Design and manufacture of textile-based sensors

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4.1 Introduction

Technical textiles are used primarily for their technical functionality in many different industries. To monitor the functionality of textiles, it is possible to integrate sensors into the textiles. Because textiles are made of yarns or two- or three-dimensional structures, the sensor systems should be designed as a part of them accordingly. Smart textiles are concerned with textile-based sensors integrated mechanically and structurally into a textile. The definition is given in Section 4.2.

The state of the art in developing textile-based sensors extends from sensor fibres to over-coated yarns and textiles, but without using a methodical approach. Therefore, a standardized tool that allows the development of textile-based sensors for different application fields has been created for textile manufacturers. It is called the smart 7-step tool, and it is described in Section 4.3.

The development of a textile sensor and its interpretation of a specific application have been associated with many investigations into different conductive materials, which are lengthy and costly developing processes. Knowledge has already been generated on textile sensors, which now require an appropriate classification and structure. A classified catalogue, which allows a direct selection of textile-based sensor modules on the basis of measured values, will be presented in the second part of Section 4.3.

Smart textiles describe a huge field of functionalized textiles and materials. Commonly, smart textiles are defined as intelligent materials and systems that are capable of sensing and responding to their surrounding environment in a predictable and useful manner (Schwartz, 2002). According to its behaviour, a smart textile can be classified into categories of sensing, actuating and adaptive functions (Tao, 2001). The functions may be in the form of an additional electronic component or a part of the textile structure.

Three levels of the integration of electronic components and circuits can be distinguished (Figure 4.1): textile-adapted, textile-integrated and textile-based.

The first level, textile adaption, refers to the manufacturing of special clothing accessories to put in electronic devices (e.g., MP3 players). In the second level, the integration of electronic components means creating an interconnection between electronic elements and the textile within (e.g., metal push-buttons), for possible removal. The last level of integration of electronic components is based on the textile structure itself (e.g., with electro-conductive or metallic-coated multi-filament yarns).

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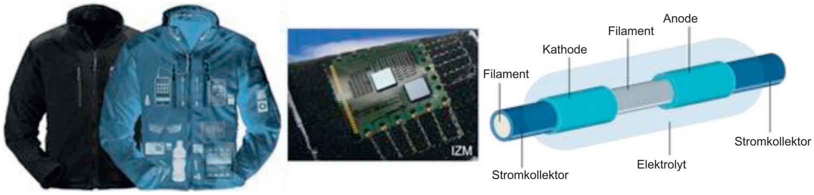

Figure 4.1 Levels of integration of electronic components (ita, n.d.).

A lot of research projects regarding smart textiles concentrate on the development of textile-based sensors and actuators that can be bonded to a wearable system for technical protective clothing or medical textiles. Currently, in the field of medical applications, there are a number of projects funded by the European Commission that work on the improvement of health monitoring based on the smart textiles. The development of textile-embedded sensors for measuring physiological parameters is the subject of several research projects (WEALTHY, Wealthy, n.d.; MyHeart, Mermoth, n.d.; STELLA, Scientific, n.d.; OFSETH, Talk2myshirt, n.d.), and arrives in the combination of sensed signals (PROETEX; Proetex, n.d.).

However, the products have not yet reached market maturity. Most of the above-mentioned products are still in the prototyping phase. The main reason that smart textiles are not available on the market is that the textile industry has not yet been produced for the broad mass market (Schwartz, 2002).

The classified catalogue for textile-based sensors is a tool to give textile manufacturers an overview about all existing sensors and their working principles.

4.2 What are textile-based sensors?

It is important to build sensors that are based on the textile instead of being merely integrated into or applied to them. This is attended by a higher relevance of expertness in the field of textile engineering, as the textile itself now has to fulfil requirements to which, before, only the sensor had to conform.

4.2.1 Definition of textile-based sensors

The textile-based sensor is part of the textile, as seen in Figure 4.2. The textile is also considered part of the sensor.

4.2.2 Variations of textile-based sensors

Textile-based sensors are always made of textiles and define themselves through their textile structure. The textile structure can be divided into four levels (Figure 4.3). There are different technologies to manufacture textile sensors. All different kinds of technologies are shown in Figure 4.4. The weaving and embroidering technologies are described in Section 4.5.

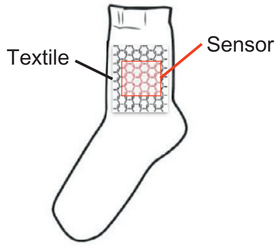

Figure 4.2 Textile sensor in the *supporting* textile.

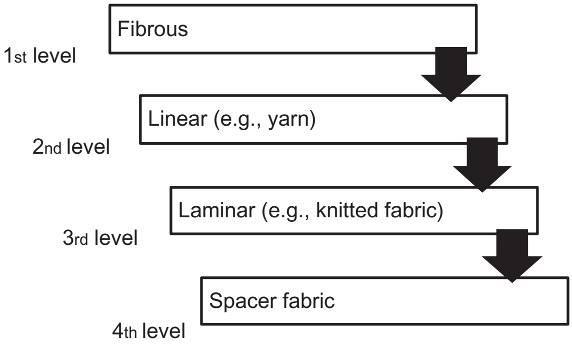

Figure 4.3 Levels of textile structure.

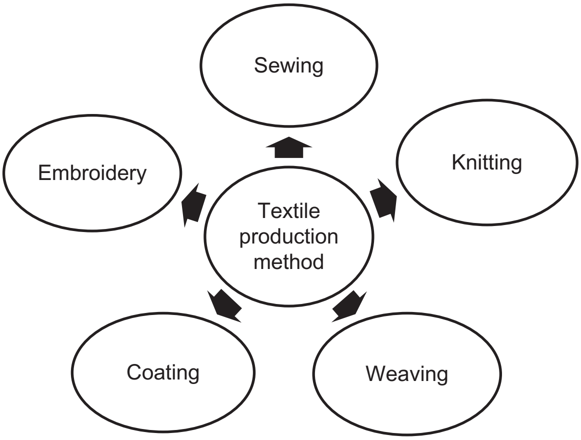

Figure 4.4 Production methods.

4.2.3 Fibres

The use of fibre glass-technology in textile finishing is a remarkable step towards technological progress. Proceeding miniaturization involves significant advantages that at the same time comply with important quality requirements such as variety, rapidness, accuracy and reliability (Daniel, 1990).

The main advantages of optical fibres are a low weight and a small volume. In addition, in fields of high electricity there are no transmission problems, as there is no problem with electrical grounding.

As a consequence, glass fibre will find more use in factories, railway lines and power plants. They are already commonly used in medical science, chemical process control, the mining industry, vehicles and vessels. Glass fibre is also used to measure the change of temperature by detecting the varying refraction index in the cladding of the fibre. Charging levels and concentrations of liquids can be measured by using the principle of reflection, as the liquid has another refraction index compared to the fibre. But problems may be caused by surface corrosive action and contamination.

Taking advantage of the microbending effect, one even can measure the pressure, which helps improve plant and process safety as well as the quality of products. Light escapes from two aligned glass fibres when core or cladding are under mechanical stress.

4.2.4 Yarns

Yarns are most commonly used to detect stresses caused by mechanical abrasion or influences of UV radiation. A proceeding devastation of the yarn, especially in applications that could mean a certain threat to security, must be avoided at all costs.

4.2.5 Two- or three-dimensional textiles

There are several technologies to combine single fibres to sensor modules. On the one hand, knitting allows one to tie the fibres tightly, without risking influence on the functionality. On the other hand, enwinding allows one to work conductive elastic threads into elastic tapes. It also allows for an adjustment of the force-dilatation ratio in the fibre.

4.3 Methodical approach to developing textile-based sensors

The state of the art in developing textile-based sensors extends from sensor fibres to over-coated yarns and textiles, but without using a methodical approach, and overviewing the already existing textile-based sensors. Therefore, a standardized tool that allows the development of textile-based sensors for different application fields has been created for textile manufacturers. It is called the smart 7-step tool, and it is described in this section.

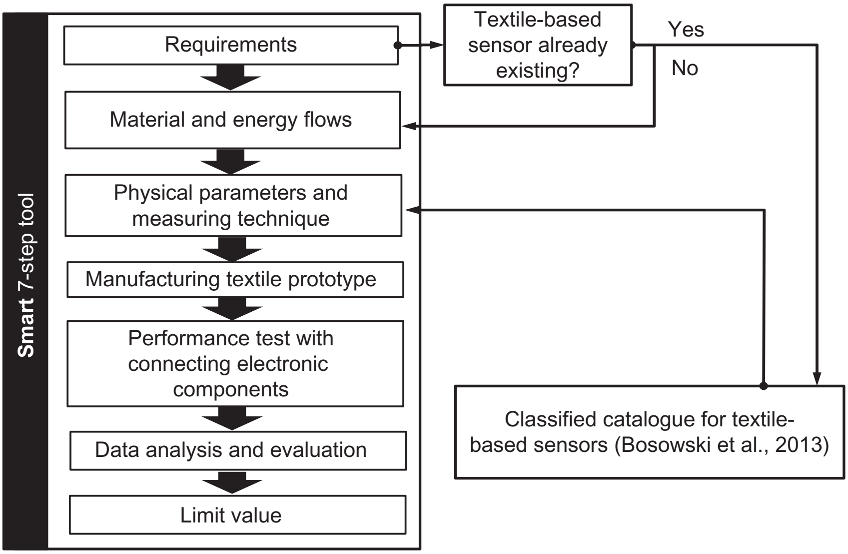

Figure 4.5 Smart 7-step tool: methodical approach for developing textile-based sensors (using the classified catalogue for textile-based sensors; Bosowski et al., 2013).

4.3.1 Smart 7-step tool

The smart 7-step tool consists of seven steps to develop a textile-based sensor for a special application area and product with a certain functionality. It concludes a classified catalogue for textile-based sensors, which allows the textile manufacturers to use already existing textile-based sensors (see Figure 4.5).

4.3.1.1 Requirements

Concerning the area of application, textiles can be divided into clothing and technical textiles, with the latter defining themselves by their functionality in the first place. Textile sensors' *requirements* generally result from the different application areas and their functionality. Depending on the purpose of the product, the number of requirements varies quite a bit. In the **first** step, it is important to differentiate between *basic* and *wished requirements*. Afterwards, the designer can use the classified catalogue (Bosowski et al., 2013) to select an already existing textile-based sensor for his or her product. Finding a suitable solution, he or she can proceed to the **third** step. If not, the **second** step must be realised.

4.3.1.2 Material and energy flow

In the **second** step, a similar approach to the *material and energy flow* must be performed. In general, the function of sensors is receiving physical values or materials and process characteristics, and transforming them into binary, one- or multidimensional electrical measurement signals. Those signals then can be transmitted to a

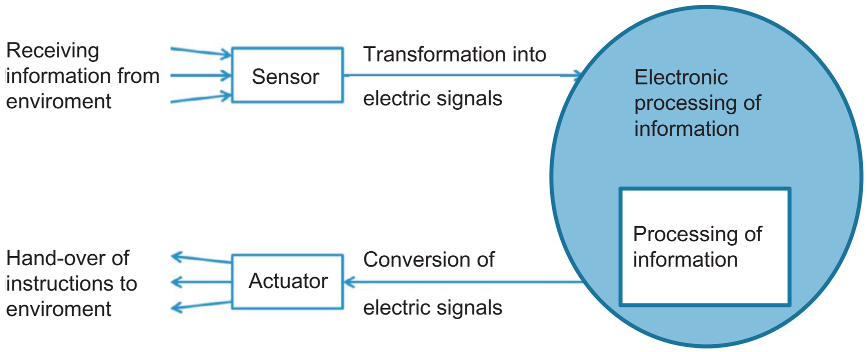

Figure 4.6 Principal function of sensors.

higher system for the purpose of further processing (Figure 4.6). This analysis aims for a theoretical sensor concept, which is caused in process characteristics.

4.3.1.3 Physical parameters and measuring technique

After determining the sensor concept, the physical parameter for measuring with the sensor must be set up. Textile sensors that are part of the textile itself must react to all different kinds of forces. Therefore, various sensor concepts, which rely on physical, chemical and thermal *parameters*, are suitable for application. They help detect forces, displacements, thermal energy, humidity, chemicals, UV radiation and other actions. Then, the received information from the environment can be transformed into electric signals. In this **third** step, one must decide where to place the conductive threads between the nonconductive one, and which manufacturing technology is suitable for the product requirements.

4.3.1.4 Manufacturing textile prototype

There are different technologies to manufacture textile sensors; see detailed examples in Section 4.5. All different kinds of technologies are shown in Figure 4.4. At this **fourth** step of the developing process, textile prototypes will be produced for their first testing. The textile prototype can also be selected from the classified catalogue (Bosowski et al., 2013).

4.3.1.5 Performance test with connecting electronic components

To invert the barrier of the interconnection of the electronic components and textile sensor, it is important to make sure that the interfaces between the components are focused from the beginning of the development. Therefore, already in this **fifth** step, it is important to build an interdisciplinary team with experts who are familiar with the problems and issues of interconnection of electronic components. The whole concept of the product must be seen as a whole system, and not just as a product made by different components. The interconnection between the electronic components (hardware) and the textile-based sensor must be part of a task that will be focused on system integration. For each component, a specific connection must be used that fits the requirements of the product. Therefore, tests must be done to achieve the best fitting solution right from the beginning.

4.3.1.6 Data analysis and evaluation

Sensor technology is a part of digital systems for measurement and control, called *sensor-based monitoring systems*. Sensor-based online monitoring systems are composed of suitable sensors, adapted electronics and appropriate hardware and software that serve the real-time acquisition of process and product data. The needed subfunctions for acting between the system components are the acquisition and processing of measuring values, as well as the definition of limit values and the recording of measuring values, as seen in Figure 4.7. The monitoring system can interfere with the manufacturing process when detecting a deviation from established parameters such as temperature, tension, pressure, liquid concentration, diameter or filament breaks (Ramakers, 2005). In this **sixth** step, the textile sensor connected to the system components must be analysed for its measuring and detecting qualities. In some cases, the sensor quality cannot be sufficiently achieved by the textile structure, so one has to redesign from the third step.

4.3.1.7 Limit value

The seventh and last step can be explained by the following example: A tactile sensor is based on the principle of capacitive sensing. The sensors not only show where contact occurs, but also show how much pressure is applied at each location. Red and orange outputs indicate areas with greater pressure, while blue and green indicate low pressures. To differentiate between the pressure areas, limit values must be defined by measured sensor signals, because it is important to generate high-quality signals with the textile sensor.

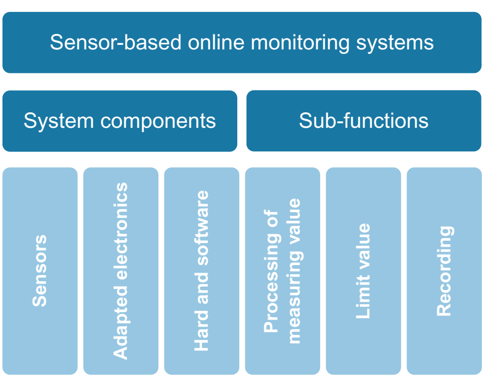

Figure 4.7 Sensor-based online monitoring systems.

4.3.2 Classified catalogue for textile-based sensors

Existing construction catalogues already aim to make state-of-the-art technology accessible. Systematic methods applied in the catalogue help one to understand existing procedures and to develop new and innovative sensor systems (Figure 4.6; Ramakers, 2005). This section compares the benefits and conveniences of a classified catalogue for textile-based sensors. Moreover, the underlying classification and structure of the catalogue, as specified in VDI-guideline 2222, are explained. Its application leads to the catalogue as found in the appendix, representing the state of the art of textile technology.

Benefits and conveniences are helping produce smart products. The catalogue on hand was designed according to VDI-guideline 2222, sheet 2, 'Compilation and application of construction catalogues' of February 1982. Its purpose is to provide suggestions for the methodical use of textile-based sensors.

Figure 4.8 shows the particular criteria for a methodically correct approach of compiling and applying the construction catalogue.

Given that construction catalogues make no claim to be complete, as they can only represent the state of the art of technology, they still enable the realization of reproducible construction processes. As a consequence, in terms of effectiveness and efficiency, this adds up to an economy of scale. In order to ease and enable direct and goal-oriented access, it is necessary to structure the catalogue according to design-methodical points of view.

This way not only can a certain level of convenience be achieved, but designers are also encouraged to rely on the catalogue. For this purpose, values such as validity, integrity and consistency must be considered essential criteria when compiling the catalogue.

4.3.2.1 Classification and structure

The various stages, beginning with the initial design issue to the point of the final solution, are all part of the design and construction process. Therefore, the construction catalogue represents at least parts of this process.

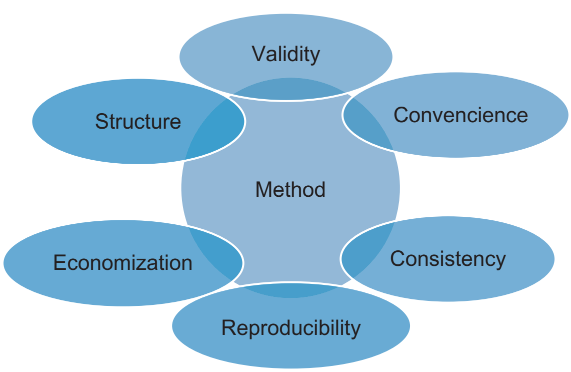

Figure 4.8 Method of construction: compilation and application of construction catalogues.

References						
1	2	3	4	5	6	Nr.
Application area	Sensor type	Parameter	Construction principle	Geometry	Materials	

Figure 4.9 References.

Compiling the catalogue according to VDI guideline 2222, when working with a catalogue-containing solutions that are phrased rather generally, the actual problem must be abstracted and then implemented analogically to the depicted functions. As a consequence, only the initial stage of the problem-solving process is covered within the catalogue, whereas the virtual part of the solving process remains unaffected.

Primary references within the catalogue are the classes of functions, which are based on the different application areas of textile sensors. Specific textile sensors are related to each particular class (VDI, 1982).

4.3.2.2 Usability

A reconciliation of several different characteristics between issue and depicted solution requires a clear arrangement of the latter. Therefore, it makes sense to display all solutions on one axis and oppose them to the characteristics on the other axis. In terms of the catalogue on hand, it is advisable to make use of a linear, one-dimensional arrangement of solutions (VDI, 1982).

The first column contains those *references* that deliver a quick impression of the supposedly relevant solutions (Figure 4.9). Those references are arranged from important to less important.

Following the superordinate criterion *application area*, the sensor type can be distinguished between mechanical, chemical or thermal sensors. Specifying measuring principles by naming different measured variables allows one to limit feasible solutions. The final designation of *construction principles*, *textile geometry* and material helps one to understand how the sensor shall be applied in the process (see Figure 4.10).

The block called *solutions* is the core of the catalogue, as it contains all significant information (Figure 4.11). An indication of sources enables one to revert easily to original documents in order to search for detailed information. The *procedural*

Application area	• Agrotech • Clothtech • Hometech •... • Buildtech • Geotech • Indutech
Sensor type	• Chemical • Thermally • Mechanical
Parameter	• Electromagnetic light spectrum • ... • Electrical current
Construction principle	• Fibre • Woven fabric • ... • Nonwoven • Knitted fabric
Geometry	• Fibrous • Laminar • Linear • Spacer fabric
Materials	• Cotton • Carbon fibre • Steel wire • Glas fibre • Synthetic polymer • ...

Figure 4.10 Structure and content of the references.

Solutions	
Procedural principle	Schematic diagrams
1	2

Figure 4.11 Solutions.

<table>
<tr><th colspan="9">Characteristics for access</th></tr>
<tr><td rowspan="2">Examples for application</td><td rowspan="2">Variations</td><td>Advantage</td><td colspan="6" rowspan="2">Assortment of solutions</td></tr>
<tr><td>Disadvantage</td></tr>
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Figure 4.12 Characteristics for access.

principle describes the crucial aspects of function and design of the sensor. *Schematic diagrams* help to enhance the understanding of the sensor's application.

The last section is called 'characteristics for access' (Figure 4.12) and adds to the other sections by naming different *examples for application*, possible ways for *variations*, and *advantages and disadvantages*. Moreover, characteristic values may limit the *assortment of solutions*.

4.4 Types of textile-based sensors (measurement parameters)

Sensors that are part of the textile and that are resistant to mechanical, chemical and thermal influences must react to all different kinds of forces. Therefore, various sensor concepts that rely on physical, chemical and thermal mechanisms of action are suitable for application. They help detect forces, displacements, thermal energy, humidity, chemicals, UV radiation and other influences.

In order to enable integration into the textile, textile technological workability must be secured, and sensor integration should take place during the production. For the purpose of measuring different influences at the same time, sensors should be groupable. Moreover, a modular construction method guarantees optimal adaption to the operating conditions. Depending on these modular connections, influences through materials, combinations of materials or additive compounds, the way of producing fibre or the finishing treatment, the characteristics and possibilities of the sensors may vary.

4.4.1 Capacitance sensors

A capacitor is an electric component consisting of two opposing electrodes that are divided by an insulating material. When a voltage is applied to a circuit, the electrodes are positively and negatively charged. There is no electric current in the system, because the insulator prevents the flow of electrons. Between the charged electrodes, an electric field is built up. Basically, a capacitor is an energy storage element, often used in electric circuits to buffer fluctuations in the power supply. As the capacity is dependent on the distance between the electrodes, capacitors can be used as pressure or deformation sensors. Multiple electrodes are arranged on a textile surface, opposed to a base electrode on the other side of the structure. The electrodes are separated by a flexible material. As the textile is exposed to mechanical pressure (resulting in deformation), the distance between the electrodes varies, resulting in a change of the electrical capacity. The scheme of a movement sensor due to the textile parallel plate capacitor is shown in Figure 4.13. By using several electrodes (capacitors), the distribution of pressure can be measured.

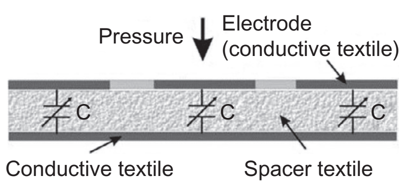

Figure 4.13 Scheme of a movement sensor due to the textile parallel plate capacitor.

4.4.2 Temperature sensors

Temperature is one of the critical parameters to be monitored in many spheres, such as manufacturing processes, structural health monitoring, in-home and health care applications (Barroca et al., 2013; Gefen, 2011; Ghaddar et al., 2011; Scheibner et al., 2011). Textile-based temperature sensors demonstrate great advantages for applications in intelligent structures in comparison with electronic sensors like the former ensure variability in the structure geometry, a combination of the identified properties and functions. For example, textile-based sensors can cover a larger area, ensuring distributed temperature sensing. They are also flexible and lightweight, and suitable for both the thermal assessment of a structure as well as health care applications (Li et al., 2012; Jones, 2009). For example, in health care applications, temperature sensors based on the smart textile technology can provide an evaluation of temperature changes on skin surfaces and in the near-body environment. These data can be used in physiological assessment, control and improvement of patient comfort and monitoring of wound healing. Technical specifications of a textile sensor vary according to the application requirements. Mostly, solutions for textile-based temperature sensors are based on transferring the operation principles of conventional sensors to smart textile technology.

To date, a great variety of approaches to manufacture a textile-based sensor for temperature estimation have been investigated. There have been developments implemented by fibre engineering, coating, weaving, knitting, technical embroidery and printing technologies. By their operation principle, the reported temperature sensors are designed like thermocouples, resistive, semi-conductive and optical sensors.

Initially, a thermocouple can be referred to as one of the simplest solutions for temperature sensor implementation, due to its uncomplicated structure. A thermocouple consists of two dissimilar metal materials coupled in one point, with a voltage related to the temperature difference produced at the junction between the metals (Figure 4.14a; Park et al., 1993).

The achieved data can be further converted into an output temperature signal by the electronic circuit. The resistive temperature sensor works as the resistance temperature detector (RTD) (Figure 4.14b). The working principle of such sensors is based on the changes of metal electrical resistance related to the temperature (Park et al., 1993; Beckerath et al., 1995).

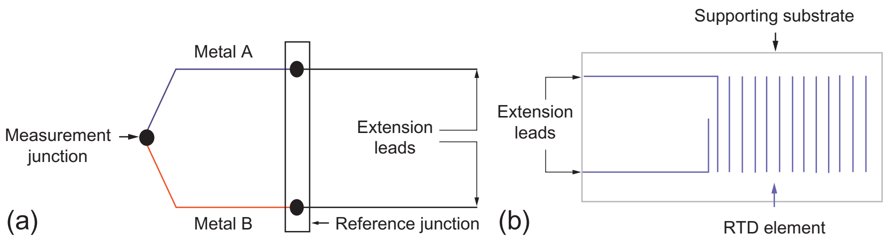

Figure 4.14 Scheme of (a) a typical thermocouple and (b) an RTD sensor.

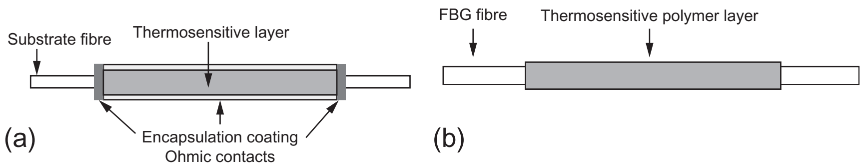

Figure 4.15 Concept of a polymer-based single-yarn temperature sensor (a) and FBG-based sensor (b) (Li et al., 2012; Sibinski et al., 2010).

Both described types of the mentioned temperature sensors are commonly fabricated with conductive yarns or by application of metal monofilament wire. Semiconductive sensors are polymer based, and temperature signal is achieved according to the spreading resistance analysis of semiconductors (Park et al., 1993). Another type of temperature sensor is a fibre Bragg grating (FBG)-based sensor, which is a sensitive optical material reflecting a particular wavelength of light and transmitting the others (Li et al., 2012; see Section 4.7).

Fibre engineering and coating technology encourage development of miniature fibre-based sensors based on the thermo-sensitive polymers, carbon nanotubes and FBG-based sensors. The first type of temperature sensor commonly consists of a dielectric substrate fibre or yarn, which is coated with a thermo-sensitive layer and then encapsulated with a protective coating (Figure 4.15a). Due to their physical properties, polyvinylidene fluoride fibres (PVDFs) are often reported as one of the most advantageous substrate materials, and carbon nanotube compositions and graphite-polymers as materials for sensitive layer development (Sibinski et al., 2010).

Temperature assessment performed by fibre-based sensors can be implemented also by optical technology. One of the promising approaches is coating of FBG fibres with thermo-sensitive substances such as a mixture of methyl ethyl ketone peroxide and cobalt naphthenate. Optical estimation of temperature measurements ensures high accuracy of the results, but the functional coating enhances the performance of the sensor (Li et al., 2012).

Such fibre-based sensors can be efficiently processed by conventional textile manufacturing technologies such as weaving and technical embroidery to create a new intelligent structure or encourage additional functionality in the existing structure. Although fibre engineering is a promising technology for many applications, some of them require more simple and low-cost solutions, especially when temperature estimation of a large-scale area is required.

For wearable, health care and large-area applications, textile-manufacturing technologies such as weaving and knitting can be successfully applied to develop a temperature-sensing fabric through integration of thermo-sensitive compounds during the production process. For example, Ziegler and Frydrysiak have investigated scenarios to develop textile thermocouples by incorporating woven, knitted and non-woven textile structures (Ziegler and Frydrysiak, 2009). Locher et al. used copper monofilaments to build a hybrid woven fabric for temperature sensing (Locher et al., 2005). In another research project, intelligent structures were developed by knitting with the use of different electro-conductive yarns (Husain and Dias, 2009;

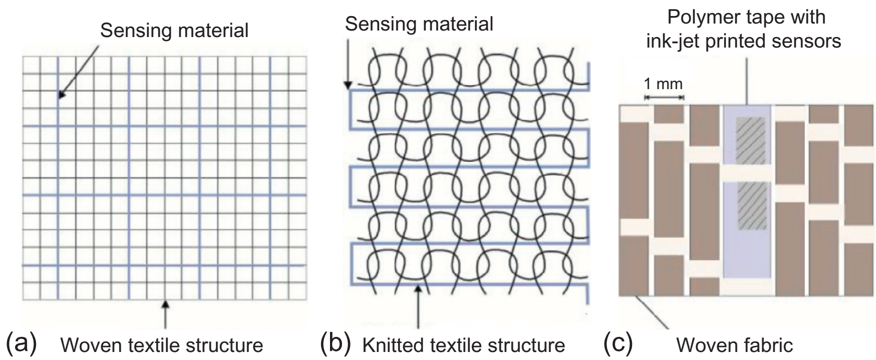

Figure 4.16 Designs of woven, knitted and textile-integrated printed resistance temperature sensors (Locher et al., 2005; Husain and Dias, 2009; Husain et al., 2014; Kindeldei et al., 2011, 2013).

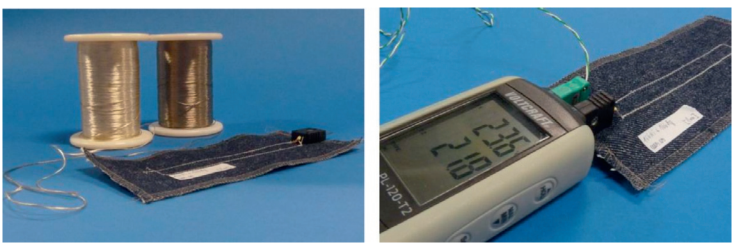

Figure 4.17 A textile thermocouple embroidered by TFP with nickel and silver yarns (ITA).

Husain et al., 2014). In these two studies, temperature estimation is based on measuring the resistance changes of the thermo-sensitive electro-conductive material. Figure 4.16a and b illustrates two examples of temperature-sensitive fabric designs implemented by weaving and knitting (Locher et al., 2005; Husain and Dias, 2009; Husain et al., 2014).

Textiles for temperature estimation can be developed also by such textile-finishing technologies as embroidery and printing technology. For example, at ITA, tailored fibre placement (TFP), an embroidery technique, was used to develop textile thermocouples by combining relevant conductive yarns and metal monofilaments (Figure 4.17). Seeberg et al. (2011) have demonstrated scenarios for application of screen printing to implement a thermocouple directly on textiles by combining polymer and metal substances. A research team from Zurich used printing technologies to manufacture a miniature-resistive temperature sensor on a Kapton foil that was integrated into textiles during the weaving process (Kindeldei et al., 2011, 2013). Figure 4.16c displays the concept of the approach.

The state of the art shows great variability in solutions for temperature estimation with textile-based structures. These have the potential to be advantageous in spheres such as structural health monitoring, health care in physiological monitoring and comfort estimation. Despite this, most of the developments are still carried out in the frame of research projects.

4.5 Manufacturing textile-based sensor technologies

In the developing process, one must decide where to place the conductive threads between the nonconductive ones, and which manufacturing technology is suitable for the product requirements. In the next section, the weaving and embroidering technologies will be shown. Both technologies have the advantage that the conductive threads possess a very stable and robust position because of their textile structure, which is a precondition for functional sensors.

4.5.1 2D weaving

2D weaving is a high-speed, economical process that been used for thousands of years. Fabric is formed by warp and weft yarns that are interlaced with each other in the 2D-weaving process.

Figure 4.18 illustrates the arrangement of warp, weft and fabric. The most important thing is that if warp yarns want to move up and down, each warp yarn has to pass through the heddle's eye. This affects the design of the fabric and extends the abrasion to which the yarn is subjected during weaving.

However, next we will introduce two simple weaving patterns, plain and atlas weave, to show the differences in the attitudes in textile structure just by changing the pattern. This creates tremendous possibilities for designing textile sensors.

4.5.1.1 Plain weave

Plain is the simplest weaving pattern among all of the weaving patterns. The most important thing about plain is that it is the tightest weaving pattern. Plain weave has the following characteristics:

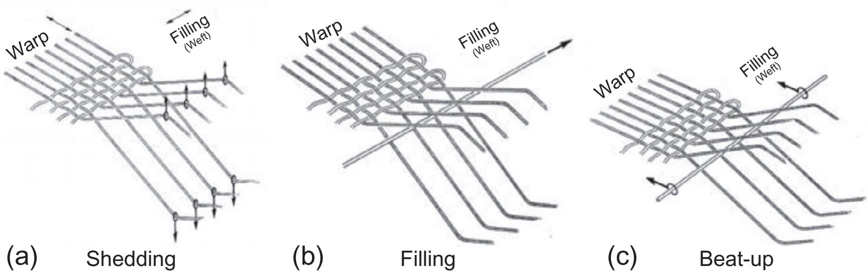

Figure 4.18 Stages in 2D weaving: (a) shedding, (b) filling and (c) beat-up.

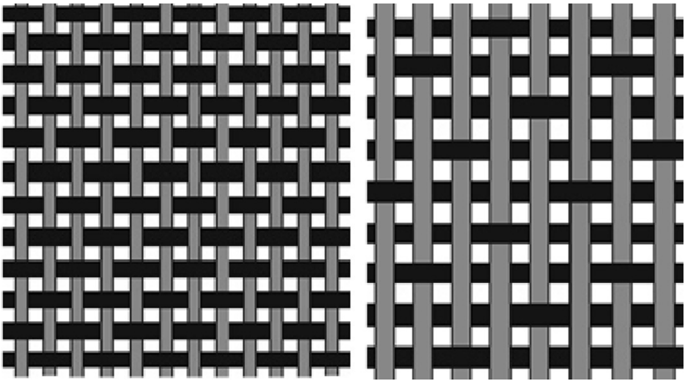

Figure 4.19 (a) Plain weave and (b) atlas weave.

- It has the maximum binding points.
- The warp and weft yarns interlace each other one up and one down, and they alternate.
- The warp and weft yarn density is limited.
- The fabric that is produced by this pattern is relatively strong and tight.
- Both sides of the weave are identical.
- Each thread gives the maximum amount of support to the adjacent threads.

In the plain weave, the principle is that the warp and weft yarns in each series interlace with each other alternately under and over (Figure 4.19).

4.5.1.2 Atlas weave

The aim of the atlas pattern is to manufacture a smooth and glossy fabric face. In order to reach this result, adjust the points of interlacing of the warp and filling so that they will be covered by the joining warp or filling floating threads. Again, be sure to distribute them well all over the repeat of the pattern, so that no two points join. In the atlas (or satin) pattern, each warp/filling yarn floats over four filling/warp yarns and interlaces with the fifth filling yarn. The properties of a satin (Figure 4.19) weave are as follows:

- In a fabric that is woven by the satin pattern, there is just one interlacement between each warp and weft yarns. That is why it looks glossy.
- The amount of the material is very high on the surface.
- The satin pattern is looser than the plain pattern.

4.5.2 Embroidering

Embroidery is a textile-finishing method that can be used to apply a given yarn material to a textile substrate in a defined geometry (Bosowski et al., 2013). This type of pattern is first defined and punched in software. Following these definitions, it is then converted into embroidery machine code. Three kinds of embroidery methods are

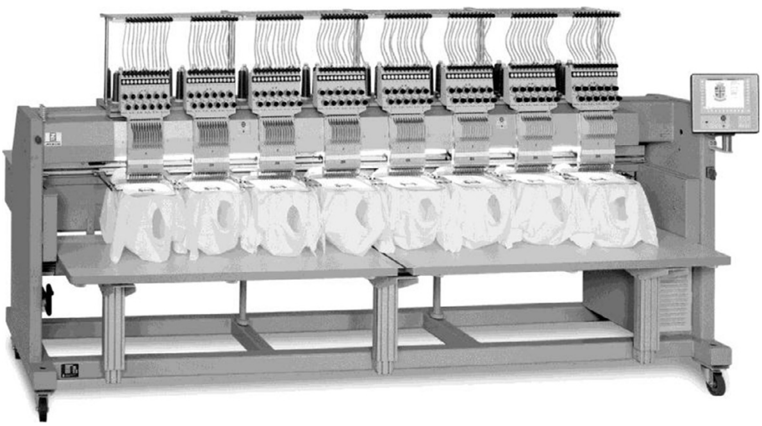

Figure 4.20 Tubular embroidery machine with eight heads.
ZSK Stickmaschinen GmbH, Krefeld, Germany.

currently defined in the literature: chain-stitch embroidery, standard embroidery and TFP. All three methods can be used to create different kinds of textile sensors. In the next sections, the three embroidering methods will be described, and samples of textile sensors obtained by these specific methods will be shown.

All three classes of embroidery are typically used when attempting to increase productivity in automated manufacturing. There are various machine configurations available, including up to 11 parallel embroidery heads for TFP, and more than 56 parallel heads for standard embroidery (Figure 4.20). Due to this performance productivity, embroidery technology can have decent efficiency when configured with other multi-head machinery. Potential applications of the technology range from decorative embroidery in carpeting and tablecloths to TFP embroidery for resistive automotive seat heating systems. Due to these established embroidery applications, embroidery technology is poised to further functionalize textiles with new developments such as embroidered textile sensors.

4.5.2.1 Chain-stitch embroidery (Ari)

The chain stitch, also known as the Ari stitch, has been found to be particularly interesting in the construction of textile-based sensors. The chain stitch is geometrically similar to crochet, which allows it to have very specific textile properties. A highly useful technique, the chain stitch is generally used for constructions such as kettle and moss embroidery. Because moss embroidery machines are built differently than traditional embroidery machines, careful attention must be given to select the correct machine for the end application.

Furthermore, even though the machines are mechanically different, they both use a similar embroidery technique. Moss embroidery is created by a single-thread system. In this system, the needle goes through the carrier material and pulls the thread out

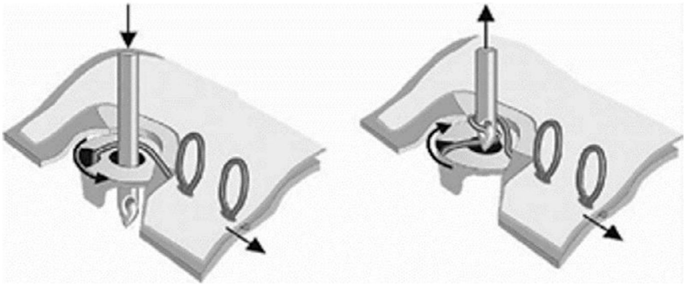

Figure 4.21 Principle of moss embroidery.
ZSK Stickmaschinen GmbH, Krefeld, Germany.

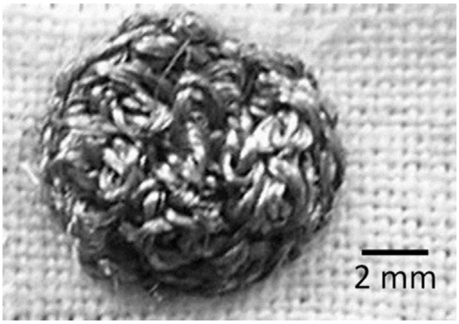

Figure 4.22 Textile electrode obtained by moss embroidery.

from under the needle, plate side up. Then, a loop is created by a rotary motion of the needle on the upper side of the carrier material. Repeating this pattern frequently, and with tight density, produces a moss-like surface (Figure 4.21).

Moss embroidery is particularly important when creating textile-based contact sensors. When the single-thread system utilises a conductive thread, the moss embroidery can be used to build a three-dimensional structure to create textile structures like the electrodes shown in Figure 4.22. These electrodes can be used as sensor electrodes for body signal monitoring such as electrocardiography (ECG), electroencephalography (EEG) or electromyography (EMG). The three-dimensional structure granted by moss embroidery provides better skin contact than flat embroidered electrodes. This is particularly true for hairy areas of the body like the scalp, or men's arms, legs and chest. The resistive natural hair has a significantly smaller area than the conductive electrodes and therefore has a negligible impact on the signal generated. Another advantage of this three-dimensional structure is that due to the contact pressure, the surface of the electrodes adapts to the skin and the body geometries. Rounded forms can be easily created that contour to the natural undulations of the skin and also have a high surface-to-skin area. The disadvantage of this method is that because of the inherent mechanical properties of the one-thread system, the embroidering can behave like a knitted textile. This is particularly undesirable in sensor technology, because if one break in the conductive thread occurs, that could produce a break in the entire sensor unit, rendering it useless (Figures 4.22 and 4.23).

4.5.2.2 Standard embroidery

Standard embroidery technique includes a double lock stitch. This double lock stitch, also known as Sozni stitch, is a two-thread system. In this system, the needle, or upper thread, is stored on a conical bobbin. The bobbin thread forms the stitches on the underside of the garment. The bobbin, or lower thread, holds the top embroidery thread near the garment. The base fabric, on which the embroidery is created, is held under tension through the use of an embroidery frame. These frames can consist of simple metal clamps to more involved hydraulic systems that allow for faster base fabric removal. The tension provided by the frame improves accuracy of the embroidery, while also allowing for a clean and predictable stitch. During the embroidery process, the frame that secures the basic fabric is controlled by a computer and moved in the *x*- and *y*-directions in order to create the programmed pattern. The needle punches through the fabric and interlaces the upper thread with the bobbin thread by means of a rotating gripper located below the base fabric (Figure 4.24).

Figure 4.23 Two kinds of textile electrodes with different geometries obtained by double lock stitch—standard embroidery.

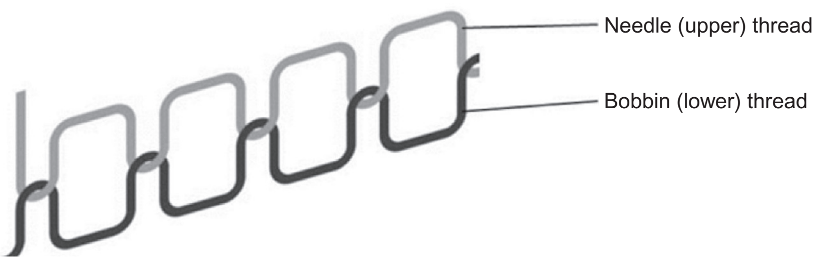

Figure 4.24 Double lock stitch—standard embroidery.

The double lock stitch, also known as standard embroidery, can be particularly well suited to creating electro-conductive pads. This is due to the inclusion of electro-conductive yarns as upper and/or lower threads, allowing for more control to fit the desired application. If both the upper and lower threads are electrically conductive, the conductivity goes through the entire fabric. If just the upper thread is electro-conductive, the underside of the fabric can be electro-insulated if an adequate base material and thread tension are used. Manipulating these properties in different locations of the textile can allow for use-specific variations in textile construction. The desired type of sensor and its ability to output relevant data depends on the yarn material, the pattern and the signal processing. In Figure 4.26, two different sensor electrodes with variations of the geometry obtained by standard embroidery are shown. These electrodes can further include the previously mentioned moss electrodes if there is an end use such as sensor electrodes for body signal monitoring (ECG, EEG, EMG). The advantage of the lock stitch embroidery is that these sensors can be produced on standard multi- or single-head embroidery machines. By using a multi-head embroidery machine, the functional parts (electrodes) and the design parts of a pattern can be embroidered in one step, similar to conventional embroidered design applications. This can save time and money and improve the accuracy of the sensor.

4.5.2.3 Tailored fibre placement

Another recently developed embroidery technique is called the TFP method, which further consists of a three-thread system. TFP is a textile-manufacturing technique that has been heavily influenced by advanced sewing constructions. This technique allows for continuous placement of a selected textile material. This material can be placed and punched in a highly controlled geometry. This procedure has traditionally been used in the composite industry for the optimization of materials to fit customized loading conditions. The fibrous material that acts as the roving is fixed by an upper and lower stitching thread onto a base material. This step ‘locks’ the selected third fibre into a geometry and further preserves that geometry by the use of an upper and lower stitch. Figure 4.25 shows the principle of the TFP method.

A variety of fibres, such as carbon, glass, basalt, aramid, natural, thermoplastic, ceramic fibres, and also metallic threads, can be applied and combined within one design. This creates limitless applications of TFP technology, especially in the role of sensors and the inclusion of their corresponding electronics. The method of TFP is extremely versatile, as it is less material dependent than other forms of embroidery. Materials that usually cannot be embroidered directly can now be placed on a textile due to the fibre placement and fixation provided by TFP. This leads to a high amount of possible sensor geometries and more controllable variability in their end uses. The following images include several types of TFP-embroidered sensors.

The temperature, moisture and strain sensors shown in Figure 4.26 can be used to monitor the process of wound healing. The illustrated geometries can be used to measure the temperature due to a change of electrical resistance, the moisture content due to a change of capacity and the strain due to a change of inductance.

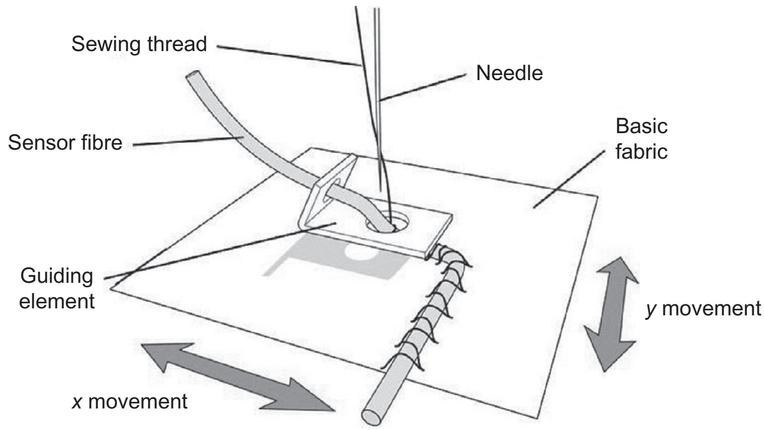

Figure 4.25 Basic principle driving tailored fibre placement (TFP) technologies.

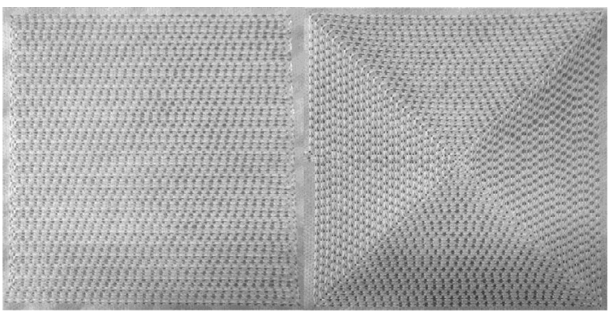

Figure 4.26 Different geometries of TFP-embroidered moisture, temperature and strain sensors by applying copper fibres on a wound dressing (double meander (left) and spiral (right)).

Figure 4.27 shows a textile thermocouple as temperature sensor. In this application, a stainless steel yarn and a constantan fibre have been applied to a mattress in order to measure the temperature in the bed. The theory is that two different metal rovings, which have a great difference in thermoelectric voltage, can be used as temperature sensors.

4.6 Applications of textile-based sensors

Concerning the area of application field, textiles can be divided into clothing and technical textiles, with the latter defining themselves by their functionality in the first place (Gries, 2007). Textile sensor requirements generally result from different application

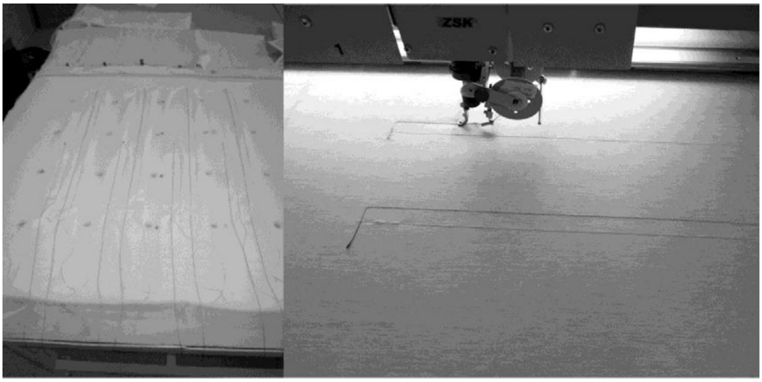

Figure 4.27 Textile thermocouple as temperature sensor by applying stainless steel yarn and constantan fibre on a mattress by TFP embroidering.

areas. Depending on the purpose of the product, the amount of integrated electronics varies quite a bit. Smart clothes can be divided into five degrees of intelligence (Table 4.1; Carvajal Vargas, 2005).

A lot of thinkable applications help men on many occasions. Sensors that detect data correlating to physical body functions (e.g., pulse, temperature) offer comfort and safety. Even visual aids for amaurotics may be common devices in medical science in a few years. Information would be transmitted from the sensor through the textile, which then stimulates the cutaneous nerves. Textile sensors can serve meaningfully in the monitoring of hazard areas, infirm or chronically sick persons and sportspersons. Soft sensors are textile piezoelectric resistor-sensors for the detection of movement and respiration. The piezoelectric effect can be enforced by exterior mechanical influences. They add importance to the functional textiles.

Movement and acceleration sensors integrated into the textiles could transmit data to a microprocessor, which then analyses and evaluates the information. This way, feedback on wrong movements could prevent harmful posture and movement after injuries and in rehabilitation. Protection systems for motorcyclists, for example, can be realised through movement sensors.

Depending on the application area, sensors from different production-method levels are combined in one system. As a consequence, the textiles used for textile-based sensors must be adjusted carefully to the particular application to guarantee the system's proper functionality.

4.6.1 Humidity and moisture monitoring

Humidity and moisture monitoring and control, along with temperature management, are important in industrial, medical and in-home applications. The amount of water vapour in the air is of great importance in many manufacturing processes, including food, pharmaceutical, semiconductor, construction, textile and wood industries. Humidity level and moisture amount affects physiological, biological and chemical

Table 4.1 **Hierarchy of intelligence for textiles (Möhring et al., 2006)**

<table>
<tr><th>Level</th><th>Degree of intelligence</th><th>Movement and acceleration sensors</th></tr>
<tr><td>1</td><td>Stupid</td><td rowspan="8">
</td></tr>
<tr><td>2</td><td>Ignorant</td></tr>
<tr><td>3</td><td>Trivial</td></tr>
<tr><td>4</td><td>Sensible</td></tr>
<tr><td>5</td><td>Smart (materials are able to function as sensors/actuators)</td></tr>
<tr><td>6</td><td>Clever (materials adapt to general requirements)</td></tr>
<tr><td>7</td><td>Intelligent (information processing systems and feedback control systems are integrated into sensors and actuators; e.g., microprocessors)</td></tr>
<tr><td>8</td><td>Wise (able to make ethically correct decisions)</td></tr>
</table>

processes. High moisture concentration encourages the growth of bacteria, mould and fungus, while too little water vapour in the air may cause health problems for persons with respiratory diseases and allergies, dysfunctions of equipment and certain damage of constructions and materials. Hereby, humidity level management has a wide range of applications and is required for microclimate control, monitoring the saturation of moisture in different constructions and all sensorial applications where the water vapour amount is an interfering agent (Rittersma, 2001; Patissier, 1999; Zampetti et al., 2009; Ma et al., 1995; Laville and Pellet, 2002; Miyoshi et al., 2007, 2009; Telliez et al., 1999; Canhoto et al., 1996, 2004; Smits et al., 2011; Shi et al., 2013; Gavhed and Klasson, 2005; Reijula, 2004; O'Reagan and Lazich, 2010).

Initially, moisture can be referred to as absolute humidity that indicates the actual amount of vapour. Relative humidity (RH) refers to the percentage of the vapour in the air at a prescribed temperature compared to the amount of vapour that could hold in the air at this temperature. Capacitive humidity sensors consist of two electrodes and a dielectric placed between the electrodes. RH values are determined according to the capacitance changes of the dielectric constant, which is the RH and temperature of the dielectric. Thus, the main requirement for the dielectric material is hygroscopicity, that is, easy absorption of vapour in the environment. The operation principle of resistive humidity sensors is based on measuring the changes in electrical impedance in the hygroscopic medium. The hygroscopic material absorbs water and ionic functional groups are dissociated, resulting in an increase in conductivity. Thus, as the humidity increases, the resistance of the material decreases. Figure 4.28 displays the general concept for the described sensor structure (Chen and Lu, 2005).

Although there are a great variety of electronic humidity sensors, some applications require new solutions that can be provided by smart textile technology. For example, in recent years in some industrial sectors such as food packaging and RFID devices, the demand for flexible and lightweight sensor constructions has increased. Moreover, flexibility is a fundamental issue to ensure humidity control in many textile constructions, such as mattresses and car seats. Above that, textile humidity sensors have great potential as an asset in wound and skin pathology management.

Different technologies such as lithography, inkjet printing, soft micro-electro-mechanical systems (MEMs) techniques, electro-spinning and sol–gel have already been investigated (Zampetti et al., 2009; Starke et al., 2011; Oprea et al., 2007; Virtanen et al., 2011). These technologies enable the production of miniaturized

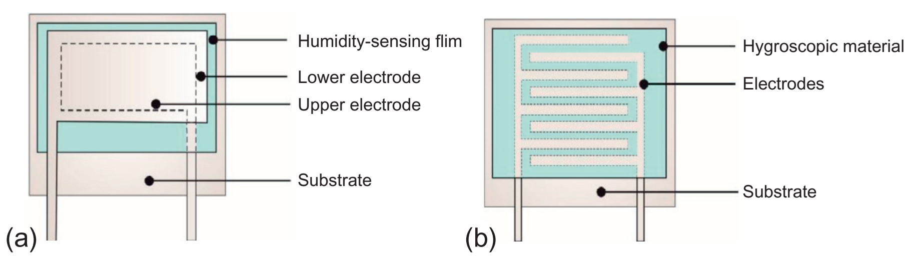

Figure 4.28 General scheme of a (a) sandwich-layered capacitive and (b) resistive sensor.

and flexible humidity sensors. However, for some applications, covering large areas may be of greatest importance, while the measurement accuracy or response time may be lower than what is required for miniaturized sensors. In such cases, textiles can be the material of choice.

To date, different approaches and sensor structure sensors have been investigated, and the working principles of conventional capacitive and resistive humidity sensors have been transferred to textiles (Kindeldei et al., 2011, 2013; Consales et al., 2011; Boussu et al., 2013; Salvo et al., 2010; Coyle et al., 2010; Moriss et al., 2009; Pereira et al., 2011; Weremeczuk et al., 2012). Efficient measurements of RH usually require a complex approach by joining such technologies as weaving, embroidery, fibre engineering and printing technologies. The choice of the most appropriate approach is determined by the chosen sensor structure, materials and applications. As in other sensor types, textiles can be initially used as a carrier of a humidity-sensing structure.

Nevertheless, due to specific textile properties such as moisture absorption and transport, textiles can be also an active compound of a sensor. Moreover, the choice of a textile can be influenced by other requirements, such as durability of the material or its tactile characteristics. Beyond that, conductive textiles are a good candidate for implementation of sensor electrodes.

State-of-the-art solutions vary in their integration level (Cherenack and van Peterson, 2012). Pereira et al. described a textile-based humidity sensor using cotton as a hygroscopic material and conductive yarns woven into textiles as electrodes (Pereira et al., 2011; see Figure 4.29a). A research team in Poland explored a combined solution. They used textiles as a substrate on to which electrodes were printed and the sorption layer was deposited (Weremeczuk et al., 2012; see Figure 4.29b). Researchers at ETH Zurich miniaturized printed humidity sensors on a polymer tape, which they subsequently wove into a textile structure (Kindeldei et al., 2011, 2013). Applications of such sensor designs are limited to geo-textiles, and to some extent to monitoring in sportswear when the sweating rate is high or skin resistance response is very good.

On the other hand, fibrous, textile-integrated and textile-based ink-printed and lithographic RH sensors seem to have more efficient performance due to the sensing properties of the used polymer materials. These offer a shorter response time to humidity

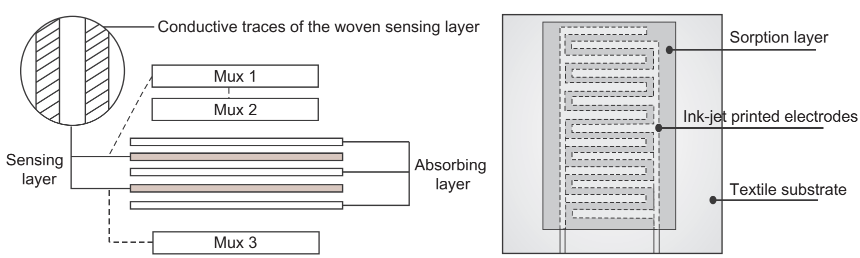

Figure 4.29 Examples of (a) a textile-structured sensor (Pereira et al., 2011) and (b) inkjet printed on textile sensor (Weremeczuk et al., 2012).

changes at various humidity ranges (Kindeldei et al., 2011, 2013; Devaux et al., 2011; Reddy et al., 2011). Although fabrication of these types of sensors is more complex, they have a broader range of potential applications in climate or microclimate control in clothing or other structures.

4.6.2 Pressure-mapping systems

Interface pressure mapping involves using sensors to quantify the pressure between two contacting objects, such as a person and his or her support surface. Pressure mapping has many widespread applications, but in assistive technology it is commonly used by clinicians to determine the suitability of a wheelchair cushion, and by researchers investigating support surfaces, risk factors for ulceration and ulcer prevention protocols. Pressure-imaging technology can be used in industrial and engineering environments for product design and verification, process control or quality assurance.

These pressure-mapping systems can be made in many configurations for different uses, but the most commonly encountered clinically are the thin mats used by seating specialists. These mats are composed of a matrix of small sensors and a cover. When a person sits on such a mat, the sensors read pressure at individual locations on the thigh or buttock. This data is transferred to a computer, where a clinician can analyse it. Evenly distributed pressure is preferred.

Some pressure-mapping systems are based on a piezoresistive technology (see Figure 4.30a; for example, the stretch-based sensors from FSA, Winnipeg Canada; FSA, n.d.). This means that the resistance changes with applied pressure. Piezoresistive semiconductive polymers are sandwiched between two layers of highly conductive ripstop nylon fabric. The floating sandwich allows conformability to the compound curved surfaces of the seating environment as the slippery layers move freely and minimises hammocking. The changes in resistance that result from the different pressures on the semiconductor are interpreted by the interface module and relayed to the computer, where they are displayed as an array of colours and digital

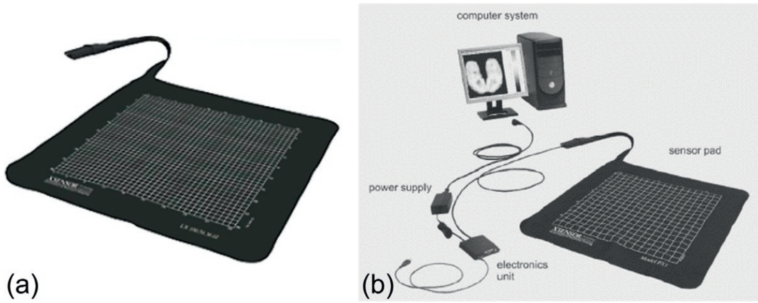

Figure 4.30 Stretch-based (a) piezoresistive pressure sensor (FSA, n.d.) and (b) capacitive pressure sensor (Cork, 2007).

pressure values. Corrections are made along the way for hysteresis (direction of loading), creep (changes with time) and individual sensor variations.

Based on this material, Vista Medical is offering a lot of pressure-mapping system products on the market under the brand BodiTrak, such as the 'Sock Sensor' (Vista Medical Ltd. (Hrsg), 2012; Boditrak, n.d.).

The resistive pressure sensor is comprised of a matrix of capacitive-sensing elements. Pressure applied to the surface of the sensing element causes a change in capacitance that is correlated to a change in pressure. Proprietary Windows-based software compensates for sensor non-linearity, hysteresis and creep over time, resulting in enhanced accuracy. XSENSOR's capacitive-based pressure-imaging sensors can graphically display pressure distributions in real-time between virtually any two surfaces in contact (see Figure 4.30b). The sensor element is accurate, thin, flexible and robust. These physical characteristics minimise any artificial influences created by the presence of the sensor during data collection (Cork, 2007).

To build tactile array sensors, PPS arranges the electrodes as orthogonal, overlapping strips (Pressureprofile, n.d.; see Figure 4.31a). A distinct capacitor is formed at each point where the electrodes overlap. By selectively scanning a single row and column, the capacitance at that location, and thus the local pressure, is measured. PPS's proprietary drive and conditioning electronics can scan through an array at high speed while optimizing settings to achieve the maximum sensor response from each sensing element.

Alphafit's technical textiles are made of sensory filaments. With this sensory filament, it is possible to measure surface pressure on three-dimensional variable surfaces. Textile three-dimensional pressure measurement is useful for all things foot related. The filament itself measures the pressure. The textile system works without the need of inserting any industrial sensors. This measurement system can be integrated into any textile. Production is stunningly simple and can be done on a large variety of textile materials for many different applications. With the pressure-sensitive filament, special textiles can be produced for each and every part of the body, such as the hands, feet and knees. Possible areas of application also include numerous industrial uses. The original idea was to develop a measurement tool for orthopaedic shoemakers in order to prevent sore feet in patients suffering from diabetic foot syndrome.

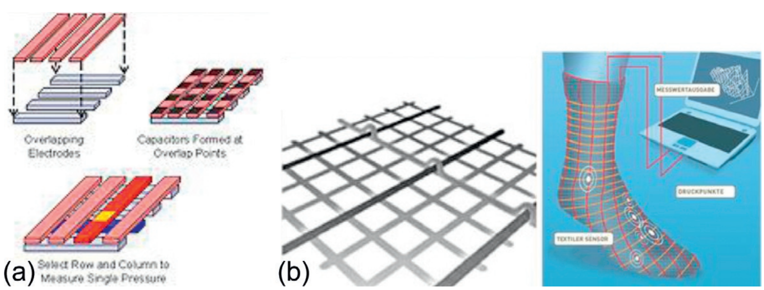

Figure 4.31 (a) Array sensors (Pressureprofile, n.d.) and (b) a prototype of the 'Smart Sock': three-dimensional pressure measurement (Alpha-fit, n.d.).

Nowadays, possible applications include the areas of medicine and sports. Above all, this pressure-sensory sock is perfect for custom-fitting ski boots (see Figure 4.31b; Alpha-fit, n.d.).

The specific combination of materials and techniques enables the creation of a textile capable of measuring multitouch pressure sensing. This property is used in a wide variety of textile-based sensing products in a range of markets that require pressure mapping.

4.7 Future trends

This section highlights future trends in textile-based sensors.

4.7.1 Fibre-coated sensors

FBG is a type of distributed Bragg reflector constructed in a short segment of optical fibre that reflects particular wavelengths of light and transmits all others. This is achieved by creating a periodic variation in the refractive index of the fibre core, which generates a wavelength-specific dielectric mirror. FBG can therefore be used as an inline optical filter to block certain wavelengths, or as a wavelength-specific reflector. Specifically, FBGs are finding uses in instrumentation applications such as seismology, pressure sensors for extremely harsh environments, and downhole sensors in oil and gas wells for measurement of the effects of external pressure, temperature, seismic vibrations and inline flow measurement. As such, they offer a significant advantage over traditional electronic gauges used for these applications

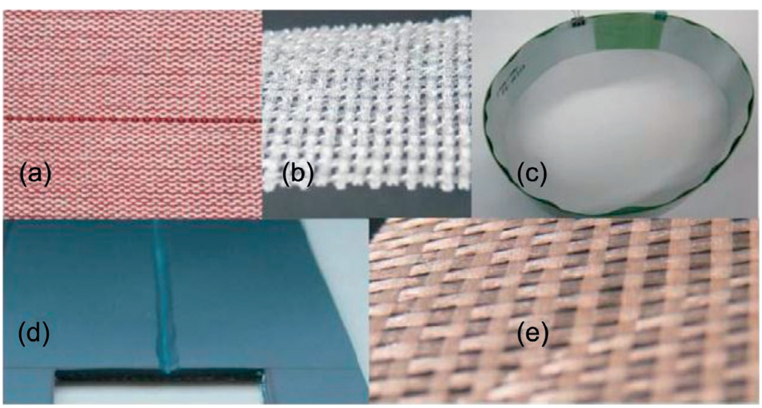

Figure 4.32 Integration of Bragg fibre in woven structures: (a) as warp thread; (b) into a 3D woven; (c) embedded in a conveyor belt; (d) inserted into a groove and (e) threaded into flat-woven fabric (Schloßer et al., 2009).

in that they are less sensitive to vibration or heat and consequently are far more reliable. In the 1990s, investigations were conducted for measuring strain and temperature in composite materials for aircraft and helicopter structures. Figure 4.32 shows some examples of weaving integrated Bragg fibres.

4.7.2 Printed sensors

Textiles with light-emitting properties will find a huge field of application, which supports the survival of the European textile industry like in the field of protective clothing (e.g., rescue workers, firefighters, road workers, postal workers, delivery personnel) as well as in light-emitting flags or banners, which emit specific information in darkness. Further application fields are recognised in flexible displays/screens, which could be easily incorporated into fashion textiles or technical textiles. Printing luminescent (OLED/LED) inks on textiles realistically offers huge potential and represents a quantum leap in general and in the printing industry in particular. A wide range of deposition and patterning techniques can be used for the development of electroluminescent (EL) OLEDs. Most prominent in this context are various deposition techniques such as chemical and physical vapour depositions, and printing techniques ranging from reel-to-reel processing to non-contact printing methods. Printing of the luminescent products can be done using different technologies:

(a) conventional screen technologies (flatbed or rotary screen),
(b) digital inkjet technology (drop-on-demand): piezo and valve-jet technologies, both representing the state of the art in digital printing.

The application of functional light-emitting particles on such interdigital textile structures can be simply done by screen printing the electroluminescent material on top of the woven interdigital structures. The thickness of the active layers prepared by coating or screen printing is often thicker than necessary to fulfil the chosen application. Therefore, it represents a waste of material and a loss of performance. However, when looking at the applications, inks for EL devices consist of particles with a diameter bigger than a few micrometres, which makes screen printing a first-choice technology.

A more flexible technique that can be built well into the modern production logistics of textiles and apparel is digital inkjet printing. Therefore, inkjet printable light-emitting particles with OLED and electroluminescent properties have to be developed and then applied on fabrics. In this way, self-shining textiles could be prepared more effectively and with increased performance and less costly material. Inkjet printing represents an innovative printing technique for textile materials and will become considerably important in the near future, because this technology will shorten the time to print and fulfil the strong industry need to respond in real-time to customer needs. Furthermore, it has a positive impact on the environment by the rational use of resources. Inkjet printing is a technology where small droplets of liquids or dispersions are ejected through small nozzles (diameter <20 μm) to impact the substrate at a precise location. The concept is very simple but leads to numerous implementations.

4.8 Conclusion

The development and application of textile-based sensors demands a new way of thinking. Expertise from the textile, electronic and computer science branches must be combined with knowledge of biological, chemical, physical and medical branches to help emerging application areas and solutions (Carvajal Vargas, 2005). The developing process of a textile-based sensor starts from ground zero every time. There is no standardized tool for choosing sensor modules and materials for designing functionalized textiles, although knowledge has already been generated on textile sensors in many well-known research projects. A classified catalogue that enables direct selection of sensor modules gives developers in the textile industry and research in the near future an overview of all developed textile-based sensors in different application areas.

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