronic smartness. In fact, the ultimate vision is smartness, and the use of electronics is just a means to an end.

1.2.2 Integration level

A combination of textile and smart functions in one product can be achieved on different integration levels. The first smart-textile products were inhomogeneous and consisted of textile and electronic parts that were rather attached to each other than really integrated. Over the years, smart-textiles developers have approached higher levels of integration. The shape and size of electronics were made more textile compatible so that they could be processed on textile machines and incorporated directly into fabrics. The integration of electronic functionality into yarns and fibres will be the next step. In this way, the electronics are not visible and do not disturb the desired textile look and feel. However, several problems need to be solved for this type of integration, and basic research still has a long way to go. The main challenges are the durability and reliability of the functions, as well as the scalability and industrialization of the fabrication processes.

1.2.3 Technological trade-off

So far, smart-textiles development has been characterized by a trade-off between smartness and level of integration. Most prototypes with smart functionality do not have a high level of integration, which means that several system parts – such as processing capabilities and energy supply – are placed in external devices. The few examples of ‘monolithic’ smart textiles only have a very limited functionality. This conflict can be illustrated with two examples of smart-window-shade concepts. Vili (2007) incorporated shape memory materials into textile window shades, in order to achieve an opening/closing of the woven structure depending on the surrounding temperature. This behaviour is sensitive only to the temperature, and it does not take into account other parameters such as the surrounding brightness, nor can it be influenced by the user. In contrast, the energy curtain (Fig. 1.1) is much more sophisticated and contains solar panels, batteries, LEDs and optical fibres. It can collect energy during the day and lights up the room during the night (Backlund, 2006). This system requires several electronic components and batteries but, in return, it offers a higher level of smartness.

Some researchers believe that textiles always will be just a part of a smart system where most of the processing power is outside the textiles. Others aim at pure textile systems where all the smartness is within the textile material. Their goal is to achieve a mergence of textile and electronic functionality within one

1.1 The energy curtain includes solar panels, batteries, LEDs and optical fibres. The user controls how much energy is collected during the day and how the room is lighted up during the night (Interactive Institute).

material. Either way, for both visions, experts from different disciplines have to join forces and push the boundaries. Textile engineers have to work together with material scientists, chemists, physicists, electrical engineers, designers and product developers from different branches. This kind of multidisciplinary cooperation is challenging because of the different ways of thinking, different languages and different approaches involved. However, in the last few years, tremendous changes have occurred because, in several disciplines, new enabling technologies have been established. Some of these new technologies have been known for a long time but can now be applied practically and combined for the first time. These major technological breakthroughs enable completely new approaches in smart-textiles development, as the next sections show.

1.3 New enabling technologies for smart textiles

In materials science, groundbreaking results have been achieved in the area of conductive polymers. Textile engineers have made substantial progress in the processing of substances and materials (e.g. nano-sized or non-polymer) that traditionally have not been used in textile technology. Especially relevant for smart textiles are new processes such as electrospinning, composite manufacturing and printing. In electrical engineering, the interest in flexible electronics and in organic electronics has drastically increased over the past few years. This trend perfectly matches the smart-textiles vision. Smart-textiles developers benefit from new electronic devices that are more and more textile compatible – which means flexible, organic, lightweight, low-cost and low power. Last but not least, advances in mobile electronics like the smart phone have a great influence on smart textiles. The following section provides an overview and examples of these recent technological achievements.

1.3.1 Textile technologies: towards nano and composite

Nanotechnology has been booming in many areas during the last few decades. The properties of nanoscale particles differ significantly from bulk material due to their high surface-area-to-volume ratio and their quantum mechanical effects. In the textile area, nanotechnologies are used to create fibres and fabrics with increased performance and added functionalities such as water-repellent, UV-protective, wrinkle-resistant, self-cleaning, anti-bacterial or anti-static abilities. There are already some nanotextiles on the market, mostly with dirt- or water-repellent properties. Nano-sized silver particles are used for their antimicrobial properties in a wide range of consumer products. Very promising nanomaterials for the future are based on carbon nanotubes, which possess extraordinary mechanical strength and high thermal and electrical conductivity.

The three major manufacturing technologies for nanotextiles are:

1. *Fabrication of nanofibres*: The best-established process for nanofibres fabrication is electrospinning. In this process, electrostatic forces are used to draw fluids into a fibrous form (Reneker and Fong, 2006).
2. *Surface modification of fibres and fabrics*: Technologies employed for applying nanocoatings include plasma treatment, atomic layer deposition (ALD), grafting of polymer chains, and self-assembly of monolayers, to name a few (Gorga, 2010).
3. *Filling of fibres with nanoparticles*: The embedding of nano-sized fillers, such as metal oxide or carbon into polymer fibres, leads to composite fibres with specific properties e.g. electrical conductivity.

The recently developed coaxial electrospinning technology enables the fabrication of composite nanofibres with a core-sheath structure or with embedded nanoparticles. Ko *et al.* (2008) demonstrate the possibilities of this so-called co-electrospinning process.

Bringing functional non-textile materials into fibrous forms is the great strength of nanotechnology. For this reason, nanotechnology plays an important role for smart textiles. First results show the potential of nanotechnology for creating sensor fibres as well as conducting and semiconducting fibres. Enz *et al.* (2010) produced temperature-sensitive fibres with electrospinning. Lima *et al.* (2011) presented an approach to spinning carbon nanotubes into yarns by scrolling carbon nanotube sheets. Sibinski *et al.* (2010) developed temperature-sensitive fibres with carbon nanotube coatings. Furthermore, ALD has been investigated as a method by which to produce conductive and semiconductive nanocoatings on fibres and fabrics (Jur, 2011).

1.3.2 Polymers: towards conducting and semiconducting

As far back as the 1970s, it was discovered that some polymers can be made electrically conductive. Until then, polymers were known for their electrically-insulating properties. In traditional polymer materials, valence electrons are bound in fixed and immobile sigma-bonds. It was thought that charge flow was only possible in materials like metal. However, some polymers (the conjugated polymers) possess a special molecular structure of alternating single and multiple bonds. In this structure, electrons can hop along the molecule chains if one or more electrons are removed or inserted. This process can occur in an oxidation or reduction process called ‘doping.’ With this invention, polymers can have electron mobility and imitate metal behaviour.

‘Conducting polymers’ have been synthesized before by mixing polymers with metal or graphite powders. However, in the case of this new class of materials, the conductivity was an intrinsic property. Therefore, the name intrinsically conducting polymers (ICPs) was recommended (Plieth, 2008). The main drawbacks of ICPs were their instability in air and their poor processability. It took several decades of basic research until the field of conductive polymers reached a transition to practical applications.

Now, this technology is also entering the textile world: Textile applications of conductive polymers range from anti-static fabrics or actuators for ‘artificial muscles’ (i.e. stimuli-responsive materials that react by modifying their shape or dimensions), wound dressing products with anti-bacterial properties or temperature, and optical- or strain-gauge sensors (Ferreras, 2011). Ferreras (2011) developed lightweight, low-cost strain sensors by coating fabrics with organic conductor films. Their fabrication method is compatible with printing technology.

Apart from the metal-like conductivity, the semiconductive properties of polymers have gained more and more importance. The variability of the conductivity, such as the ease with which the materials can be reversibly switched between their insulating and conducting forms, has enabled the development of organic field effect transistors (OFETs) (Inzelt, 2008; Plieth, 2008).

Electroluminescence in organic material has been recognized since the 1950s, but the drawback was the need to apply high voltages to create a light emission. The increased conductivity of modern conductive polymers has allowed them to generate higher amounts of light with lower voltages and has led to commercial applications in opto-electronic devices, such as organic light-emitting diodes (OLEDs) and photovoltaic cells (OPVs) (Kim J, 2011). Nowadays, we use OLED displays in everyday life in mobile devices. In the long term, the flexible nature of organic semiconductor materials will allow for the commercial development of opto-electronics into curved and flexible structures.

The tremendous impact of organic conductors on electronics is described in the next section. The technological progress in so-called plastic electronics is of great importance for smart textiles.

1.3.3 Electronics: towards large-area, flexible and printable

Miniaturization of electronics

The main driving force in the development of electronics always was the demand for miniaturization and performance increase. This goal was achieved by the integration of circuits onto semiconductor substrates. For these integrated circuits (ICs, microchips) single-crystal silicon is the semiconducting material most used (silicon wafer technology). The key transistor structures and the corresponding fabrication technology are called complementary metal-oxide semiconductors (CMOS). ICs have consistently migrated to smaller feature sizes over the years, allowing more circuitry to be packed on each chip. This high integration density not only enabled circuits with more functionality but also ones with higher computing power. In the last few decades, the integration has reached an amazing level. In the 1980s, the term ‘very large-scale integration’ (VLSI) was introduced and stood for thousands of transistors on one single chip. Today’s ICs contain several billion transistors.

Large-area electronics

In the beginning of the 1990s, enormous interest for large-area electronics (also called macroelectronics) emerged. This trend was triggered by new requirements on displays. For several applications, a large size display is preferable, at best combined with a high resolution, a flat shape and a high image quality. Thus, a technology was needed for the active controlling of a high number of display pixels on a large area. Silicon wafer technology requires 'thick,' rigid and expensive silicon substrates and is therefore not suitable for large areas. Thin-film technology was the answer. In contrast to bulk silicon transistors (i.e. CMOS) thin-film transistors (TFTs) are made of amorphous silicon and can be deposited on non-semiconductor substrates (e.g. glass). The key benefit of thin-film technology is the ability to use low-cost, large-area and even transparent substrates. One further advantage is that amorphous silicon can be deposited at lower temperatures (below 500°C instead of ~1000°C). The result of this new technology was the expansion of flat-panel displays into numerous applications of our daily life, such as liquid crystal displays (LCDs) (Sun, 2011).

Organic electronics

The discovery of organic semiconductors opened up further possibilities for large-area electronics. The light-emitting properties of some organic semiconductors make them perfect for opto-electronic devices like displays. The development of OLEDs led to a new generation of large-area displays that consume less energy than LCDs and have lower manufacturing costs. The great advantage of OLEDs is that they emit light themselves and do not require a light-emitting backplane like LCDs. Today, OLEDs still are controlled with silicon-based TFTs. However, in the future, the switches could also be realized with transistors made of organic materials (e.g. organic field effect transistors, or OFETs). This would further reduce the thermal impact on the substrate as well as the manufacturing costs.

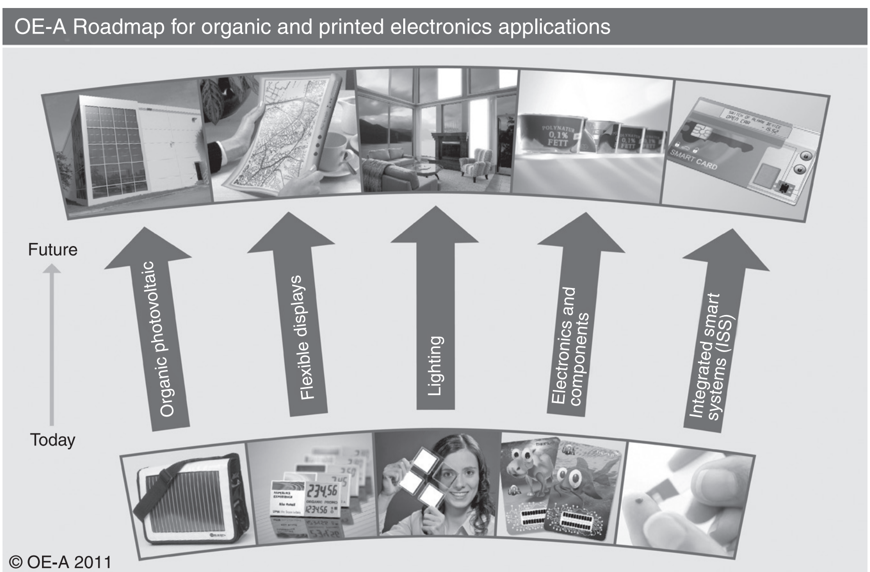
Flexible electronics

Parallel to the development of large-area electronics, another field of research has rapidly grown – namely flexible electronics. The main goals for the first flexible electronic devices were reductions in weight and size, and these were achieved by thinning of silicon-ICs (e.g. solar cells for satellites). Below a certain thickness, even bulk silicon chips become flexible. But, of course, this kind of bendability is not comparable to the drapability and elasticity typical of textiles. The next approach to making electronics flexible was to use thin-film technology on flexible substrates such as plastic or steel foils. This technology enabled, for example, a roll-to-roll fabrication of flexible thin-film solar cells

(Cheng and Wagner, 2009). The emergence of organic semiconductors had a major impact on flexible electronics, similar to the one it had on the aforementioned large-area electronics. The possibility to manufacture organic semiconductors at low temperatures is perfectly compatible with flexible substrates like plastic foils.

Printable electronics

A key manufacturing technology for organic electronics is printing. The most important benefits of printing are low-cost and large-scale fabrication. Several companies have developed printing technologies, for example, for OLEDs (DuPont, HP, Sony), for radio-frequency identification (RFID) and for solar cells. Jung *et al.* (2010) produced roll-to-roll printed RFID tags. Hübler *et al.* (2011) presented solar panels that are printed on paper. Enabled by nanotechnology, new printable inks have emerged that contain conductive particles. Das *et al.* (2011) evaluated novel printable materials. The roadmap of the Organic Electronics Association (Hecker, 2011) provides a good overview of technological developments in the fields of organic and printable electronics (Fig. 1.2). Two major challenges for the realization of organic devices are the limited lifetime of these devices and their sensitivity to atmospheric oxygen and humidity.



1.2 Roadmap of Organic Electronics Association (OE-A).

Stretchable electronics

From a textile point of view, one important question is how flexible electronics can become. Is it possible to make electronics not just bendable, but also stretchable and elastic? Some research groups already are working on different approaches to stretchable electronics. To date, the three main fabrication strategies for stretchable electronics are:

1. embedding ultra-thin silicon circuits in pre-stretched silicone rubber;
2. integrating thin-film circuits in an elastic, rubbery mesh;
3. distributing the electronic circuits on rigid platforms that are interconnected with stretchable metallization (Lacour, 2009).

Kim *et al.* (2011) recently reported the development of skin-like membranes that contain electronics. This kind of 'epidermal electronics,' as the researchers call it, can be attached to human skin like a tattoo.

Textile electronics

All the new electronic technologies that are moving towards large-area, flexible and printable have a huge potential to be adapted to textiles. In the following sections, the advances in implementing electronic technologies in textiles are shown.

Within the sixth framework programme of the European Union (2002–2006), several research projects in the area of smart textiles were carried out (cluster SFIT, which stands for smart fabrics, interactive textile). The first achievements were the development of textile-embedded sensors for the measurement of physiological parameters (e.g. within the projects WEALTHY, MyHeart, MERMOTH, OFSETH, BIOTEX, and PROETEX). Applications included personalized healthcare management (e.g. BIOTEX: Coyle, 2010) as well as smart garments for emergency operators (PROETEX: Curone, 2010). Most of the textile sensors monitor heart rate or breathing. In other projects, textile pressure sensors (Meyer *et al.*, 2006) and textile strain sensors (Mattmann *et al.*, 2008; Shyr, 2011) were also developed, mostly for posture and activity monitoring.

The first approaches to embedding whole electronic circuits into fabrics were based on woven fabrics with embedded conductive yarns (Cottet *et al.*, 2003; Locher *et al.*, 2004; Kirstein *et al.*, 2005). Silicon chips were mounted on so-called interposers (interfacing circuit boards) in order to adapt the distance of the chip connections to the larger distance of the conductive yarns. In this way, conductive yarns could be connected to chips and act as circuit paths.

Kim *et al.* (2010) applied printing technology to achieve more planar electronic circuits in fabrics. The European project MicroFlex aims to use standard printing techniques to realize micro-electromechanical systems (MEMS) and active films for sensing and actuating on fabrics.

The project STELLA demonstrated stretchable electronics for health monitoring devices and for car interior heating and lighting fabrics for the first time (Gonzalez, 2011). In 2010, two follow-up projects of STELLA started. The PLACE-it project aims to realize large-area and flexible opto-electronics systems, in particular light-emitting foils for interior lighting applications. The goal of the PASTA project is to create a conductive fibre with small silicon dyes that can be integrated into yarns. The envisioned applications range from monitoring applications for sportswear to interior textiles and industrial components. The project FLEXIBILITY aims to advance organic large-area electronics (OLAE). Multifunctional OLAE modules will be realized, such as printed, textile-integrated sound modules.

Several research groups are working towards the integration of electronics on the fibre and yarn levels. OFETs have been created on yarns and cylindrical shapes (Lee and Subramanian, 2005; Maccioni *et al.*, 2006; Hamedi, 2009). Mattana *et al.* (2011) developed transistors on cotton fibres. These examples show that electronic technologies are becoming more and more textile compatible in terms of shape, mechanical properties and fabrication processes.

1.3.4 Information technology: towards Internet and computing everywhere

The end of last century was characterized by the massive impact of information technology on our lives, on global society and on economics. The transition to an information society started when ICs revolutionized the world of electronics and led to the widespread use of personal computers. Technological advances made electronics smaller and, eventually, even mobile. In 1973, Motorola introduced the first mobile phone. Then, the Internet became a global network for everybody and enabled the easy and fast exchange of information. Today, the technological capacity to store, compute and share information is still increasing rapidly. In 2011, the projected amount of information created and replicated surpassed 1.8 zettabytes (1.8 trillion gigabytes) – and this figure will grow by an estimated factor of nine in just five years (Gantz, 2011). Hansmann *et al.* (2003) put it aptly when he wrote, ‘Information is the new currency of the global economy.’ The next step was the mergence of mobile telephony, personal computing and Internet services into multi-use handheld devices. The first mobile phones with wireless Internet connection were introduced in the late 1990s. Today, the so-called smart phone industry is booming. The smart phones run mobile operating systems and allow the installation of various software applications. According to estimates, by 2015, there will be at least 2 billion smart mobile devices in use globally (Kenney, 2011).

Researchers are now working on future mobile electronics that are wearable. Their goal is to create intelligent body-worn electronics that act as personal assistants. The research field of wearable computing belongs to the general vision of ambient intelligence. Experts believe that future electronics will surround us in a pervasive and ubiquitous manner:

> An ambient intelligence environment is capable of recognizing and responding to the presence of different individuals, working in a seamless, unobtrusive and often invisible way (Vasilakos, 2008).

New wireless technologies and distributed sensor networks enable this trend. Innovative sensor technologies allow the placement of sensors into everyday objects as well as close to the body. Barbaro (2010) illustrates how wearable technology has paved the way to a wide possibility of interesting biomedical applications, in particular in the field of individual physiological monitoring for diagnosis, therapy and rehabilitation. Even the on-body analysis of chemical substances, for example, in sweat is now possible.

Electronic devices are more and more distributed and the Internet is evolving from mobile towards embedded. Machine-to-machine (M2M) communication could be the next technological revolution after the mobile Internet. The vision behind M2M is the 'Internet of things,' that means embedding mobile Internet features into low-cost devices and connecting billions of everyday objects. 'Although this vision is not new, it is only now gathering momentum as ubiquitous connectivity is finally becoming a reality, and Moore's Law has driven device cost and size low enough to justify "smart devices everywhere" ' (Wu *et al.*, 2011). It can be expected that the massive interest in smart devices and ambient intelligence will push the development of smart textiles.

1.3.5 Consequences and impact on smart textiles

The previous sections revealed that the worlds of textiles and electronics are moving closer. On the one hand, electronics can increasingly have typical textile features such as flexibility, large-area and roll-to-roll processability. On the other hand textile technologies enable the processing of non-textile materials such as conductive particles in fibres or coatings. With these new enabling technologies, it is getting easier to combine the benefits of textile materials with electronic functionality. The realization of products that are smart and textile at the same time seems to be attainable. Some manufacturers even implemented automated assembly lines for the production of smart textiles. For example, the company TexTrace recently presented a manufacturing line for woven RFID labels. Nevertheless, it is still debatable when smart textiles will become widely commercialized.

Technological feasibility does not automatically guarantee commercial success. Yet several examples show that it sometimes takes a long time until the right application emerges and the breakthrough of a technology occurs. Several major technologies such as conductive polymers, electrospinning and thin-film electronics were discovered a long time ago and have only now broken through.

Electrospinning technology traces back into the last years of the 1800s but only reached a broad dissemination in the 1990s when the interest in nanotechnology increased (Reneker and Fong, 2006). Conductive polymers were introduced already in the 1970s with the discovery of polyacetylene and the process of oxidative doping (Plieth, 2008). However, only recently are conductive polymers rapidly gaining attraction in new applications such as organic LEDs and solar cells. Apparently, the emergence of new applications and the combination of methods from different disciplines can lead to an unexpected and rapid dissemination of a technology. The next section analyses new approaches and influencing factors in the commercialization of smart textiles.

1.4 New approaches in commercialization of smart textiles

The following aspects play a major role in commercializing smart textiles:

- What are the strengths of smart-textiles technologies?
- Are they predestined for specific application areas?
- Do smart textiles aim to replace existing products or satisfy new needs?

The following section evaluates strategies and chances in the smart-textiles business.

1.4.1 System-oriented development and focus on user needs

Healthcare has always been considered a key application for smart textiles. However, the first approaches of textile-based health monitoring failed mainly due to the difficulty of achieving certified medical reliability at reasonable costs. Now, the commercial focus is more on lifestyle monitoring. One major trend is sports monitoring. Partnerships are being formed between apparel companies and technology companies to develop and produce innovative ways of tracking, recording and sharing athletic performance. In 2010, Polar Electro teamed up with Nike to introduce the heart rate monitor Polar WearLink+. Recently, adidas gained commercial success with miCoach, a training tool including sensing shirts and football boots that measure performance data such as speed, number of sprints and distance. Nevertheless, the clothing and fashion market is rather difficult for smart textiles. For most fashion products, design and low cost are more important than sophisticated functionality. Even in the case of the athletic monitoring products, the profit comes largely from software selling rather than from the clothing itself.

Another popular application field for smart textiles is interior design. Philips is active in this area and offers luminous textile panels with integrated LEDs. Smart textiles provide a unique selling point for interior products because of their pleasant acoustic, haptic and optic properties in addition to their electronic functionality. Several textile manufacturers, designers and architects have developed ideas for smart furniture, interactive surfaces and car interiors. However, a piece of smart fabric is not marketable without a concept for the complete electronic system, including user interfaces, power supply, etc. Companies such as Philips can meet this need for system-oriented product development. Their luminous panels fulfil plug-and-play criteria and are delivered with standard connections for a power cable and an Ethernet cable. The user can install the system easily, upload and manage the dynamic content and even connect the system to building management systems. Similar to Philips, adidas and Nike also have access to their users and are experienced in developing end products. With this prerequisite, they manage to bring smart-textile systems to market. Yet for most of the textile manufacturers, system development is a critical point, as they normally supply just fibres and fabrics. For the breakthrough of smart-textile products, this barrier has to be overcome either by partnerships between component suppliers and end-product manufacturers or by the establishment of new 'system-building' companies.

Such new smart-system providers could come up with the required knowledge of the end users and their needs. The term 'system provider' also means that the focus is on finding solutions rather than on selling a specific type of product. The approach is not to ask 'What functionality can I put into a textile?' but rather 'What functionality is needed in a specific context, and which object could fulfil this need?' Depending on the task, several objects can contribute to smart services. In living spaces, vehicles or articles of daily use, some functions are best placed in textile surfaces, but others reasonably should be embedded in solid objects. The famous but unsuccessful smart jackets with embedded MP3 players demonstrate the failure of non-system-oriented product development. Well-engineered electronics like smart phones are hardly improved by textile gadgets like interfaces in sleeves or loud speakers in collars. This experience of unsuccessful smart garments also applies to technical textiles. Manufacturers of textiles for industrial applications and machines (i.e. belts, filters, etc.) are tempted to add value to the textile components by making them smart. However, a closer look at the whole system often reveals that sensors and actuators are much more easily embedded into non-textile parts of the system.

Focusing on the core competences of textiles helps to find suitable applications. Smart textiles are certainly predestined for large-area distributed sensing tasks. Apart from architecture, also branches such as civil engineering and agriculture deal with large surfaces. Within the European project POLYTECT, several smart geotextiles based on fibre-optic sensing systems have been developed, for example, for monitoring ground movements (Belli, 2009; Messervey, 2009). Could large-area textile sensor networks one day also monitor cultivated land, dykes or even glaciers? Some glaciers are actually covered with textiles in order to reduce melting (Fischer, 2011). The possibilities are endless, and focusing on system-oriented development might finally lead to the market success of smart textiles.

1.4.2 Do-it-yourself trend: chances for commercialization of smart textiles?

The do-it-yourself (DIY) movement started as a countermovement to the consumer culture many decades ago. The leading thought behind DIY was to move away from mass-produced goods towards unique handwork. There was a growing belief in the importance of the individual, in self-reliance and personal independence. The Internet has pushed this trend and has led to a boom in DIY culture. The web enables easy and global dissemination of DIY instructions. Online guides and YouTube tutorials are available for many topics such as home improvement, electronics, music production and fashion. On Internet platforms, such as Instructables.com, Techdiy.org or Makezine.com, the DIY community exchanges know-how and experience. In recent years, an explosive growth of online shops (e.g. Etsy.com) proved that DIY also has business potential. On these e-commerce pages, DIY products are sold from person to person.

DIY has already entered the smart textiles world as well. One major step has been the development of textile compatible electronic components that are accessible to a broad public and are easy to use. One example is the microcontroller board named LilyPad (Buechley *et al*., 2008) by the High-Low Tech group of MIT. This circular-shaped flexible board was commercially introduced in 2007. It can be sewn to fabrics with conductive threads and connected to several sensors and actuators such as LEDs. It is based on the open-source computing platform Arduino and can be easily programmed. Following this development, new online shops, books, workshops and online databases emerged that are specialized on DIY smart textiles, for example:

- www.plugandwear.com (online shop, tutorials, workshops);
- www.kobakant.at/DIY (workshops, online database);
- DIY-books: *Fashion Geek* (Eng, 2009), *Fashioning Technology* (Pakhchyan, 2008) and *Switch Craft* (Lewis, 2008).

Figure 1.3 shows the result of a DIY workshop conducted by Kobakant: a T-shirt with a small solar-powered motor that moves an attached feather. Despite this popularity, some smart-textiles experts deride the DIY movement. From their point of view, handicraft and gadgets are not scientific, not marketable and economically irrelevant. Yet the smart-textiles area benefits from the DIY movement in many ways.

First, thanks to DIY, a broad public has gained access to smart-textiles technology and got to know its potential. This way, user acceptance of this new technology can be enhanced and concerns can be reduced. Furthermore, smart-textiles developers can learn from the DIY community about possible applications

1.3 In this DIY solar shirt, a solar cell powered motor moves a feather (manufactured in a workshop of Mika Satomi, Kobokant).

and user needs. Researchers can use DIY products to perform real-world studies of the interactions between people and technology. Another positive effect of DIY toolkits is the spreading of smart-textiles technologies in the area of design, art and performance. It started with some individual fashion designers who experimented with smart textiles and expanded to well-known artists who have performed with interactive stage outfits. British musician Imogen Heap performed with musical gloves that enabled her to manipulate sounds and to compose on the fly with hand gestures. The light fashion clothes designer Moritz Waldemeyer developed illuminated video jackets for artists such as Take That and the Black Eyed Peas. Several exhibitions demonstrate the relevance of smart textiles to design (e.g. Prettysmarttextiles.com). Most smart textiles in the area of design and fashion are handmade masterpieces and are not comparable to marketable products. However, for the first time, they make publicly aware that smart textiles can be aesthetic and not just technical.

Finally, DIY has tremendous consequences for education. Now it is possible to teach smart-textiles topics not just in theory but also with hands-on experiments and workshops. In practical projects, students can experience the possibilities of this technology as well as the challenge of collaboration with other disciplines. Several schools and universities have carried out smart-textiles projects, where students with different backgrounds have worked together. One example is the e-motion project of www.design.udk-berlin.de/Modedesign/EMotion (the Berlin

University of the Arts (UdK), Germany). Another interdisciplinary student project is ‘Ready-to-live,’ which is a cooperation of the Wearable Computing Lab of the Swiss Federal Institute of Technology Zurich (ETH) and the Swiss Textile College (www.ready-to-live.ethz.ch/English). The participating students from the two disciplines of electrical engineering and fashion design seemed as different as day and night. However, they worked together with great enthusiasm and success. They appreciated the DIY approach and the possibility to get in touch with other ways of thinking. Figure 1.4 shows one of the interactive items of clothing that were presented at the final fashion show.

Smart-textiles projects are trend setting for future educational models – not just for university students but also for schoolchildren. Several research groups are exploring the potential of smart textiles in education. The EduWear project developed an educational low-cost construction kit for wearable interfaces (Katterfeldt *et al*., 2009). The TeeBoard project resulted in an education-friendly construction platform for e-textiles (Ngai, 2010). These projects point out another important aspect of smart textiles in education: namely the potential to attract

1.4 In the fashion show ‘Ready-to-live,’ interactive clothes are presented. The clothes react to the movements of the wearer, e.g. with changing light effects. This student project was a cooperation of ETH Zurich and Swiss Textile College.

women to engineering and computer science. So far, these fields are mainly male-dominated. The integration of electronics and textiles create 'new spaces that historically have not been open to girls' (Kafai, 2010). Smart textiles provide the role of technology with a social context, which is an important component of attracting women to STEM (science, technology, engineering, and maths) (Lovell, 2010).

In conclusion, the DIY trend plays an essential role in the progress of smart textiles. The future of smart-textiles technology will be affected by end users who design and build their own products. Industrial companies can learn from the DIY community. Thus, DIY offers the opportunity to find new approaches to commercialization.

1.5 Future trends

The previous sections have shown the beginning of a new era of smart-textiles development: one that is characterized by novel enabling technologies and by the convergence of different disciplines such as electronics and polymer sciences. Yet in which direction will smart textiles develop? The next sections reveal potential topics that will shape the future of smart textiles. The possibilities of Web 2.0 and new applications with a focus on the global energy issue are interesting aspects of this future.

1.5.1 Web 2.0 and e-research

In recent years, the web has changed from being a publishing medium to a participative medium. New features of the so-called Social Web or Web 2.0 include tools and services that emphasize sharing of content among users and online collaboration (Murugesan, 2010). Some of the most widespread social software applications are:

- *Blogs*: The blog is a short term for web log and has its origin in online diaries. Nowadays a blog represents a kind of personal online journal that is frequently updated with comments, links, images, and other media pertaining to a given subject. The blog makes a statement and offers a space below for readers to comment and respond. Twitter is a microblogging service for posting short messages.
- *Wikis*: A wiki enables communities to write documents collaboratively. It is used as an online database for knowledge management, corporate intranets and group learning. One well-known example is the collaborative online encyclopaedia *Wikipedia*.
- *Social networks*: The idea behind platforms such as Facebook, Myspace, Google+ and LinkedIn is to share ideas, activities, events, and interests within individual social networks. According to Nielsen's *Social Media Report 2011*,

4 in 5 active Internet users visit social networks and blogs (Nielsen, 2011). Facebook is clearly the favoured social network in many countries.

- *Folksonomy* is also known as collaborative tagging. Tags act like keywords of a text and allow users to annotate and categorize content. Social websites use tagging to classify and find information.

Recently, the potential of Web 2.0 tools for business and marketing has been discovered by many companies. Several companies as well as non-profit organizations use social media for PR, branding and interaction with customers. For example, Nike has established a running community portal on Nikeplus.com, where users can monitor their sports performance. The web also has significant influence on research and technology development. Based on the progress of the web and of IT infrastructures a new generation of research has emerged, called e-research. E-research is characterized by the interaction between globally distributed teams of researchers. Virtual research communities share computer power and storage and collaborate across traditional boundaries of disciplines and locations (Wusteman, 2008). The social media support group interaction not only in research but also in industrial product development. Ahram *et al.* (2011) demonstrate the benefits of social networking as a collaborative tool for smarter product design. Social networking facilitates teamwork, collaborative online discussions, idea generation and peer review activities. The sharing of experiences enhances a team learning process.

Also in the smart-textiles world, researchers increasingly use Web 2.0 and e-research tools such as portals, blogs and online tutorials:

- SYSTEX is an EU-funded platform for Smart Textiles and Wearable Microsystems. Apart from workshops and conferences ('Smart Textiles Salon'), activities also include an online database (www.systex.org).
- Several universities and schools have established knowledge centres for smart textiles. One example is the Future Textiles initiative of the Danish design and management college TEKO (www.futuretextiles.dk). Seminars and competitions as well as exhibitions ('Pretty Smart Textiles') are organized.
- The Smart Textiles initiative of the Swedish School of Textiles of University of Borås aims at supporting textile companies and at promoting textile innovations (www.smarttextiles.se). Research is conducted in the Technology Lab and the Design Lab. A blog (www.stdl.se) provides information about projects and events such as the Ambience conference and summer camps.
- PhD students of the Textiles Futures Research Group, University of the Arts, London initiated a blog in order to engage in a dialogue about innovative textiles (textilefuturesphd.blogspot.com).
- Another interesting website is Fashioning Technology (www.fashioningtech.com). The author Syuzi Pakhchyan reports in her blog on the latest smart-textiles products and designs.

- +Plastic Electronics has a section about smart fabrics in their online and print magazine (www.plusplasticelectronics.com).
- Online shops and tutorials can be found at plugandwear (www.plugandwear.com) and SparkFun (www.sparkfun.com).
- Kobakant has an extensive online database of wearable technology (www.kobakant.at/DIY) and step-by-step instructions of DIY workshops.
- The blog of talk2myShirt (www.talk2myshirt.com) gives reviews and background information on textile-based wearable electronics and offers a weekly podcast (eTextile Lounge). Talk2myShirt is starting a new connection community platform that serves as an interaction place for experts of wearable electronics. It will provide an interactive whiteboard for the creation process and tools for the involvement of consumers.

These activities show that smart-textiles developers are moving towards online collaboration and interactive sharing of information. The Social Web helps to overcome the barriers between different disciplines and could lead to a revolutionary e-research approach in smart textiles.

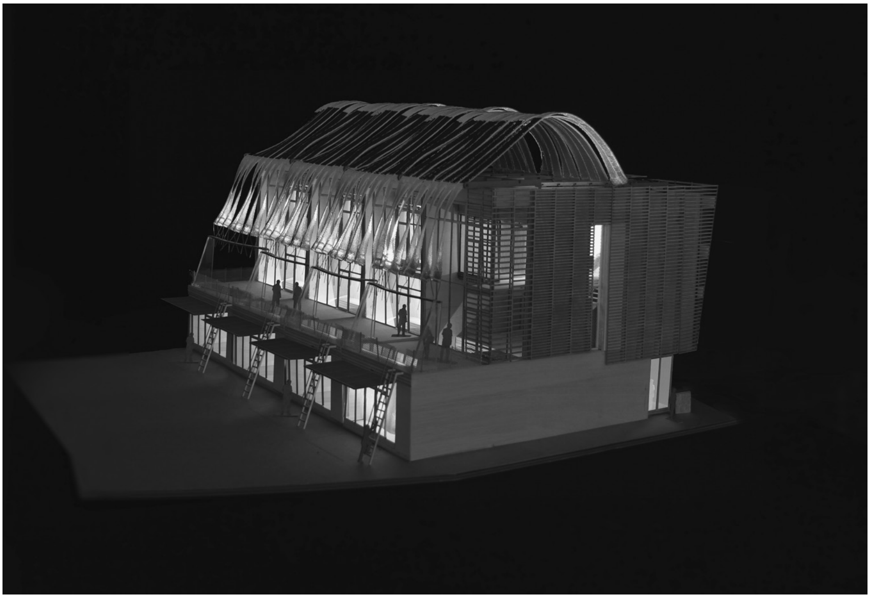
1.5.2 Global energy issues

A sustainable energy supply is widely regarded as one of the most important intellectual and technological challenges of the twenty-first century. Climate change concerns and shortage of fossil fuel reserves are driving the development of alternative energy technologies. Energy from renewable resources such as sunlight, wind, rain, tides, and geothermal heat is becoming increasingly popular. An interesting aspect of renewable energy is the possibility of distributed electricity generation. In contrast to large centralized facilities for burning fossil fuel, renewable power sources can be small and decentralized. This allows electricity generation at the point of need, even in rural and remote regions. Small-scale wind generators and solar panels on the roofs of buildings are the first examples of this approach. The idea of autonomous electronic systems goes even one step further by powering devices directly with integrated miniaturized energy harvesters. Advances in MEMS technologies enable the embedding of energy harvesters in small wireless devices. Energy harvesting devices convert ambient energy such as vibrations, temperature gradients or solar power into electrical energy. The human body offers a variety of energy sources for wearable devices. Kinetic generators in wristwatches and shoes, for instance, capture energy from body movements.

This trend of distributed and embedded energy harvesting opens up tremendous possibilities for smart textiles. Textiles have the potential to act as energy suppliers, not just for electronic systems within the fabric but also for external devices:

- Several research groups are working on energy-harvesting microsystems. Researchers at the University of Southampton are building vibration-powered generators that could be integrated into clothing (Beeby, 2006).

- Konarka Technologies presented OPVs in a flexible wire format (Lee, 2009).
- Bedeloglu *et al.* (2010) examined the applicability of polymer-based solar cell materials onto thin polypropylene textile substrates and manufactured textile-compatible photovoltaic tapes.
- In the course of the EU-funded project DEPHOTEX, photovoltaic threads for automotive applications and clothes were developed (www.dephotex.com).
- Riaz (2011) and Wang (2008) have described concepts for piezoelectric nanogenerators.
- The architect Sheila Kennedy designs buildings with energy-harvesting textile surfaces (Soft House project, Fig. 1.5). In the non-profit initiative Portable Light Project, she provided photovoltaic textile kits for the developing world. Her goal was to enable local people to create and own energy-harvesting textile blankets, bags and clothing using available materials and traditional weaving and sewing techniques (Anonymous, 2008).
- Hu *et al.* (2010) recently demonstrated carbon nanotube coated textiles that can act as supercapacitor energy storage devices.
- Vatansever *et al.* (2011) used piezoelectric polymer fibres for energy scavenging from raindrops and wind.



1.5 The Soft House, designed by Kennedy & Violich Architecture, demonstrates how domestic infrastructure can become soft and flexible. The smart energy-harvesting textile cladding bends to respond to sun angle and twists to open views or create privacy.

These projects show the need for innovative energy-harvesting approaches. Smart textiles could play a pioneering role in meeting the energy demands of modern society. Their unique material properties make them perfect for new forms of drapable energy technology. With smart textiles, energy harvesting and storage could become soft and flexible. It could be distributed over large areas, as well as be embedded in fabrics surrounding the humans. Energy will be a key application area of future smart textiles and could possibly lead to a breakthrough of smart textiles.

1.6 Conclusion

This chapter has shown that technologies from different disciplines are moving towards similar goals: electronics are becoming soft and embedded, and textiles are becoming composite and functionalized from the macro- to the nano-level. These trends are opening up new perspectives in smart-textiles development. Some promising new approaches have been presented in this chapter, such as focusing on system-oriented product development, learning from the DIY movement, using Web 2.0 tools, as well as addressing global issues. These ideas could help and inspire researchers and companies to make the vision of smart textiles a reality.

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