Smarten up garments through knitting

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Abstract. Smart textiles are a growing and fascinating field with enormous potential in the field of wearable electronics: shirts with integrated electrodes, socks stimulating the blood circulation or heating clothing are just a few examples of wearable, smart textile products. Most often, the technology of choice for on-the-body-worn smart textiles is knitting as it results in stretchable and, hence comfortable garments. This presentation explores the knitting technology in respect to smart textiles giving an overview of current research activities as well as commercially available products on the market. It further intends to foster the transfer of research approaches into business applications as well as to develop new challenging research ideas.

1. Introduction
We are living in a knowledge driven society that is facing an increasing impact of science and technology on all aspects of life through products and services, and consumer needs. More and more objects surrounding us in our everyday life get smart and so textiles do as well. The field of smart textiles is not a discrete area; it is more an interdisciplinary subject incorporating science, technology, design and human sciences, and its future lies in the potential of combining different technologies. When talking about smart textiles we often talk about the convergence of textiles and electronics – a combination of materials capable of accomplishing a wide spectrum of functions to increase, for instance, our well-being and health [1]. Smart functions, however, can also be integrated using phase change materials [2], optical fibers [3], etc. Such smart textiles can be used in a broad range of applications, from automotive to civil engineering to sports and medical purposes.

A smart textile textile material interacts actively with its environment, i.e. it responds or adapts to changes in the environment or to an external input. To be able to carry out this interaction, it is often incorporated into a system, comprising textile and non-textile parts. The system ideally comprises six different components: sensor, actuator, internal and external communication, power source and data processor [4]. Each of these components has been realized at least partly out of woven, knitted, braided fabrics or non-wovens over the past years [5,6] and research activities are still constantly increasing. Against this background, this paper gives an overview on recent advances in the research and development of these components. Above that, as the research diversified over the past years, we concentrate on knitted fabrics and highlight their uses to realize different smart textile components.
2. Knitted sensors and electrodes

One of the typical properties of knitted fabrics is their stretchability. In a knitted fabric made of conductive yarn, the resistance will change during elongation [7]. Thus, knitted fabrics can be used as stretch sensors, with the exact properties dependent on yarn and knitted structure (Fig. 1).

Farringdon et al., e.g., have examined knitted strips and found a linear increase over a broad range of elongations [8]. Such a sensor can, e.g., be used to measure arm or leg movements.

Large strains occurring at high temperatures can similarly be measured using knitted fabrics from stainless steel or carbon fibers, with the latter showing higher sensitivity and better repeatability [9]. The elongation-dependent resistance can also be used to detect breathing frequency. Using electro-conductive yarns, Zieba and Frydrysiak have produced knitted samples with conductive stripes from polyacrylonitrile staple fibers coated with copper sulphide (produced by Euro-static), combined with non-conductive parts from cotton and polyester. Elongation in vertical and horizontal direction have shown to produce differences in the measured resistance, allowing for using such samples as breathing sensors [10]. Combinations of stainless steel yarn and elastane parts have also been shown to be suitable for measuring the respiration by resistance and inductance changes [11]. Nevertheless the dependence of the sensing properties on yarn type, yarn input tension, knitted structure and other parameters must be taken into account [12].

Another possibility to measure respiration is using piezoelectric crystals which generate electric voltage due to deformation during breathing [13]. Piezoresistive sensors can be produced by coating conductive polymer sensors on knitted or woven fabrics, often resulting in higher gauge factors (changes in resistance per strain) than in conventional elongation sensors [14]. Such sensors can also be used to create gloves or complete wearable motion capture systems for man-machine interactions [15,16].

Finally, breathing can be measured using optical fibers [10]. The static deformation of a knitted sample with included optical fibers leads to a change of the light which is led through the optical fiber onto a photodiode. The photodiode voltage is approximately linearly correlated with the elongation. Such macro-bending transducers can be easily achieved by integrating optical fibers in half-loop or U shape. Stretching the fabric results in an increased curvature radius and thus reduced losses in the fiber [17]. Signal analysis in single-mode optical fibers, however, is impeded by mode coupling between the fundamental mode and reflection modes, resulting in undesired oscillations in the curves of loss due to fiber bending [18-20]. This problem has to be coped with using defined wavelengths [17]. Alternatively, multimode fibers can be used in which the special intensity of the modal power is modulated; the change of the intensity profile can be related to the stress applied on the fiber [21].
Conductive knitted fabrics do not only respond to elongation but also to pressure. Especially spacer fabrics with two conductive sides, separated by a non-conductive spacer thread (Fig. 2), can be used as textile switches or pressure sensors [22]. It is not only possible to measure their resistance but also to use them as parallel-plate capacitors with a capacity inversely proportional to the distance between the plates. A spacer fabric in the shape of an array of parallel plate capacitors enables to localize pressure on the fabric and in this way, e.g., designing a sensor which can measure sitting postures or lying orientations [23].

![Figure 2. Weft-knitted spacer fabric with conductive (grey) and non-conductive (blue) yarns in both planes, separated by a non-conductive spacer thread.](image)

Knitted electrodes can also be used as ECG or pulse sensors [24,25]. Additional to the usual problems of textile ECG electrodes, i.e. varying resistances between skin and electrodes as well as motion artifacts, knitted electrodes have the additional disadvantage of varying resistances inside the electrode due to elongation effects [26,27]. Nevertheless, knitted ECG sensors have been developed by several research groups in different projects, such as MyHeart [28-31] or MERMOTH [32,33]. The ECG signals can be increased by higher contact pressures and additional moisture [34]. However, in many cases more stable and reliable ECG signals can be detected by non-elastic woven electrodes which are integrated in a knitted sensory shirt [35].

Finally, knitted fabrics can also be used as a base for a sensory coating, detecting chemical elements such as ammonia [36].

3. Knitted actuators
Actuators transform electrical or other signals into outputs which can be recognized by people, e.g. in form of light, sound, or motion. Such signals can be used to inform the wearer of a smart garment about the input gained by textile or textile-integrated sensors, can warn them if any threshold values are exceeded, or just react on a detected change in the environment by counteracting, e.g. by heating up a textile if the skin temperature of the user gets too low.

One of the possibilities to include a tactile actuator is based on shape memory materials, such as shape memory alloys (SMAs) or shape memory polymers (SMPs). Such materials can consist of chemically crosslinked glassy thermosets or semi-crystalline rubbers as well as of physically crosslinked thermoplastics or block copolymers [37]. In all cases, they react on temperature, resulting in thermomechanical deformation and recovery [38,39].

They can be used as actuators as well as sensors. First tests were performed with respect to integration of such materials in knitted fabrics [40]. In this way, interesting shapes and time-dependent effects can be added to knitted fabrics, while the manufacturing process is still challenging [41].
The integration of light in textiles can be performed using LEDs, optical fibers, or electroluminescent (EL) wires. While LEDs are usually integrated in textile fabrics by sewing, embroidery or gluing [42], optical fibers can be knitted (see examples in chapter 2). EL-wires can easily be included in woven fabrics; knitting them, however, can easily lead to the destruction of the electroluminescent effect. Additionally, it should be mentioned that they require a high voltage supply which makes them less easily usable in clothing than low-voltage LEDs [43]. Nevertheless, several research groups have developed methods to create electroluminescent coatings on textile materials, mostly on woven fabrics which are not as flexible as knitted fabrics [44-46].

As a last example for knitted actuators, heating elements have to be mentioned. Heating clothing is useful especially for people working outside. Heated knitted fabrics can be composed of conductive yarns, e.g. from metal or metal coated filaments in combination with textile filaments, which are heated due to resistive losses if a current is flowing through the fabric [47]. The temperature reached in this way depends on the parameters of the power source as well as on those of the yarn, especially its resistivity and cross section. By introducing a control unit, the heated clothing can be regulated with respect to external and skin temperatures [48,49]. This is of special importance since not only the manufacturing method but also the contact pressure at the binding points influences the degree of heating [50].

4. Knitted transmission lines
Signal and energy transmission in smart textiles necessitates conductive fibers or yarns. Depending on the desired application, especially on the distinction between direct current and alternating current in the high frequency range, and on the textile production method, different wires or yarns have to be chosen. Additionally, crosstalk between neighboring transmission lines has to be taken into account since conductive fibers and yarns are usually not electrically shielded [51].

Conductive threads can, e.g., be created by filling fibers with conductive materials such as carbon or metal powder, coating of fibers with metals or conductive polymers, or using filaments and fibers which are inherently conductive, i.e. from metal or conductive polymers [52]. Fig. 3 shows two of these alternatives. Usually, compromises between knittability, washability, conductivity and other desired parameters are necessary.

Transmission lines can either directly be implemented or afterwards be added using printing, coating or spraying electroconductive materials as well as embroidering or sewing [53]. Integration of conductive materials in knitted fabrics can be used to produce antennas, e.g. for RFID or bluetooth applications [54].

![Figure 3. Conductive transmission lines from copper strand (left panel) and silver-coated polyamide filaments (right panel) in single-jersey knitted fabrics from non-conductive materials.](image-url)
5. Other knitted smart textile components
Smart textiles using electronic elements need power supplies. To develop purely textile power sources, several attempts have been made. Energy storing technologies can be separated in three different approaches: textile capacitors, textile pseudo-capacitors, and textile batteries [55]. Besides coating layer systems on textile fabrics [56], it is possible to create fiber-capacitors and -batteries and to create woven or knitted textile fabrics from them [57-59]. Nevertheless, problems may occur especially during the knitting process which is challenging for the functionalized yarns [60]. This may lead to damages of the coating and resultant loss of the desired energy storage capacity.

In future development, such mechanical impacts have to be taken into account as well as the necessary increase of energy storage capacity to allow for long-time use of smart textiles without non-textile parts.

6. Challenges and opportunities
Knitted fabrics are of favorable use among the desired fabric constructions when it comes to on body worn electronics due to their stretchability and hence comfort properties. However, as mentioned in this paper, elasticity is often a property that counteracts with reliable electronic properties.

Hence, a challenge is the development of knitted structures with different elasticity levels throughout the fabric. In this way, the conductive or functional parts can be stiff, while the nonfunctional part is highly stretchable.

Another challenge has to be addressed from the material side. Yet, many interesting functional materials, like piezoelectric, chromic materials or hydrogels changing volumes, exist, but in a form that is not processable through knitting. Here, advances in functional and smart fibers and yarns have to be made.

The integration and interconnects are also a widely discussed drawback in the field of smart textiles. This challenge will only be overcome if knitting machineries adapt to process novel materials as well. An example of good practice can be found in the embroidery sector, in which machines can already process LEDs and connect them with embroidered conductive yarn traces fully automatically.

Last but not least, once knitted smart textiles are ready to enter the market, standards are needed for documentation of the performance and safety of these new products by setting up new test procedures. A step towards this direction is done by the European Committee for Standardization (CEN) to create a working group around smart textiles. Hopefully, more initiatives in this vein will be started in the near future to enhance the smart textile market.

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