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Smart Textiles

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ISSN 1571-5035
Human–Computer Interaction Series
ISBN 978-3-319-50123-9 ISBN 978-3-319-50124-6 (eBook)
DOI 10.1007/978-3-319-50124-6

Library of Congress Control Number: 2016961340

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Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

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Chapter 1
Introduction to Smart Textiles

Stefan Schneegass and Oliver Amft

Abstract This chapter introduces fundamental concepts related to wearable computing, smart textiles, and context awareness. The history of wearable computing is summarized to illustrate the current state of smart textile and garment research. Subsequently, the process to build smart textiles from fabric production, sensor and actuator integration, contacting and integration, as well as communication, is summarized with notes and links to relevant chapters of this book. The options and specific needs for evaluating smart textiles are described. The chapter concludes by highlighting current and future research and development challenges for smart textiles.

1.1 Introduction

Over the last two decades research around textile electronics evolved from initial research explorations into a industrially relevant area. Starting from pioneering investigations on how to integrate conductive lines and circuits into textiles made during the late 1990s, successive steps led to denser integration, additions of sensors, actuators, user interfaces, and complex textile circuits. While there have been many applications of textile electronics, including industrial filtration, a central aim has always been to realize clothing that could provide additional functionality due to *active components* and would eventually include a complete wearable computer. Hence, the term *smart garments* was created. Over the past years, smart textile patches and full smart garments have spun new application fields as well as shaping existing applications centered around sensor-based monitoring and interaction.

Sensor-based monitoring applications include acquiring vital signs in medical surveillance, estimating physical activity in sports, and safety systems for soldiers or

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© Springer International Publishing AG 2017
S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_1

firefighters. Their unobtrusive character makes smart garments particularly suited for any physiological and physical monitoring task. In contrast to wearable devices that are used as add-ons to the wearer's gear, clothing, enriched with smart textiles, can provide a convenient integration in everyday life for their wearers. Moreover, smart garments may not change the perception of clothing and thus enables wearers to privately use technology, which is sought in many monitoring applications. Often, it is underestimated, how much body coverage and integration space clothing provides to host monitoring functions, ranging from shirts and pants to jackets and underwear, respectively.

An essential feature for any monitoring application is the data quality provided. One long-standing challenge in the field of smart garments is thus how to maximize artifact resistance and measurement robustness, while retaining textile-like mechanical bend and stretchability. A variety of strategies to maximize the signal-to-noise ratio (SNR) are being considered, from mechanically or chemically optimizing electrode contact and conduction, to multimodal sensing and data fusion. However, it is not only the momentary signal quality that matters. Frequently it is the regular usage, handling, and cleaning procedures, which critically affects longer-term reliability. Most of today's textile handling procedures were established for classic fabric and textiles, thus resulting in quick deterioration of sensors and SNR. A typical example is washability and, in particular, the laundry cycle count that a smart garment can sustain without deteriorating in function. Another key challenge is scalability of the textile and garment production processes. Over the last century, textile production evolved into low-cost, large-volume processes. The production processes are contradictory to the diversification of smart garment production requirements across applications. Essentially, there is insufficient volume in each smart garment application to warrant investment by textile manufacturers. We continue to discuss the challenges for smart garment monitoring in the chapter contributions detailed further below.

Smart garments shape the way we may interact with computing systems in the future. Current interaction techniques on mobile devices mainly realize explicit input from users via touch and speech to execute certain commands. In contrast, smart garments move interaction from finger tips to a intimate body contact. Combined with the ubiquity of clothing in our everyday life, interaction becomes continuous and potentially involves the whole body. Explicit and implicit interaction techniques allow users to control computing systems while input and output devices in smart textiles remain unobtrusive. A new core element is implicit interaction based on the measurements of subconscious behavior and state such as of a user's physiological condition, posture, or movement during everyday activities. Implicit interaction in smart textiles may leverage its potential in combination with explicit user input involving full-body and arm gestures.

Similar to monitoring-centered smart garments, is the robust function and information quality provided to the application level essential for textile-integrated interaction solutions. The requirements for interaction in smart textiles extend further into establishing proper abstractions for application-layer software, privacy design, and aesthetics. The application-abstraction relates to frequently required services including (1) connectivity to external devices, (2) persistence of the vast data amount created, and (3) drivers to sensors and actuators. The eventual smart garment design is not only determined by monitoring and interaction needs, but must address privacy concerns and aesthetic aspects to yield wearer engagement.

In this chapter, we introduce the most important concepts related to the field of smart textiles and garments. Important milestones of the history of wearable computing and smart garments are summarized. We continue to explain current development and evaluation processes of smart textiles, with references to the subsequent chapters of this book. Finally, challenges and opportunities are presented that need to be tackled for smart garments to become mainstream.

1.2 Wearable Computing, Smart Garments, and Smart Textiles

A *wearable computer* is a computing device that is body worn and, thus, closely connected to the user. It has the potential of interweaving itself with its users and their everyday life achieving true pervasiveness. In contrast to mobile devices such as smartphones, wearable computers are always on, always ready, and always accessible [1]. They do not need to be explicitly switched on but automatically react to the wearer's explicit (e.g., a voice command) or implicit (e.g., change in heart rate) input. There are many different definitions of wearable computing. For example, Steve Mann defines a wearable computer as follows:

> **Wearable Computer** is a data processing system attached to the body, with one or more output devices, where the output is perceptible constantly despite the particular task or body position, and input means where the input means allows the functionality of the data processing system to be modified.
>
> *Steve Mann* [2]

There are two strands of wearable computing devices that need to be distinguished. First, *wearable gadgets*, for example, fitness bracelets, or eyewear computers, are miniaturized computers that can be attached to certain body parts such as the wrist or head. They provide input and output capabilities as well as connectivity to either a central device or directly to the World Wide Web. Nevertheless, the user needs to attach these devices explicitly, may forget or chose not to use the device, and the device is always an addition to the user. In contrast, *smart garments* (also referred to as smart clothing) are clothes which are enriched in functionality through sensing, processing, and actuation.

Smart garments are particular garments, built—at least in part—using *smart textiles*. Smart textile patches are in their base structure related to classic textiles, i.e., they consist of woven or knitted fabrics. In addition, however, smart textiles integrate functionality, e.g., to track a wearer's postures, gestures, vitals, or provide feedback. Van Langenhove and Hertleer define smart textiles as follows:

> **Smart Textiles** are textiles that are able to sense stimuli from the environment, to react to them and adapt to them by integration of functionality in the textile structure. The stimulus and response can have an electrical, thermal, chemical, magnetic, or other origin.
>
> *Lieva Van Langenhove and Carla Hertleer* [3]

Cherenack et al. defined three different categories of smart textiles [4]. The first category of smart textiles uses the textiles as carrier to integrate off-the-shelf electronic components. Conductive yarns and fibers replace cables to connect different sensors, actuators, or processing boards. Smart garments of this sort serve for rapid prototyping solutions before investing into further integration steps [5]. In the second category, more and more of the electronics is substituted by textiles. Textiles serve as sensors or actuators, and only some parts of the system use traditional electronics. In contrast to the first two categories, the approach in the third category significantly differs. The idea for these textiles is rather smarting up textiles and not including electronics in textiles. Logic boards and electronic components, such as transistors, are made out of textiles in this category [6].

As sensors and actuators are continuously available, it is conceivable to replace classic computer input with information automatically extracted from sensors. Moreover, the actuation functions allow a wearable computing system to react and show its internal state to the wearer. The automatic interpretation of situational sensor data related to user activity, user state, environment, and location is summarized under the term *context awareness*. Context awareness thus means to augment the wearer's perception with relevant information at the right moment. Several definitions of context and context awareness have been established. The reader is referred here to the definitions of Chen and Kotz:

> **Context** is the set of environmental states and settings that either determines an application's behavior or in which an application event occurs and is interesting to the user.
>
> *Guanling Chen and David Kotz* [7]

Smart textiles and garments can thus contribute substantial data to the context interpretation and even process sensor data to provide appropriate reactions via its actuators. The need to derive and track context is again a driver for realizing smart textiles and garments. Context awareness is a wide research and application field on its own and addressed in this book to the extend of interpreting sensor data derived from smart textiles.

1.3 History of Wearable Computing and Smart Textiles

In a broad sense, wearable computing refers to devices that support wearers with data input/output and functionality based on the context awareness. The history of wearable computing dates back long before the actual development of computers as known today. Glasses and watches provide a benefit to the users and enhanced their senses. Providing explicit input, abacus calculators that could be worn as rings were developed by Chinese pioneers back in the Qing Dynasty era (1644–1911).[1] While this device is neither electrical nor adopting, it incorporates basic input and output features.

1.3.1 The First (Electrical) Wearable Computer

Edward O. Thorp conceived the first electronic wearable computer in 1955 [8]. The goal of this machine was to calculate roulette probabilities. Thorp realized his idea together with Claude Shannon and others in 1961 by using switches in the shoe for input, acoustic output through a tiny earplug, and a small handmade computing unit was worn at a belt [9]. They achieved a 44% performance increase when playing roulette. The first wearable computer that was systematically researched was published in 1968. Back then, Ivan Sutherland presented a head-mounted display using small CRT displays placed in front of the user's eyes [10]. Using half-silvered mirrors, the user was able to see the virtual as well as the physical environment. Following this seminal work, a main focus in the field of wearable computing remained eyewear computing. One of the pioneer in this field, Steve Mann, developed several prototypes that use a near-eye display, on-body computer, and one-handed input device [11].

As of today, the number of wearable gadgets increases significantly. In addition to eyewear computing, different sensors and actuators placed at different locations on the user's body were used to obtain knowledge about many different aspects of context, such as the wearer's current health status or performed activity (cf., a design space discussing the different placement and sensing possibilities is presented by Schneegass et al. [12]).

[1] http://www.chinaculture.org/classics/2010-04/20/content_383263_4.htm.

1.3.2 Smart Textiles and Smart Garments

In the early 1990s, the benefits of smart textiles became apparent. The unobtrusive character of smart clothing [13] and the possibility to interact with this type of wearable computer even at night [14] motivated a new strand in wearable computing research. One of the first textile-based wearable computers was the sensor jacket [15], which measured the wearer's upper body posture utilizing eleven knitted stretch sensors placed over the joints. Detecting the posture was researched in various projects. Harms et al. showed how smart textiles could be rapidly integrated with motion sensors [16]. On the level of the sensor, investigation lead to novel sensor constructions. Mattmann et al. analyzed a yarn sensor that is nearly hysteresis-free while measuring elongation along body parts, e.g., the back [17]. Later, Shyr et al. use a textile strain sensor to infer on the flexing angle showing that the resistance of the sensor linearly correlates to the flexing angle of the leg or arm of the user [18]. Cho et al. compared different conductive textiles and their performance for measuring joint angles [19]. By integrating these sensors into a knee sleeve, Munro et al. showed that they were able to prevent injuries for athletes [20]. They used conducting polymer technology and audible feedback as soon as they reach 25 and 45 degree knee flexing to keep the leg in an optimal range. In another example, Helmer et al. show that by using strain sensors they were able to analyze Australian football kicking actions without interfering the normal movement of the athlete [21]. In addition to implicit detecting and analyzing activities, garment can also be used for explicit input, for example, through touch input [22].

In addition to physical measures, physiological status of the wearer is a investigation focus across many research projects. One of the first approaches was the Georgia Tech Wearable Motherboard [23, 24] that allowed developers to plug in different sensors into a single garment. Paradiso et al. presented a smart garment that can be used as wearable healthcare system [25]. In the multinational European MyHeart project, a underwear was developed and evaluated in cardiovascular diseases, providing electrocardiogram (ECG), respiration, and several other measurements [26]. The SimpleSkin shirt combines physiological and physical sensing [27].

In particular, the integration of electrodes and measurement of cardiorespiratory activity has received broad attention. Cho et al. developed an ECG shirt [19] and compared three different types of ECG electrodes (i.e., embroidered, knitted, and a combination of both). They showed that the combined fabric achieves the best performance. Choi and Jiang presented a system intended for cardiorespiratory measurement to monitor sleep condition [28]. They used belt-worn sensors for measuring respiratory cycle and RR-wave interval using polyvinylidene fluoride film and two sensors made of conductive fabric. An example alternative utilization of smart textiles was presented by Zhang et al. who evaluated textile electrode positions at eyeglasses for Electromyographic (EMG) measurement of the temporalis muscle during food chewing [29].

The overall construction principles of smart textiles and garments are continuously extended. Dunne et al. provided an overview on textile integration strategies and component attachments [30]. Key challenge regarding the interpretation of garment sensors is their varying attachment depending on movement and body shape. Harms et al. provide an overview on a prediction framework dealing with errors due to loose fitting in orientation, skin contact, and strain sensing [31].

1.4 Building Smart Textiles

Several steps are involved in creating smart garments. While some of the steps overlap with the manufacturing steps to create wearable computing devices (gadgets), smart garments provide additional challenges in the production process that need to be tackled. De Acutis and De Rossi provide an overview on the related textile integration challenges in Chap. 17.

1.4.1 Fabric Production

Fabric production, especially preparing for mass production is a key issue (cf., Poupyrev et al. work on Project Jacquard [32]). Classic production techniques include fleece, warp knit, weft knit, weave, braid, and non-comp fabrics (cf., Goenner et al. for an overview of textile production techniques Chap. 2). Each production technique combined with the used yarn-type impacts wearability of the garment differently, thus generating different mechanical properties, such as stretchability.

1.4.2 Sensors and Actuators

Several research prototypes of textile-integrated sensors and actuators have been developed. Typical textile-integrated sensor types include textile electrodes, strain, pressure, and bending. For example, Zhou and Lukowicz (Chap. 3) use touch-resistive textiles as pressure sensors and Lorussi et al. (Chap. 4) present textiles capable of measuring the bend anlge of joints. On the output side, visual output has gained center stage as shown in the work of Peiris Chap. 5. Furthermore, haptic feedback using electrical muscle stimulation received considerable attention due to the possible integration of the electrodes into textiles [33, 34]. A detailed introduction is provided by Pfeiffer and Rohs Chap. 6.

A key challenge is the application-specific sensors used in smart garments. Certain sensor functions have often been specifically designed for an application, which does not scale to the large-volume production concept used in fabric production. Cheng et al. presents the SimpleSkin garment,which is an approach to utilize generic fabric material for different sensor types, a GarmentOS to abstract the hardware and software ‘apps’ to realize application-specific functions Chap. 14.

When focusing on the sensor integration in a textile, investigations often utilize an electronic circuit board for the sensor data processing. An electronic board can be overcome by integrating more complex structures into the textile. Varga and Troester provide an overview on textile electronics approaches Chap. 8.

Another key aspect is the integration of batteries or other forms of energy supplies into textiles. Bayramol et al. provide an overview on how energy can be harvested using textiles Chap. 10. They present different approaches and discuss their advantages and disadvantages.

1.4.3 Contacting and Integration

Different methods exist to connect textiles with electronics. The methods can be grouped into non-reversible, i.e., the electronics cannot be easily removed from the textile, and reversible methods, i.e., the electronics can be removed for charging or washing of the textile. The non-reversible methods include form-locked connections, e.g., by sewing, and cohesive joining, e.g., by soldering, epoxy-based methods. Besides reversible methods such as push buttons, magnets, or hooks, more advanced multichannel methods such as ball-grid connectors [35] have shown promising results. Mehmann et al. provide an overview on different types of connectors in Chap. 9.

1.4.4 Communication and Operating Systems

In order to use sensor values or provide feedback through actuators at the textile, information needs to be transferred from the electronic board, e.g., Arduino, FPGA, to a more powerful entity that realizes the intended application. Mehmann et al. show an approach to communication using textile antennas in Chap. 7. Alternatively, the garment-attached electronics are connected to a mobile phone or base station. Used interfaces include SPI (synchronous 1:N communication) and UART (asynchronous 1:1 communication), which can be used to connect devices offering the same interface. Among the wireless standards, Bluetooth has gained widest acceptance due to its convenient interface with mobile phones.

1.4.5 Design and Interaction Design

Most research in the field of smart textiles focuses on developing textile-based systems that provide certain functionality. While this allows the rapid development of prototypes with novel functionalities, the design of the textile itself and of the interaction is most of the time neglected. Particularly exploiting textile properties (e.g., flexibility or haptics) allow novel forms of interaction which are not realizable with non-textile systems. Gowrishankar et al. provide a set of design cases that explore these aspects of textiles Chap. 11. Focusing on the user, Hkkil presents a set of design studies in which the user experience of textiles is explored Chap. 12. In contrast, Honauer focuses on interactive costumes for professional stage appearances and derive a set of requirements from different design probes Chap. 13.

1.4.6 Application

Besides the development of the actual textile, taking the application scenario into account is crucial. Even though a textile is theoretical capable of being used in a certain application scenario, investigating if users are capable of using them in real-world scenarios still needs to be proven. Thus, specific application scenarios pose specific requirements to the textile system with regard to their usability, durability, and wearability. A particularly interesting application scenario is the sport domain. Leutheuser et al. show how smart textiles can be used to support athletes Chap. 16. Additionally, smart textiles enable novel types of protective gears which are proactively protecting users. Chen and Lawo provide examples in this domain Chap. 15.

1.5 Evaluation of Smart Textiles and Their Applications

We identified three different groups of methods used to evaluate smart garments and their potential applications. Depending on the investigation objective, a different evaluation method should be selected. The evaluation methods are valued differently in each field of research related to smart textiles.

1.5.1 Observing and Questioning Users

An approach widely established in human–computer interaction is observing and questioning the user. User observation, also known as *Ethnographic Research*, is usually considered to capture user perspective, generate new ideas, or identifying challenges for applying smart textiles. Researchers observe users without interfering with their tasks and habits. Among the new ideas, researchers can derive new application areas or products from user observations. In contrast, questioning users directly will involve them in the study. Several methods are available such as surveys, interviews, and elicitation studies. The main objective of questioning is to understand user likes and dislikes, often implemented by presenting a prototype or a final system and asking the user certain questions about the proposed system. Questioning can be combined with *laboratory studies*.

1.5.2 Laboratory Study

In laboratory studies, a system is evaluated in a controlled environment with regard to a certain aspect. Aspects could be related to feasibility, e.g., showing that a proposed system works, technical aspects, e.g., system performance or reliability, or the user, e.g., usability, user performance. In smart textile research, primary evaluation objectives are frequently related to demonstrating the feasibility and performance of the approach. Maybe this is due to the critical challenges related to robustness and reliability, as described earlier. Performance evaluations include testing of materials as to how well the material functions as a textile sensor. One large strand of work shows that approaches that are currently realized with non-textile-based systems can be realized with textile-based sensors. To demonstrate the correspondence of a new textile-based approach, it is compared to a non-textile baseline that has been previously shown to realize the measurement task.

1.5.3 Field Studies and Research Through Deployed Systems

In contrast to laboratory studies, field studies aim at evaluating smart textiles in realistic settings. Field studies pose additional challenges to the smart textile under evaluation with respect to robustness and functionality. Parameters, e.g., the placement of the textiles, cannot be controlled as in a laboratory study. Data collection and power consumption are further challenges that render field studies as cumbersome evaluations. Due to the many uncontrollable parameters, internal validity of field studies is lower compared to laboratory studies. However, facing real-life challenges with smart textiles is an essential step toward evaluating and realizing a practical value. Field studies benefit thus from high ecologic validity. For example, privacy implications and social effects can hardly be assessed in the laboratory.

Taking field evaluation one step further, research through deployed systems allows researchers to gain insights into the wearers' behavior with almost no interfering of an artificial study setup. Field studies in the entirely uncontrolled form are currently mainly used for evaluating mobile phones [36] due to their ubiquitous availability. In the next future, smart textile evaluations will need to implement field studies to fully understand the symbiosis between user and textile.

1.6 Current and Future Challenges for Smart Textiles

1.6.1 Fabrication

A key challenge toward realizing smart textiles for various applications is to derive a generic textile technology that can be used as a basis and customized according to application-specific requirements using software. While a first approach toward a generic base textile is presented in this book, additional developments are needed before the technology is readily usable across many applications. Furthermore, it is conceivable that not all sensor, actuator, or signal processing functions can be realized using a generically fabricated textile. Novel materials and printing techniques could adequately address the gap. Printing techniques are mature enough even for large-volume production and feature extraordinary flexibility regarding the materials to be printed.

1.6.2 Integration

Today, users have their own microcosm of computing devices. In addition to a mobile phone, these devices include watches, TVs, cars, and many more. By integrating the smart textiles in this microcosm, the textile can act as additional resource of data, information, interaction, etc. The user can explicitly enter commands, e.g., controlling the watch using touch gestures on smart textiles, or the textile can be used to implicitly track a user's status, e.g., turning of the TV when textile-based sensor in the bed mattress detects that the user is sleeping. Due to this integration, the smart textile becomes an integral part of the user. However, interfaces between garment and environment need to be created.

1.6.3 Textile and Data Models

In particular for smart garments, proper modeling to deal with sensor errors is still missing. Initial investigations, e.g., presented by Harms et al. on simulations of wrinkles in loose fitting and partially fitting clothing [31, 37], showed promising trends; however, further work is needed. The simulations have shown to be practical to evaluate sensor errors even before physically implementing a smart garment. Based on the available data, separately validated simulation stages can be deployed to represent body proportions, posture or movement, and sensor principles. The resulting framework can deliver reliable results toward estimating garment design and sensor realization options within the wide option space of smart textiles and garments. Furthermore, body scanning [38] and additional garment modeling strategies can be employed to eventually minimize development risks in smart garment design process.

1.6.4 Privacy and Control

Privacy has been an important topic since the advent of pervasive computing. The more data-managing devices move to the background, the less information do users receive upon potential privacy violations. Since smart textiles have the potential to become indistinguishable from regular clothing, user privacy is an important criterion, which needs to be considered during the whole design process (cf., Langheinrich's work on privacy by design [39]). Textiles are closely connected to the user's body and provide sensor data and various information, hardly available with current computing devices. The degree to which the user's privacy is protected will determine how accepted smart textiles will be in the future. Thus, smart textiles need to allow the user to stay in control of the data. The user should decide which information is shared with whom and this process needs to be as transparent as possible.

1.6.5 User-Centered Evaluations

While most smart textiles are nowadays evaluated with regard to their technical soundness, taking the user into account during the evaluation process has become best practice in other areas of research. For current smart textile research, the user role during evaluations still needs to grow. Starting evaluations by exploring the technical feasibility allows researchers to rapidly develop novel textile systems. Since the development of smart textiles has matured, a subsequent step in evaluating smart textiles needs to be taken. Applying, for instance, the user-centered design process [40] to the development of smart garments can be used to refine requirements and presents—in return—novel challenges for the textile system design.

Summary

In this chapter, the foundations important for smart textiles and garments are introduced. In particular, this chapter includes the following:

- Definition of wearable computing, smart textiles, and context.
- History of wearable computing and smart textiles.
- Development of smart textiles and garments.
- Evaluation methods for smart textiles.
- Challenges and opportunities for smart garments.

Acknowledgements This chapter was supported by the European Union 7th Framework Programme under Grant Agreement No. 323849.

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Chapter 2
Precision Fabric Production in Industry

Karl Gönner, Hansjürgen Horter, Peter Chabrecek and Werner Gaschler

Abstract This chapter describes different types of textile structures suited for smart textiles and gives a short overview of production methods for weaved, knitted, and nonwoven fabrics.

2.1 Introduction

Textiles are the basic material for all kinds of smart garments or textile electronics. Therefore, the variety of materials usable for smart or electronic purposes is almost as wide as the variety of textiles commonly available in the textile industry. Many of these textiles show very different properties resulting in a wide choice according to varying operational demands. The right combination of raw material, production process, machine parameters, and finishing conditions is crucial for the suitability of any product for special purposes.

The main methods to produce a textile plain out of one or more yarns or fibers are weaving, knitting (warp and weft), as well as using one of several nonwoven processes.

For smart textiles, applications, especially weaving and knitting, have received widespread interest since they can generate large-area precision textile surfaces.

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© Springer International Publishing AG 2017
S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_2

2.2 Precision Weaving Technology

Precision fabrics represent an attractive medium for electronic integration as they are very precise and can be automatically produced creating large-area surfaces with specific conductive properties at very high speeds. For example, typical industrial weaving machines are capable of fabricating more than 106 square meters of fabric per year in micrometers precision. Subsequent development in this field has seen a drive to integrate the desired functionalities inside the fabric architecture. This implies creating smart textiles in which electronic sensors and output devices can be introduced at the fabric level.

Precision fabrics are produced by a weaving process. Weaving is the oldest method of making yarn into fabric. While modern methods are more complex and much faster, the basic principle of interlacing yarns remains unchanged. Weaving is a process that interlaces two perpendicular sets of yarns, called the weft and warp. Weaving is done on a machine called loom. Before the weaving process is started, the loom needs to be set up with warp yarn. During the weaving process, some of the warp yarns are moved up and the rest are moved down using a "harness," and the opening created between the up- and down-warp yarns is called the shed. The raising/lowering sequence of warp yarns gives rise to many possible weave structures. In comparison, the weft yarns are rolled around several spools (known as bobbins) and inserted into the textile architecture perpendicularly to the warp yarns by a device called shuttle.

Figure 2.1 shows a close-up of the central weaving region in a weaving machine. Warp yarns are spanned parallel to each other on a loom and "pulled" through the weaving machine at a constant rate.

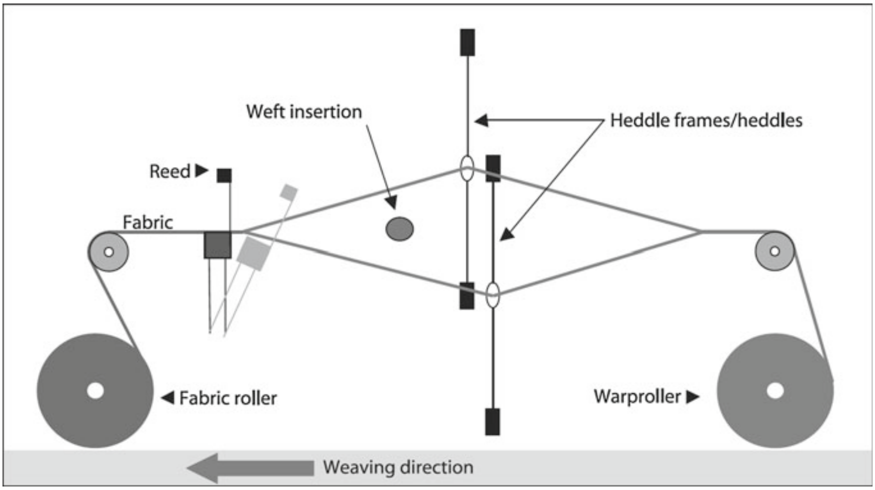

Fig. 2.1 Scheme of a weaving machine (Image courtesy of Sefar)

Some of these machines carry the weft yarns across the loom at rates in excess of 2,000 m/min. The resulting fabric is particularly strong. There are three basic weaves with numerous variations. The plain weave, in which the filling is alternately passed over one warp yarn and under the next one, the twill weave, in which the yarns are interlaced to form diagonal ridges across the fabric, and the satin weave, the least common of the three, produce a smooth fabric with high sheen.

Most fabrics are finished to make them look and feel more attractive. Finishing processes may consist of washing, thermosetting, winding, and optical control of the resulting fabric. This is the final step in the manufacturing process.

Although such "precision fabrics" are not different from standard fabrics in principal, they must have certain physical, chemical, and functional properties that are connected with their intended application. They have to be dimensionally stable, with precisely defined mesh size, with very narrow tolerances to temperature or UV radiation changes, solvent resistant, etc.

Precision fabrics for electronic applications are designed in such a way that the conductive capabilities are embedded during manufacturing, e.g., weaving of metal wires. A non-conductive fabric usually consists of polymer yarns such as polyester or polyamide, whereas conductive components ideally utilize good conductors such as silver and copper wire either in extremely thin strands or as metallic coating of polymer fibers. Polymer threads form a carrier frame, called substrate, for the conductive threads. In this kind of fabric, conductive layer and substrate are embedded into each other.

The weaving technique can also be differentiated according to the number and arrangement of the thread systems. A single-surface fabric is called a single-chain/single-weft sheet. But also multiple warp or weft systems can be provided which are fixed together and will be arranged one above the other (Fig. 2.2). Such fabrics are called two chain/one-weft or one chain/two-weft. These are reinforced fabrics such as double weave, hollow fabric.

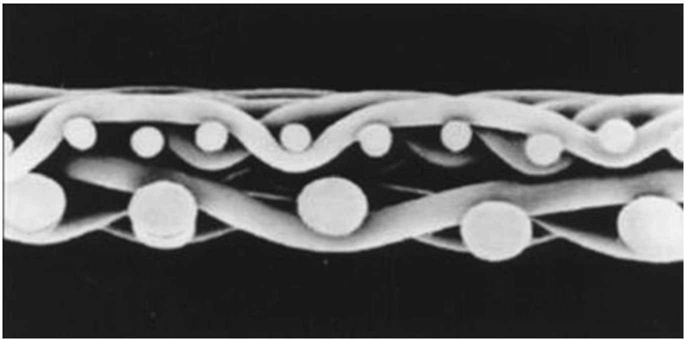

Fig. 2.2 Double layer fabric (Image courtesy of Sefar)

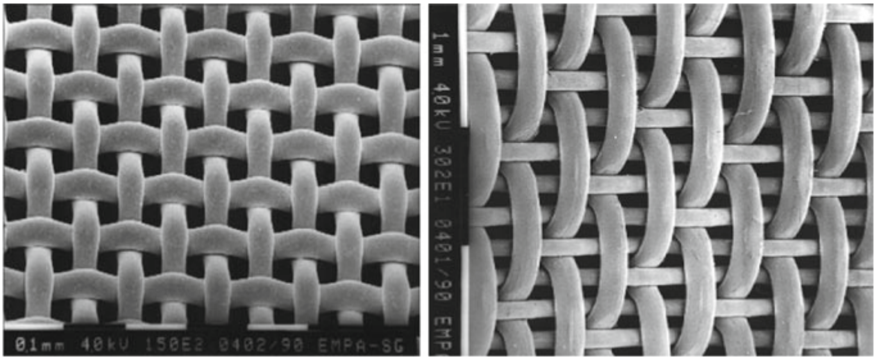

Fig. 2.3 Pictures of fabrics with different bonding types (Image courtesy of Sefar)

There can be several bonding types in a fabric. It is referred to as equilateral bonding when the number of warp and weft cross-link points is the same on both sides of the fabric, and a fabric with more cross-link points on one side is called one-sided fabric (Fig. 2.3).

2.2.1 Quality Criteria for Precision Fabrics

The crucial difference between standard fabric and precision fabric is the demands that are made regarding the quality of the fabric: Precision fabrics are characterized by exactly defined, reproducible, and systematically controlled fabric properties. These requirements mainly concern the geometry of the fabrics but are also defined by application-oriented properties, for example:

- Fiber count per cm (weave density),
- Size, regularity, and squareness of the meshes,
- Air permeability,
- Shrinking and stretching behavior,
- Regularity of the visual aspects, including color regularity,
- Cleanliness and biocompatibility (especially in personal use or in medical application, etc.),
- Placement and thickness of the conductive wires (especially in the electronic industry, sensors, e-meshes, etc.),
- Regularity of the distances between many parallel woven conductive stripes (stripe pattern), and
- Long-term stability, washability, etc.

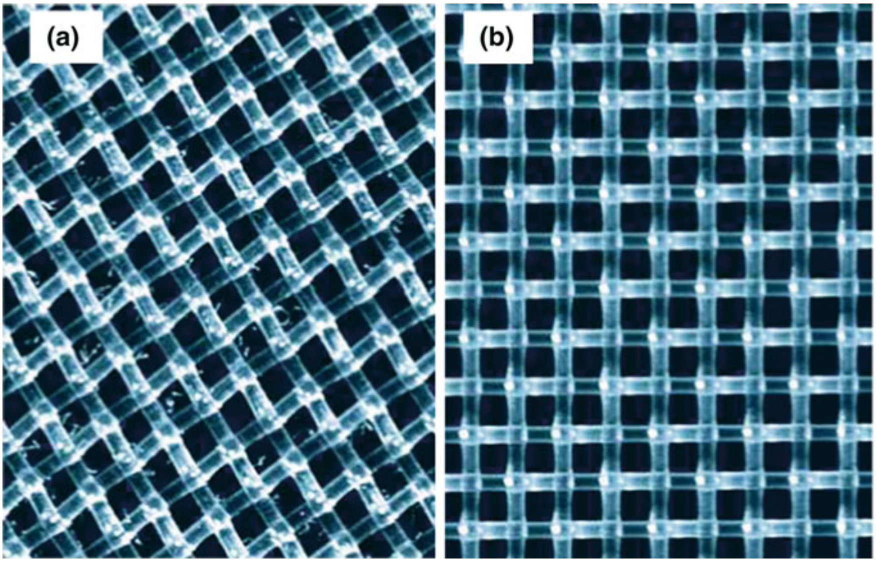

Fig. 2.4 The contrast clearly shown between a standard fabric **a** and a precision fabric **b** having a precise, reproducible mesh size and weave geometry (Image courtesy of Sefar)

These requirements affect all phases of the production process from the choice of the raw material to the production of the fabric in the weaving mill and also the finishing and making-up processes. For this reason, only yarns that display a high regularity are possible for use in the production of precision fabric. This means the diameter of a fiber may differ from the stated value only by one percent along its entire length. Narrow tolerances also apply to pore sizes, the fabric thickness, and the regularity of the surface.

If special physical or chemical properties are demanded in the application, these have to comply exactly with the specification. To guarantee the required precision and reproducibility of fabric properties, rigorous quality controls are indispensable during the entire production process (Fig. 2.4).

Several examples for precision fabrics have been used in the EU-funded Simple Skin Project. The designs show varying stripe patterns of conductive and non-conductive components in Sect. 2.3. Together with other textile materials, each type of fabric can be combined to resistive pressure sensors (here with Sefar Carbotex fabric, of Sefar and ITV) (Figs. 2.5 and 2.6), can be used as capacitive sensors on the human skin (capacitive wristband of DFKI and ITV), or can be used as base for contact pads (pocket connector of ETH Zurich and ITV).

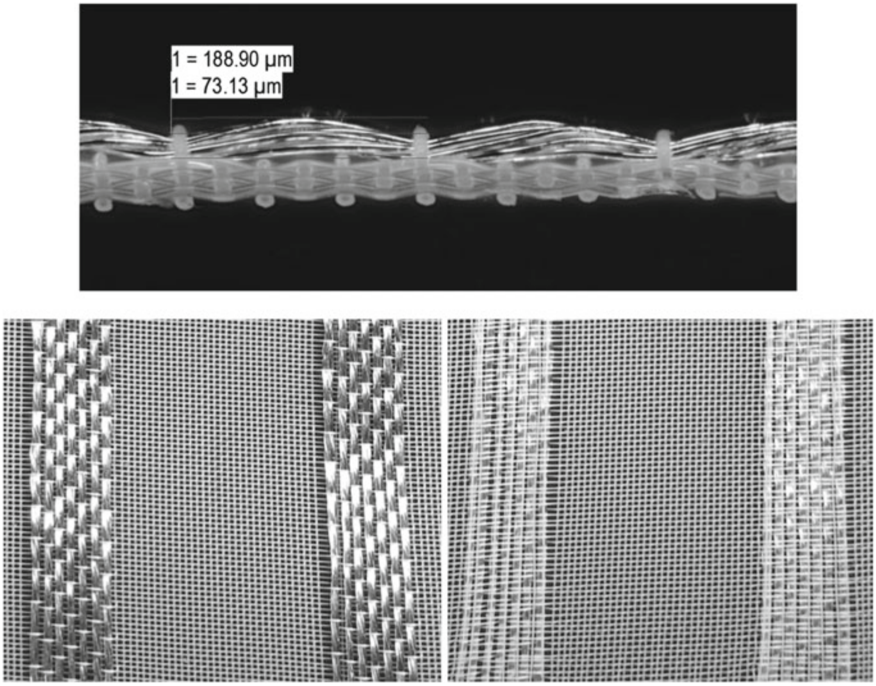

Fig. 2.5 Sefar precision fabric from side, from *top*, and from *bottom* (Images courtesy of Sefar)

2.3 Knitting Technology

General properties of both knitted and woven textiles are low weight, portable, and skin comfort (e.g., breathability) compared to standard electrical and optical systems. Woven fabrics are usually durable and provide a more stable shape than knitted fabrics. This allows for more accurate placement of individual yarns and more dense integration of electronic and optical functionalities. Furthermore, woven textiles are relatively strong and deformation resistant, whereas knitted fabrics are characterized by high elasticity and elongation, good conformability in mechanically active environments (e.g., textiles used in clothing), as well as good air permeability, thermal retention, and humidity transport properties.

Knitting is a technique for producing a mostly two-dimensional fabric made from a one-dimensional yarn or thread. Knitted fabric consists of a number of consecutive rows of loops, called stitches. Knitted fabrics can be produced of all kinds of yarns: natural materials such as wool or cotton, synthetic materials such as PES or PAC, or even spun metal or carbon fibers. According to the thickness of the processed yarns and the gauge of the knitting machine, the knitted stitches may show a wide variety of shapes and sizes. Compared to woven structures, knitted fabrics can be easily deformed and therefore adapt to different shapes according to their use. This makes

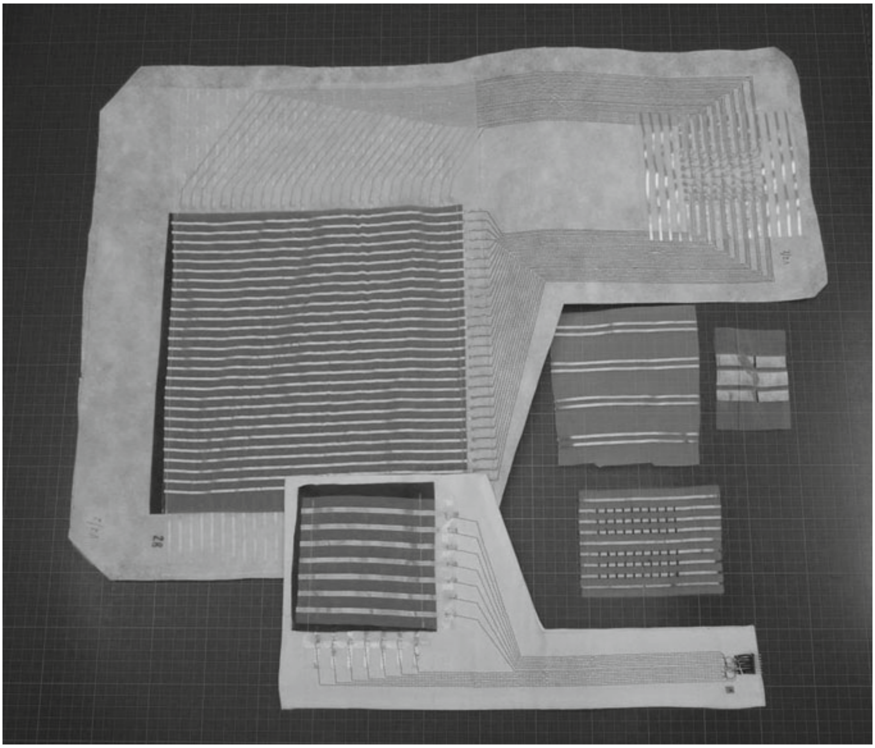

Fig. 2.6 Several types of conductive universal sensing fabrics from Sefar, on the *left* side two textile pressure sensors (Image courtesy of ITV Denkendorf)

them favorable for the clothing industry to fit the varying shapes of the human body as well as for the automotive industry to fit smoothly on 3D surfaces. Knitted fabrics can be produced on circular knitting machines or on flat knitting machines.

Circular knitting machines offer usually high production capacities of relatively simple structures, mostly plain fabrics. After textile finishing processes, these fabrics can be cut and sewn according to the requirements of their intended use. Recent generations of body wear circular knitting machines are capable of producing highly sophisticated shaped jacquard garments.

Flat knitting machines are less productive than the circulars. But they offer a high versatility in terms of theoretically unlimited pattern, shape, and structure possibilities. Different shapes and structures can be produced in knitted fabrics, with individually shaped areas of different materials including conductive and non-conductive properties (intarsia knitting), connecting threads between these areas, and other useful features.

The production quantities of the flat machines are much less than those of the circulars due to the limited number of threads that can be processed simultaneously. But as the flat knitted products can be designed and constructed very closely to the

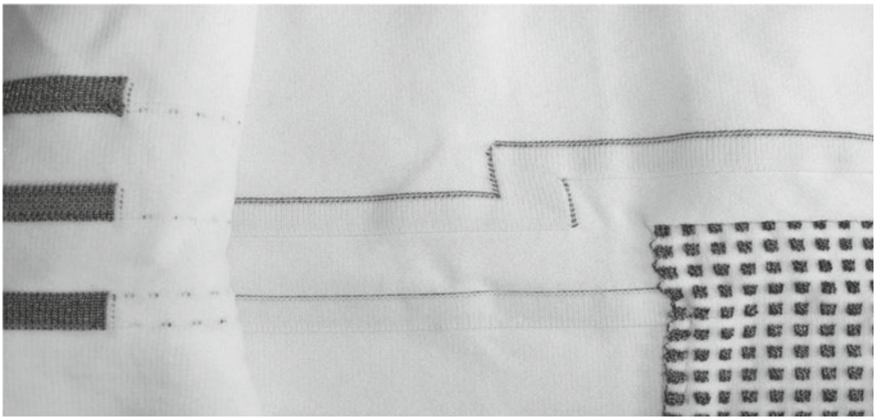

Fig. 2.7 Flat knitted intarsia structure with conductive and non-conductive yarns (Image courtesy of Stoll)

Fig. 2.8 Detail of intarsia structure (Image courtesy of Stoll)

later purpose and shape of the textile product and therefore save expensive materials as well as manufacturing costs in the following production stages, the production of complicated products on flat knitting machines can be highly competitive (Figs. 2.7, 2.8, 2.9, 2.10 and 2.11).

2.3.1 Warp Knitting Technology

Warp-knitted fabrics consist of interconnected loops, but the yarn does not follow the rows of stitches, and in warp-knitted fabrics, the yarn forms the wales. The production of warp-knitted fabrics starts with the preparation of a warp like in weaving. Warp knitting is highly productive. Modern techniques allow to feed different types of yarn

Fig. 2.9 Flat knitted fabric with laid-in wire threads (Image courtesy of Stoll)

Fig. 2.10 Flat knitting machine CMS 530 HP (Image courtesy of Stoll)

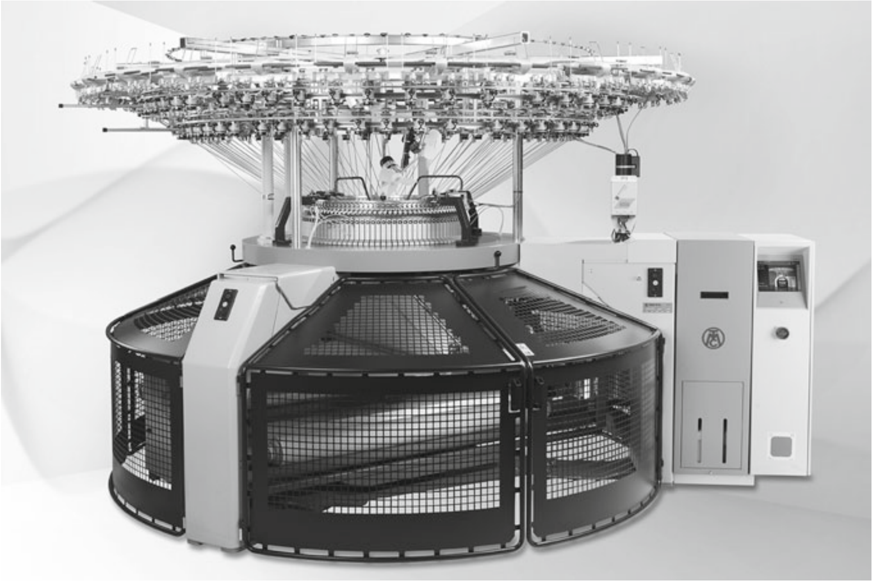

Fig. 2.11 Circular knitting machine (Image courtesy of Mayer and Cie)

into the fabric, even in weft direction. This can be used to produce partially conductive fabrics. Because the production machinery for such fabrics is very expensive and the efforts to run new patterns are very high, the method of warp knitting is appropriate for production purposes, but not for generating first prototype samples (Figs. 2.12 and 2.13).

2.3.2 Weft Knitting Technology

Weft knitting produces fabrics which are closely comparable to the knitted fabrics. The difference is made by the production process, but not by the product. Particularly, in intarsia knitting, weft knitting offers possibilities comparable to flat knitting.

2.3.3 Fleece

Fleece is a knitted fabric which was mechanically treated to produce a hairy surface. Compared to the basic fabric, a fleece has better thermal insulating properties due to the higher amount of air held within the fibers of the fleece.

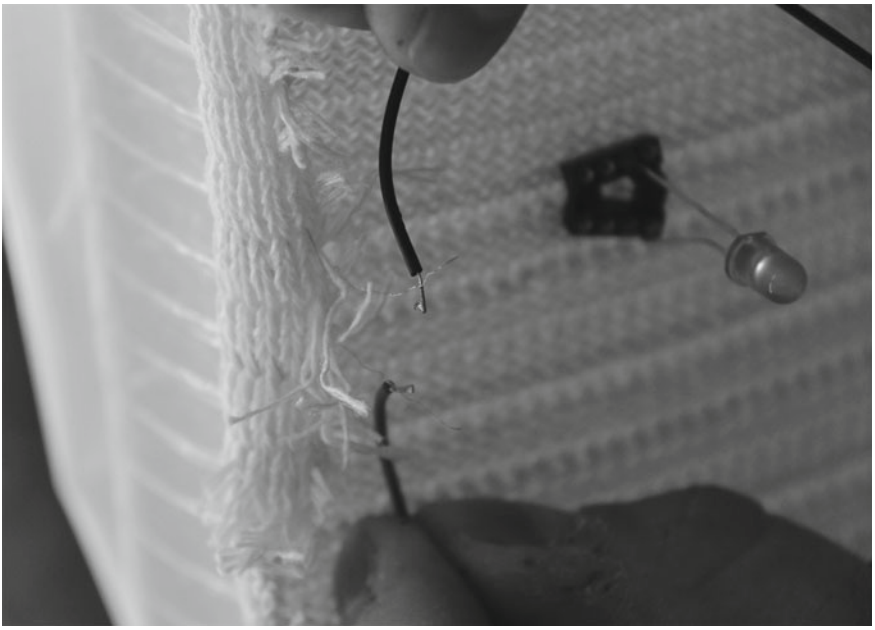

Fig. 2.12 Spacer fabric with conductive yarn, demonstrated with an activated LED (Image courtesy of Karl Mayer)

2.4 Nonwovens

Nonwovens consist of fibers which have not been spun to yarns. These fibers (filament or staple) are spread on a surface as evenly as possible and usually aiming at homogenous properties. There are many different techniques to produce nonwoven structures with the main differentiation between staple nonwovens and spunlaid nonwovens. There are several mechanical processes in cards or using aerodynamic or hydrodynamic principles. The properties of nonwoven fabrics depend on materials such as natural fibers, PP, PET, or glass. The bonding of these fibers can be achieved by applying physical influences like heat, mechanical influences such as needles or water jets, or chemical processes.

They can be produced as flat two-dimensional structures as well as in complicated shapes in three dimensions. Due to the irregular position of the fibers, it is hardly possible to produce fabrics with geometrically exactly defined property changes during production.

The nonwoven fabrics can be used as base layer for the integration of conductive yarns and of electronic components (Fig. 2.14).

A further possibility to bring electrical conductivity into a fabric that may be a nonwoven is the technique of laser direct structuring (LDS). Using fibers spun out of a special material, the textile fabric has to be exposed to a laser treatment where elec-

Fig. 2.13 Warp knitting machine HDR 6 (Image courtesy of Karl Mayer)

Fig. 2.14 SMD electrically and mechanically connected with conductive thread (Image courtesy of ITV Denkendorf)

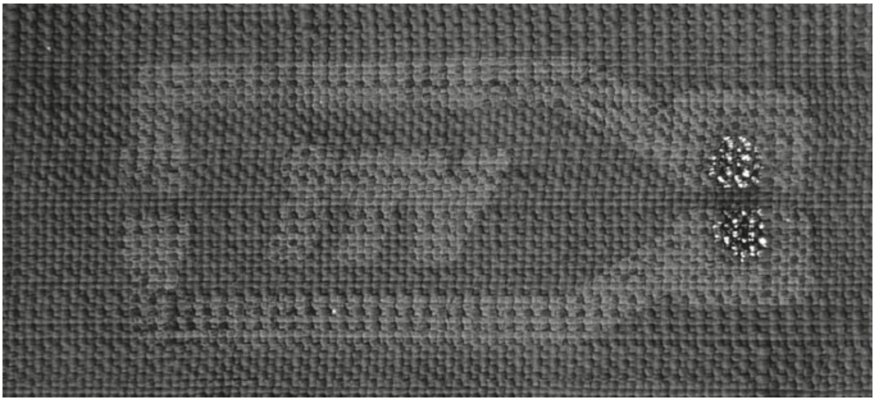

Fig. 2.15 Fabric with conductive areas after the LDS process (Image courtesy of ITV Denkendorf)

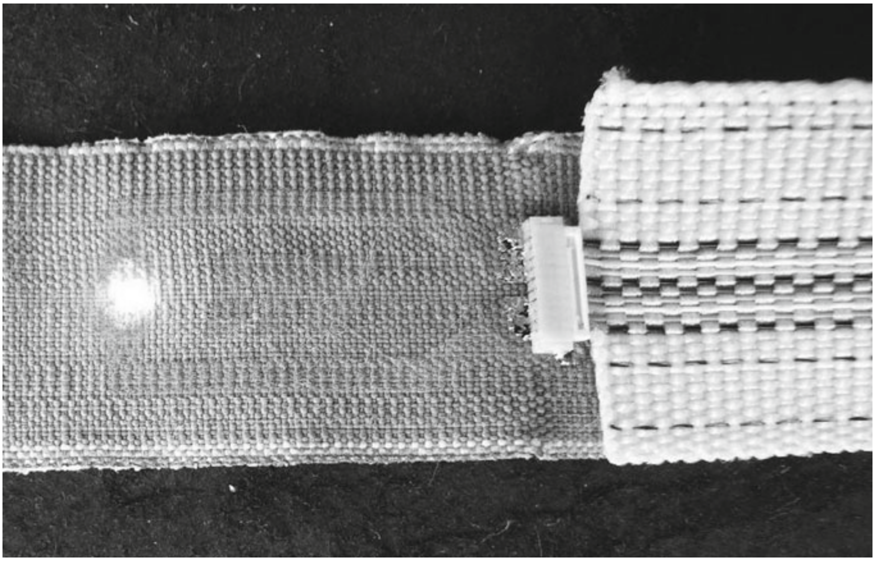

Fig. 2.16 Electrically connected fabric with activated LED (Image courtesy of ITV Denkendorf)

trically conductive areas are required. After a sophisticated chemical process, these areas are metallized with a thin copper coating and therefore conductive (Figs. 2.15 and 2.16).

This new technology offers the chance for new application areas especially on three-dimensional nonwoven construction elements.

2.5 Conclusion

The textile base and its properties cover a wide area of applications in smart textiles. They are of crucial importance for the performance of the smart textile product. The combination of textile behavior such as tactile grip, dimensional stability, breathability, washability, and many other parameters with other functional requirements—especially conductivity and further electrical properties—makes textiles suitable for many different application areas. Some of these properties are difficult to bring together in one fabric, especially the elasticity of many textiles is hard to combine with the good electrical properties of all metals. The low elasticity and poor flexural properties of metals carry the risk of early failure under everyday conditions. Different techniques such as weaving, knitting, and some nonwoven processes allow the production of textiles with a wide variety of properties and production costs.

During the last few years, big steps of progress have been made concerning the use of textiles for smart applications, but the big commercial success lies still ahead.

Summary Box

In this chapter, we provide an overview of current industrial production techniques for textiles. In particular, we focus on the following types of fabrics:

- Weaved fabrics,
- Knitted fabrics, and
- Nonwoven fabrics

Acknowledgements Acknowledgments are made to
- ITV Denkendorf: Carsten Linti and Stefan Loy, for their contributions concerning the LDS technology, for photographs of sensors and fabrics
- SEFAR AG: for photographs and picture
- H. Stoll AG and Co. KG: for photographs of flat knitted fabrics and flat knitting machine
- Mayer and Cie. GmbH and Co. KG: for photograph of circular machine
- Karl Mayer: for photographs of weft-knitted fabric and weft knitting machine

Acknowledgements are also made to
- the European Commission for funding the FP7-project SimpleSkin, during which this chapter was written,
- the Bundesministerium für Bildung und Forschung for funding the project, "Laserstrukturierte textile Schaltungsträger - LaTeSt", Förderkennzeichen 16SV5064

Further Reading

- Von der Faser zum Stoff: Textile Werkstoff- und Warenkunde Taschenbuch–2006, by Ursula Völker (author), Katrin Brückner (author) ISBN-13: 978-3582051127
- Textiles (11th Edition) by Sara J. Kadolph (author) ISBN-13: 978-0135007594

Chapter 3
Textile Pressure Force Mapping

Bo Zhou and Paul Lukowicz

Abstract While much effort in smart textile technology development has been put on acquiring biomedical signals such as ECG/EMG or tissue bioimpedance, an important alternative is mapping the pressure which is applied to the textile substrate itself. The modality has inspired researchers to instrument a wide variety of daily items and wearable garments for interactive controlling and activity monitoring in the recent years. To offer a guideline for implementing such systems, this chapter will introduce textile-based pressure force mapping sensing technology, from comparisons with other smart textile technologies to sensing principles, driving circuitry and finally several application examples.

3.1 Introduction

Pressure force mapping sensors have been a very common tool in the industrial design sector for measuring structural shapes or ergonomics of the products.

The technology behind force mapping is typically a grid of individual force sensor elements. Force sensors can be implemented based on various principles such as piezoresistive, piezoelectric, piezomagnetic, capacitive, magnetic (Hall effect [1]), and optical [2]. In principle, sensors from any of these sensing modalities can be arranged into a two-dimensional grid, and force mapping can be realized by addressing each of the element. The arrangement can be through either the digital interface, where each element has its own analog circuitry, or shared electrodes, where the measurement circuitry is out of the construct of sensitive materials. The former has complex implementation requirements, but every sensing element is isolated by nature, while the latter has structural simplicity, but cross talks and leakage of sensitive elements that share electrodes become an issue to be dealt with.

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S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_3

Most of the commercially available pressure force mapping sensors [3] are based on materials that change their electrical property (usually electrical resistance) with deformations that are caused by external pressing forces. For electrical resistance-based force mapping, the material is usually a carbonized polymer sheet. The electrodes are typically metallic materials deposited on flexible polymer substrates, and the process is similar to the current flexible PCB technology.

Capacitive-based force mapping has also been studied, such as the work in [4], where Kim et al. produced a 20-by-20 array of capacitive cells which is measured with 21.5 kHz stimulant for each cell. And the prototype is possible to be used as a force sensing touch screen. It is worth mentioning that, by the time of writing, the force-sensitive touch screens in several consumer electronic products are mostly a combination of capacitive touch pad/screen with only binary per point mapping output [5], together with one or several individual force sensors that measure the force onto the platform which hosts the touch screen [6, 7]. They essentially combine the information of 'where the touching points are' and 'how much overall force is applied on the screen,' which is different from measuring the force on every individual point.

The nature of the sensing materials, that are mostly polymer thin films, makes many force mapping sensors unsuitable for wearable and real-life ambient systems, which requires the sensors to be comfortable to use in terms of air permeability, softness, flexibility, washability, etc. Sensors constructed from textiles are most suitable for those comfort factors.

3.2 Major Features, Pros, and Cons

As wearable garments or smart objects to be designed for long-term operations, several practical factors need to be taken into consideration when making the design choices of sensing modalities, such as extreme movement, sweating, and comfort. Compared with other smart textile sensing technologies, pressure force sensing has its unique advantages such as no direct body contact, less muscle-specific tailoring, and robust against sensor placement shifting.

Techniques such as ECG, EMG, and other bioimpedance or bioelectricity sensing require a direct electrode–body contact to acquire the signals carried by the tissue's electrolyte. The electrical properties of the electrode–body contact, which can be caused by factors such as wetness and sudden movement, influence the signal quality on unignorable levels [8]. This has been addressed in recent works to develop more comfortable electrodes that are suitable for long-term monitoring [9]; in several studies, [10, 11] contactless electrodes, using capacitive coupling for ECG/EMG measurement, are also developed. Capacitive tissue activity sensing [12] also does not require direct electrode–skin contact. In studies such as [13], similar measurement method is used for sweat rate measurement, and it is obvious that capacitive sensing can be influenced by wetness factors such as sweating and body fluid; however, evaluation on whether the influence can be ignored or isolated lacks sufficient literature.

It remains interesting to see how the new developments in contact electrode-based sensing modalities would benefit in real applications.

Pressure mapping technologies do not require an electrode–body contact, since the measurement is derived from the structural changes of the sensitive material itself. Therefore, the sensing elements can be isolated from the skin with either additional regular textile layers or direct isolation coatings to avoid any complications from electrode–skin contact.

In general, pressure mapping is easily scalable in terms of sensing channels; this is mainly because of the simplicity in the measuring structure (as explained in Operation Principles). In comparison, capacitive tissue activity sensing requires several stages of amplifiers for each analog channel [12], and bioimpedance has a specific combination of electrodes of unique functionalities for each measurement setup [8]; in both cases, the scalability is limited by the complexity of the analog front end.

For different activities, electrodes need to be placed at specific locations for techniques that directly measure tissue electrical property variations. Pressure mapping, on the other hand, does not need specific tailoring of individual elements, since the matrix can cover a larger surface. And this further addresses the sensor shifting problem, since as long as the matrix covers the targeted area, one or several elements will be close to the sources of activities (e.g., muscle peak and curvature of external objects).

Pressure mapping offers a big amount of information about people's activity, it also has several drawbacks, such as higher data processing/transmission requirements, the need of special conductive and/or dielectric materials, relatively complex sensor structures, and the sensor characteristics. These drawbacks need to be taken into consideration while choosing the most suitable modalities for specific applications.

3.3 Operation Principles and Implementation

There are two major types of textile pressure mapping technologies separated by the basic physical principles: resistive and capacitive. This section will introduce the basic theory of operation and implementation examples of both types and also mention several novel sensing principles.

3.3.1 Resistive-based Pressure Mapping

The core principle of electrical resistance-based pressure mapping is the special property of electrically conducting polymer composites (ECPC), that their deformation, which could be caused by either tension or pressure, will cause its electrical impedance in the vicinity of the deformation to change [14]. ECPC are typically a colloidal form of conductive particles (e.g., carbon black, metal, and metal oxide particles) dispersed into polymer matrix [15]. Deformation will change the polymer matrix's molecular structure so that the suspended conductive particles (filler particles) form new conductive paths, which in turn change the local electrical impedance on the supermolecular level [16]. Under 20−70 °C, the temperature dependency of carbon black polymer is found to be very weak; therefore, the measured resistance variation of the composite can be practically directly linked to the pressure and tension [17].

Measuring the resistance of the ECPC materials is a basic circuit problem. The simplest implementation is a single leg voltage divider, while in precision measurement cases, the Wheatstone bridge is mostly used. A common consensus is that Wheatstone bridge offers more accurate measurement than single leg voltage divider and this is however conditional. It is important to explain this basic problem because for mapping the resistors in a matrix, especially for wearable applications, the footprint of electronics is an important topic. Take the circuits in Fig. 3.1, for example, in the voltage divider, the variable resistance R_x is

$$R_x = \left(\frac{1}{1 - \frac{V_{out}}{V_{in}}} - 1 \right) \times R_1 \tag{3.1}$$

And in the Wheatstone bridge, R_x is

$$R_x = \left(\frac{1}{\frac{R_2}{R_2 + R_3} - \frac{V_{out}}{V_{in}}} - 1 \right) \times R_1 \tag{3.2}$$

The measurement error comes from the physical analog–digital converter's error, which is essentially the error of V_{out}. As both Eqs. 3.1 and 3.2 describe a nonlinear relationship between R_x and V_{out}, the error of R_x, which is cast from V_{out}, varies in different ranges. For a known circuit, the value of R_1, V_{in} of Eq. 3.1, and R_1,

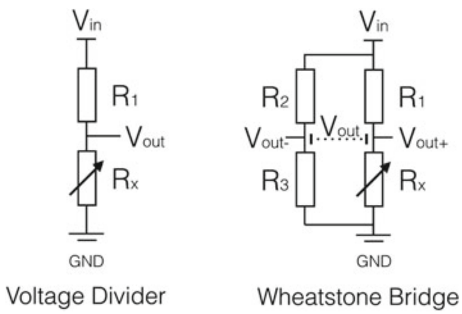

Fig. 3.1 Circuit diagram of a voltage divider and a Wheatstone bridge

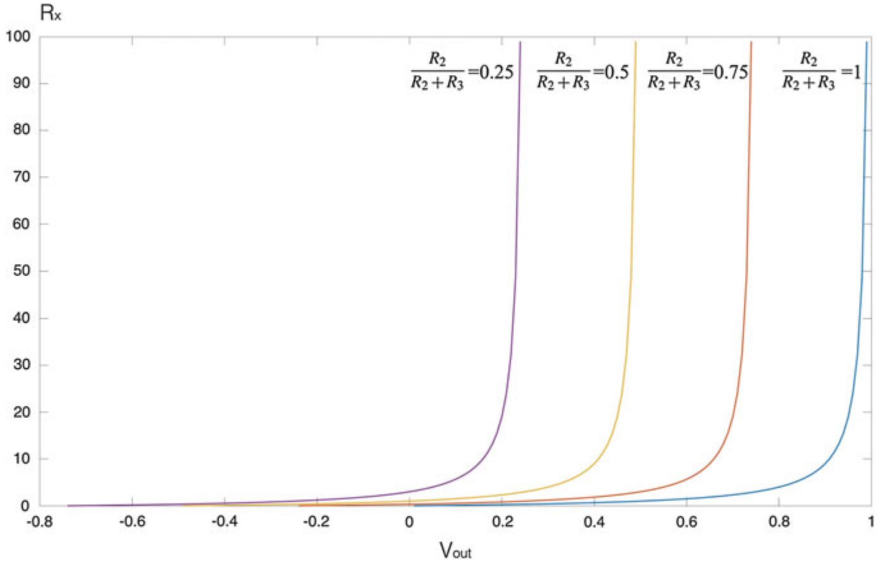

Fig. 3.2 $R_x - V_{out}$ plot of different $\dfrac{R_2}{R_2 + R_3}$ ratios

R_2, R_3, V_{in} of Eq. 3.2 is constant (if applied stable voltage V_{in}). Apparently, from Eq. 3.2 to Eq. 3.1, the only difference is $\dfrac{R_2}{R_2 + R_3}$. We assume $R_1 = 1$ and $V_{in} = 1$, and investigate how changing R_2 and R_3 would have an impact on the error of R_x. Equation 3.1 can be taken as an exception of Eq. 3.2, where R_3 is zero. Since practically both V_{out+} and V_{out-} are of range $(0, V_{in})$, we can get the meaningful range of V_{out} to be of

$$\left(-\frac{R_3}{R_2 + R_3}, \frac{R_2}{R_2 + R_3}\right)$$

We then take other three ratios of $\dfrac{R_2}{R_2 + R_3}$ as 0.75, 0.5, and 0.25, and the plot of $R_x - V_{out}$ is shown in Fig. 3.2, from which it is obvious that adjusting R_2 and R_3 will only have the effect of shifting the $R_x - V_{out}$ curve, without 'bending' the curvature. This means with different R_2 and R_3 combinations, the nonlinear circuit will have different sensitivities in a particular resistance range.

Wheatstone bridge practically introduces another voltage divider in parallel with the measurement leg. This path first offers the adjustment of the reference voltage of the analog–digital converter and second offers an additional current path from the voltage source to provide a more stable voltage regulation and preventing sever voltage drop [18]. However, modern reference voltage ICs [19] usually tolerate very low souring current on its output for better noise performance; therefore, if the actual ADC in the system uses such precision voltage reference, the bridge structure should

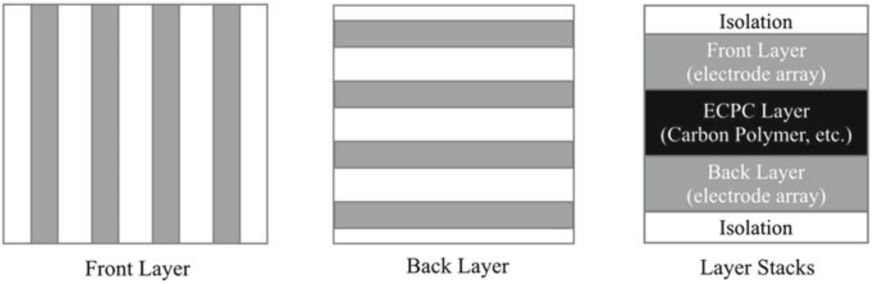

Fig. 3.3 The electrodes and layer arrangement of a simple resistive pressure mapping sensor

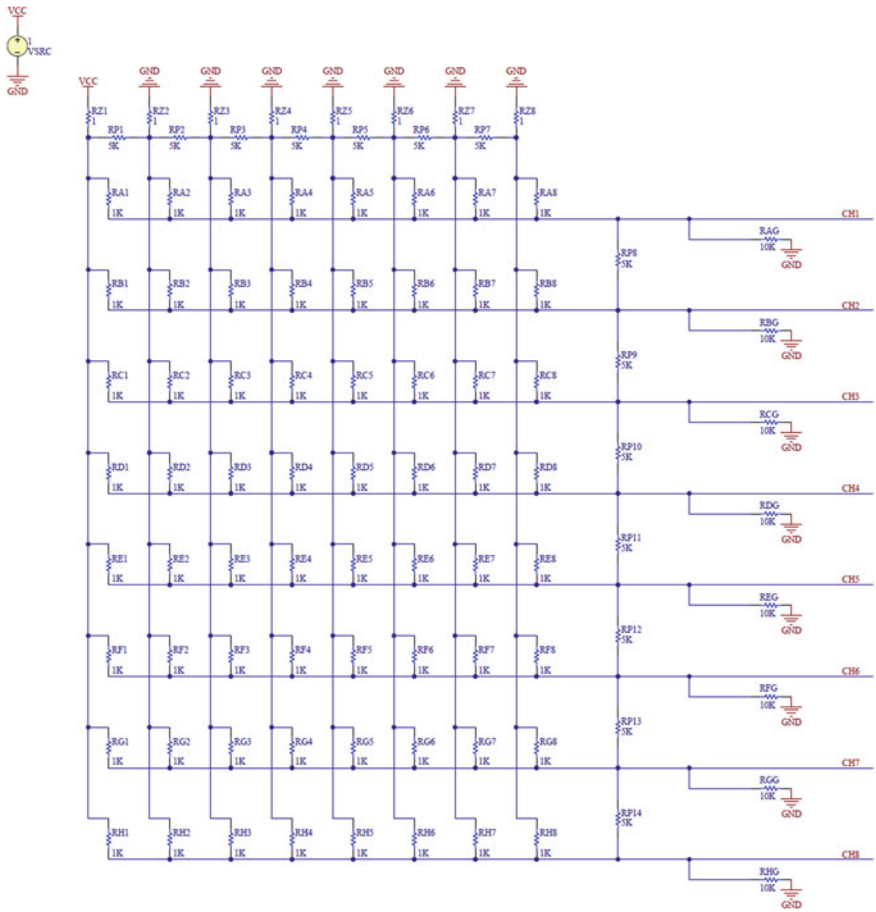

Fig. 3.4 Circuit network of a 8-by-8 resistor array

not be used. And modern low dropout voltage regulators [20] have mostly eliminated the need for an additional current path to achieve a stable voltage regulation.

Wheatstone bridge shows its advantages in the implementation of strain gauges' circuitry: As strain gauges are temperature-dependent, a dummy strain gauge can be put at the same leg (R_1) as the variant strain gauge is to cancel the thermal dependency; to improve the sensitivity, a pair of strain gauges can be placed on the top and bottom side of one flexible substrate; therefore, the pair changes reversely, and the sensitivity of the strain measurement can be doubled while canceling the thermal dependency at the same time; replacing the other leg (R_2, R_3) with a reversed pair of strain gauges on the same flexible substrate can further improve the sensitivity [21–24].

A basic bridge would require three times the number of passive components without contributing to the measurement quality. Therefore, a single leg voltage divider is sufficient to measure the resistance of ECPC for force mapping.

To measure the resistance distribution of the ECPC material, two groups of electrode can be applied on both sides of the material as shown in Fig. 3.3. For resistive mapping sensor matrix layouts with shared electrodes, the entire sensor element array is a connected network. Therefore, while attempting to address any individual sensor element, the elements that share the same electrodes will have an influence on the targeted element and vice versa. Figure 3.4 shows an ideal network of 8-by-8 dimension, where $RA1$ to $RH8$ represent the local resistance of every cross section, and they decrease as the applied pressure increases. Since on the same side of the ECPC material between adjacent parallel electrodes, there will also be a resistance, which is larger than the cross-sectional resistance, and RPx represents such parasitic resistance. During the operation, VCC is enabled at one column at a time, and the

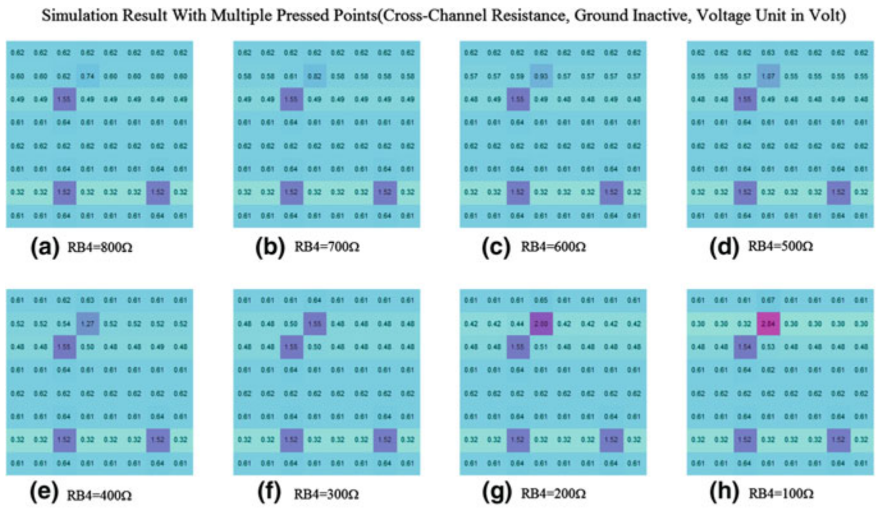

Fig. 3.5 Simulation result of changing resistor RB4 in the network of Fig. 3.4. Every value is the voltage reading that corresponds to the resistor array positions in Fig. 3.4

voltage values can be read out at CHx; a complete scanning of such sequence yields a 2D 'frame' of the voltage values, which is therefore an equivalent measure of the network's resistor values. Figure 3.5 shows a simulation result with three sensing resistors ($RC3$, $RG3$, and $RG7$) already altered (being pressed), and decreasing the resistance of $RB4$. From the result, it can be seen that both the distribution and changing values of the resistor network inflect the two-dimensional voltage readout. It is also visible that a changing resistor influences the entire row; this is because, for example, when measuring the voltage of $RC2$, the equivalent grounding resistor of the voltage divider is not simply RAG, but every resistor from the network between measuring node $CH1$ and GND. Such influence can either be removed by solving a mathematical model of the circuit, or more simply removing the minimum value of every row on the software during signal processing.

3.3.2 Capacitive-based Pressure Mapping

To measure a capacitance, an AC signal is needed (square wave, sinuous wave, etc.), and the change of the capacitor's value will influence the frequency response. The frequency needed depends on the actual capacitance range [25]. Therefore, for entirely unknown capacitance, the frequency needs to be determined empirically (typically by switching several frequency ranges) [26]. And to measure the frequency response using typical mid-range embedded ADCs, an enveloping circuit (peak detection circuit) is needed, and the minimum time required needs to be larger than the period of the stimulant's frequency [27]. Thus, in most capacitive-based sensory, the range of the capacitors needs to be predetermined and the actual performance (in terms of scanning speed) of the system largely depends on the frequency used.

The basic physical structure of capacitive-based pressure mapping sensors is two parallel conductive plates separated with a flexible, non-conductive layer as the dielectric spacer. To form a two-dimensional grid, designs similar to the previously mentioned resistive matrix, two perpendicular groups of parallel electrode stripes [28, 29], or individual square-shaped textile plates with special wiring layers have both been used [30]. A single-layered textile sensor, in which two directions of conductive yarns are woven into one non-conductive fabric substrate, is developed in [31].

The 'sandwich' layout design as shown in Fig. 3.6, from the work of [29], has significantly less embroidered wiring from the electrodes to the measurement circuit compared with the individual islands design in Fig. 3.7 [30]: in the former, the wirings are directly knitted onto the electrode layer, while in the latter, three layers of fabrics are used specially for the embroidered connections. However, the latter has better isolation from electrode to electrode; in the paper [30], the electrodes are configured as ground and sensor element in a checkerboard pattern to further improve the isolation. In the work of [31], two groups of conductive yarns are woven into one non-conductive textile layer, similar to the layout in Fig. 3.6, but with only one layer of textile composite. It is essentially an improved version from the sandwich struc-

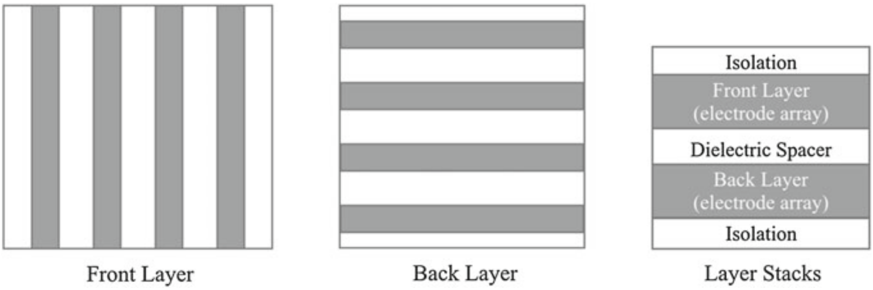

Fig. 3.6 The electrodes and layer arrangement of the 'sandwich' capacitive pressure mapping sensor in the work of [29] with perpendicular *front* and *back* parallel electrode stripes

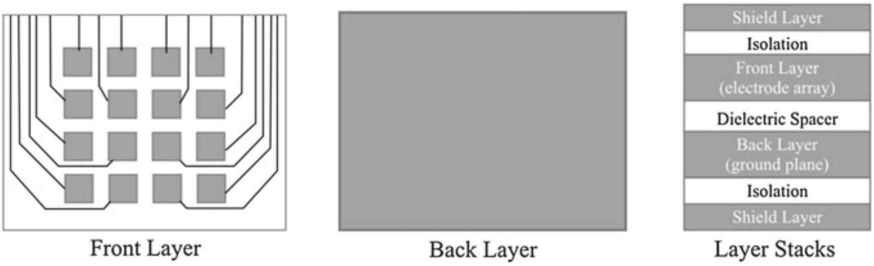

Fig. 3.7 The electrodes and layer arrangement of the 'sandwich' capacitive pressure mapping sensor in the work of [30] with individual *square* shaped electrodes

ture, using knitting pattern to integrate the top and bottom electrodes into one layer of fabric and using the fabric itself as the dielectric. Different from resistive-based pressure mapping, shielding of the sensor array is usually necessary for capacitive sensing [30].

3.3.3 Textile Pressure Mapping of Other Principles

Tomography, by injecting stimulants around the edge of a piece of material (e.g., flexible carbon textile) and by sensing the response on the remaining area of the edge to form an image of the internal structure, can also be used to form a mapping of the electrical property of pressure sensitive materials. The major challenge is the solver algorithm that translates the readings from the edge of the material to the internal electrical property distribution [34, 35]. Electrical impedance tomography has been used to measure the pressure and stretch distribution of textile sensors in [36, 37].

In [38], optical fibers are integrated into a textile substrate to form a crossing pattern. Light is being injected into one end of the fibers and received by phototransistors on the other end. The pressing of crossing fibers will cause attenuation of the light traveling within the fibers.

3.4 Transition from Research to Reality

In previous reviews [39, 40], it was predicted that smart textile sensing will play an important role in ambient and wearable intelligence in the near future. However, as still in the infancy of the technology, much research effort was put on understanding the physical principles and textile fabrication technologies. As summarized in [41], textile sensing technologies has come to an relatively mature stage concerning the fabrication and textile engineering processes. In more recent research projects [42–44], the focus has been clearly shifted from pure textile manufacturing technology into application-based user studies in more specific scenarios; from traditional health care and workplace safety to sport and lifestyle, with considerations such as the balance between performance, footprint, and power efficiency of the hardware and comfort factors enabling the smart textiles to be used daily in reality.

For textile pressure mapping technologies in particular, the major aspect to be addressed is the balance between the amount of channels and the system's performance: With the more information a spacial resolution increment brings, the greater the engineering challenge becomes. For relatively static applications such as posture or ergonomic monitoring, lower refresh rate around 1 Hz or less is sufficient; however, for more dynamic applications such as fitness, dietary monitoring, or other daily activities, the refresh rate to be sufficient is significantly larger (more than 20 Hz); and for extreme applications such as professional sport, above 100 Hz, can also be necessary. More powerful electronics brings the engineering problem to power efficiency and actual size of the hardware, which are particularly important factors for wearable applications.

Using resistive-based pressure mapping sensors developed within EU project SimpleSkin with textile materials from Sefar AG [45], and a scalable hardware architecture which guarantees minimum 40 Hz scan rate with 24 bit ADCs [46], we have explored a series of application scenarios from ambient installations to wearable garments. In [47], a matrix is embedded as a carpet to be installed on the kitchen floor, instead of only registering steps, it was able to distinguish the postures and shift of weight center of the person, which can be further related to which cabinet (both from horizontal positions and vertical positions) the person is interacting with. A larger floor-based matrix is also implemented inside a sport mat in [32]. From the footprint and dynamic pressure changes while people doing various exercises, the type of exercise can be distinguished and repetitions can be counted. In [48], a textile pressure matrix is wrapped around the cover of a couch, which can be used as a unobtrusive touch gesture input interface. A smart tablecloth with a pressure matrix underneath can be used to distinguish the differences of specific cutlery actions such as stirring noodles and cutting steaks; therefore, automatic dietary behavior monitoring can be realized to the level of not only precise time schedule, but also eating speed and food category [49]. As a wearable implementation, a smaller patch of resistive sensor is woven into a stretchable sport band which can be worn on the leg, monitoring the movement of quadriceps muscles [50]. We carried out experiments in a real-life gym environment, and the system is able to tell exactly every second whether the wearer is doing a specific leg exercise, walking, relaxing, or adjusting the gym machines; counting and qualitative evaluation is also implemented by examining the dynamic pressure changes and the pressure pattern's consistency between repetitions.

In [51], a nonwoven fabrics material from Eeonyx is used together with conductive threads to construct a multitouch surface for musical controllers. It is worth nothing that the authors investigated not only several assembling methods, but also a software diagnosis procedure which involves a special scanning sequence to determine if there is any broken (short-circuit and open-circuit) connections, and the diagnosis can be invoked both on start-up and during the operation when there is a unusual data. For wearable applications, this is very helpful since the textile sensors may be broken during operations, from impacts, frictions, twisting, etc.

Other ambient and wearable capacitive-based pressure mapping applications are also seen in [31, 52]. From the above-mentioned evaluation studies, the advantages of textile-based pressure mapping as pointed out in Sect. 3.2 can be further demonstrated. The no skin contact requirement makes it not only suitable for wearable garments, but also suitable for ambient applications for unobtrusive activity monitoring or control input.

3.4.1 Algorithms

As above mentioned, as the hardware part of pressure mapping grows into a relatively mature stage, the focus of research is shifting into application exploring. While pressure mapping can be used as a tool for experts in specific fields to inspect the surface pressure, it is also of great interest to develop machine learning algorithms to detect and recognize activities automatically for computer–human interaction and activity tracking purposes. In specific applications, the algorithms used to extract information about activity may vary, but there are several common approaches to use.

Many of the algorithms described in this section can be found in [32, 47, 49, 50].

First of all, the data format is similar to a image sensor or infrared array sensor. At every data point in time, the sensor outputs a two-dimensional matrix of values; every value is directly the analog–digital conversion result of the voltage value at every crossing row and column electrodes. We define every two-dimensional matrix as a *frame*, and the continuous sequence of those frames in the timeline as *stream*. The speed of the frames can be named as frames-per-second *(fps)* similar to the video formatting terminology. While the data is similar to image/video, most images are defined as grayscale and RGB, which have strictly 8-bit single or triple channels on every pixel; therefore, while trying to use image processing and computer vision libraries such as OpenCV, the data format should be checked.

There are generally three possibilities how the sensors can be arranged with the interest of activity:

1. the sensor covers the possible area of the interest, and the activity happens only on part of the sensor surface, such as a floor carpet or sleeping mattress.
2. the sensor is tailored to fit exactly the interest area, such as a chair cushion, car seat, or a glove.
3. the sensor covers only part of the interest area, for example, a fitness band on the leg or a small patch in the middle of a chair.

For the first possibility, it is usually necessary first to detect and segment the objects from the larger sensor area; computer vision techniques such as (dynamic) threshold, contour searching, morphological transformation, or template matching can be used. In fact, the pressure mapping data can be better for those techniques than in real images, because the background of the mapping frames is usually clean and static. Before applying those algorithms, an image resizing algorithm can be helpful to improve the resolution of the frame.

After segmenting, the first possibility is then similar to the second possibility, where the data frame exactly covers the interest area. To extract information, image moment can be a helpful technique. Image moment is a set of information that can be used to reconstruct a shape; therefore, they can help distinguish different shapes and profiles of a frame, such as Hu's 7 moments [53] and Zernike moments [54]. The image moment is more robust than using individual pixel values. First of all, the amount of pixel values can be overwhelming. Second, even after segmenting or when the sensors fit exactly the interest, the actual activity may shift. For example, while sitting in a chair, with the same posture, the person may shift a few centimeters from the last time when he/she takes the seat that would result in an entire row/column of pixels being shifted, while image moment is calculated as an interpolation of the shape as a whole.

The third possibility can also be treated as the second if the sensor is fixed in one position. However, if sensor shifting cannot be ignored, robustness against such problem should be addressed according to particular applications.

Common statistical measures such as average, max/min, area, standard deviation and variance together with image moments can be used as useful information. For slow-speed applications such as access registering and posture recognition, this collection of information is usually sufficient. While for higher speed, such as posture and sport applications, the system would generate a fast sequence of a collection of those measures. Then, temporal pattern recognition techniques can be used upon those measures, such as standard statistical analysis, frequency analysis (Fourier transform and wavelet analysis), dynamic time warping and HMM models.

3.4.2 Sensor Characteristics

Generally, for sensor instruments, properties such as linearity, repeatability, and hysteresis are very important because they are directly related to the confidence of the result. Several works have tested such properties of thin film-enclosed FSR sensors such as in [55, 56]. As seen in the work of [55], FSR sensors can have very good linearity and hysteresis properties. In [57], custom-made paper-based materials are tested. The work in [51] as mentioned above uses a special carbon material from Eeonyx, which is claimed to have minimized hysteresis and uniform resistivity and long-term stability [58].

However, most of the testings and calibrations are conducted on a flat, stable setup that isolates the pressure force. This is compatible with application scenarios such as insole, floor mat, sleeping mattress and tablecloth, where the sensors are in a relative stable position. But for other wearable applications, such as sport compression band, collar, elbow sleeve and knee pad, the sensors are constantly being bent and flexed. This would cause two problems that should be taken into consideration: (1) the connections of sensitive points are being reset on the fabric threads level. The conductive threads can be lifted away from the center material and then put back when the plane of the sensor is flexed and this could change the effective contact surface (both the overlap area of the top and bottom electrodes, and the contact surface between the conductive threads to the sensitive material); (2) in [59], carbon polymer materials can also be used as flex sensors. References [17, 60] also demonstrated the use of carbon polymer/nanotubes as strain sensors. Therefore, in the above-mentioned wearable applications, how to isolate stretching and flexing the plane of the sensors from the pressure is an issue to be concerned.

When investigating such sensor characteristics, one should combine the application goal with how precise the sensors are needed. Only to distinguish different activities, such as whether cutting or scooping on a plate above a tablecloth, whether running or doing squats with a pressure leg band, the sensors do not have to have excellent precision and repeatability as a weight scale. However, if the application is trying to distinguish how much is the joint angle with an elbow patch or how much food has been taken away from the table, the sensors should have characteristics which are comparable to a precision scale—to the best of our knowledge, textile-based sensors are yet to reach such level of performance, which makes it an interesting future research direction.

3.5 Conclusion

Overall, textile pressure mapping has great potential in smart textile ambient systems and wearable garments. While various sensing principles can be used to realize textile pressure mapping, the most applications so far have been seen with resistive and capacitive based pressure mapping. In summary, resistive-based pressure mapping

Table 3.1 Comparison of resistive- and capacitive-based textile pressure mapping sensor

	Resistive based	Capacitive based
Metallic conductive material	Yes	Yes
Conducting polymer material	Yes	No
Shielding	No	Yes
Number of layers (w/o) shielding	Three	Three, or one [31]
Adjusting node value	Mid-layer material	Mid-layer thickness
Measuring stimuli	Yes, DC	Yes, AC[1]
Scanning speed	Fast, transient	Slow to fast[2]
Measuring circuit complexity	Simple[3]	Complex[4]
Largest[5] node count @ fps[6]	6400 @ 40fps [32]	90 @ 1fps [30]

[1]Dependent on node capacitance value
[2]Dependent on AC frequency
[3]Typically one voltage divider, amplifier/filtering optional
[4]Typically requires amplifiers for analog conditioning [33]
[5]Published to date
[6]Frames per second (published to date)

requires more special material, and capacitive-based only requires conductive fabrics which are more widely available at a cost of more analog processing complexity. A comparison of the two can be found in Table 3.1. To extract information from the pressure mapping data, several computer vision techniques can be utilized in combination with temporal pattern recognition methods.

By its nature, textile pressure sensors have less repeatability and precision in terms of the sensor characteristics, while in the published application studies, their characteristics have been proven to be more than sufficient for a wide range of detailed activity recognitions. For the users' point of view, pressure mapping is very unobtrusive since it does not require direct skin contact and can be easily integrated into items in daily use. Together with their flexibility (in terms of configuration), pressure mapping sensors offer a versatile alternative smart textile sensing modality.

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Chapter 4
Strain- and Angular-Sensing Fabrics for Human Motion Analysis in Daily Life

Federico Lorussi, Nicola Carbonaro, Danilo De Rossi and Alessandro Tognetti

Abstract Human motion analysis concerns real-time tracking and recording of subject's kinematics. The possibility to perform ambulatory and daily-life human motion monitoring would represent a breakthrough for many applications and disciplines. In this context, smart textiles can provide a valid alternative with respect to conventional solid-state sensors thanks to their low cost, lightweight, flexibility and possibility to be adapted to different body structures. The present chapter analyses the working principle, the manufacture and the characterisation of textile-based strain and angular sensors. The strain sensors are piezoresitive textiles that can be used to reconstruct the human movement by measuring the associated strain fields. The angular sensors can be manufactured by coupling two piezoresistive fabrics through an insulating layer and are able to directly measure angular displacement. These textile goniometers are not sensitive to the precise positioning and to the bending profile and provide a reliable measurement system which represents an important step forward in wearable human motion detection.

4.1 Introduction

Human motion analysis concerns real-time tracking and recording of subject's 3D kinematics. Motion analysis can be associated with a classical forward kinematics problem: the measured joint variables feed a biomechanical model to determine the

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S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_4

position and the orientation of the subject's body segments. In a rotational joint, the joint variables are the set of angles between the consecutive body segments (e.g. the femoral–tibial joint of the knee), depending on the degrees of freedom (DOFs) of the joint. Conversely, in the case of a sliding joint, the joint variables are the extensions, i.e. the relative linear motions between two consecutive body segments (e.g. depression of the scapula in the scapular–thoracic complex). In physical- and/or neuro-rehabilitation, the human motion analysis is a powerful tool to assess the patient's recovery induced by the rehabilitation treatment [1]. In particular, performing a continuous evaluation of the patient's residual motor functionalities in *daily-life* conditions would represent a breakthrough in the rehabilitation field. To date, such performance information cannot be easily obtained with current commercial monitoring systems. Although the standard motion analysis instruments are well established (e.g. optical [2], magnetic [3], inertial [4]), the development and validation of ambulatory- and unobtrusive-sensing systems is still a challenge. In this context, as anticipated by De Rossi and Veltink in [5], sensing solutions based on smart textiles can provide a valid alternative with respect to conventional measurement systems employing solid-state sensors. Indeed, textile-based solutions have several advantages: low cost, lightweight, flexibility and possibility to be adapted to different body structures.

The principal joints of the human body can be approximated by rotational joints. Thus, reliable angular sensors—independent from the subject body structure—are fundamental in a motion analysis tool. However, the contribution of sliding joints can introduce significant errors, if neglected, in body posture reconstruction. Omitting the effects of the scapular–thoracic joint in arm position reconstruction, for example, may lead to position errors comparable with the length of the forearm. To monitor both rotational and sliding joints, angular (rotational joints) and strain (sliding joints) measurements are equally important for a reliable posture recognition.

In the last decade, several textile-based strain sensors have been developed. Usually, *strain-sensing fabrics* exploit the electrical resistance change due to an applied mechanical stretching. Strain-sensing fabrics were produced by coating a thin layer of piezoresistive material on conventional fabrics [6–9], by stitching/attaching conductive threads to the top of the fabric [10–14] or by knitting conductive and non-conductive yarns [15–20]. Motion-sensing garments were manufactured by applying the strain sensors to specific areas on normal clothes. The basic idea was to reconstruct the human movements by measuring the variations in the strain field due to changes in body shapes and/or geometry. In early works [8, 9, 21], we produced motion-sensing garments by coating conductive elastomer (CE) materials through a screen-printing procedure. CE-based sensing garments were applied in the detection of the upper limb movement for neurological rehabilitation, as described in [22, 23]. The main limitations were the sensor's low accuracy (order of 10%), their long transient time (order of 60 s) and their considerable hysteresis (order of 20%). In particular, the transient time of CE sensors imposed the development of dedicated algorithms for predicting the regime value after the solicitation [8, 21]. The described drawbacks limited the application of CE-based prototype to the detection of slow and wide movements, making them unsuitable for reconstructing fast and small movements. In following works, knitted piezoresistive fabric (KPF) proved to be a good tool for human motion detection [17, 18, 20]. KPF strain sensors constituted an improvement with respect to CEs in terms of response time and reduced hysteresis, making them more suitable for wearable motion capture applications.

In addition to the limitations due to the intrinsic characteristics of textile-based strain sensors, the reconstruction of human posture is highly affected by the relative position of sensors with respect to the joints to be monitored. This issue was often addressed by employing tight-fitting garments, with the negative effect of reducing the user acceptance and comfort, especially in home rehabilitation contexts. However, even using adherent garments, it was not easy to obtain reproducible performances due to the sliding/flexing of the sensors on the fabric. In addition, it was difficult for the users to wear the sensing garment in the same way after donning and doffing. The described limitations have affected the usability of the strain-sensing garments, due to the complex calibration procedure [21] or have restricted the use of textile-based strain sensors in the application of gesture classification [14].

In recent works [24–26], the authors have developed a new generation of textile-based sensors that can be used to measure angular displacement of flexing structures. These *angular-sensing fabrics*—the *textile goniometers*—are obtained by coupling two layers of strain-sensing textile through an electrically insulating stratum. Double-layer textile-based goniometers are not sensitive to precise positioning and to their intermediate bending profile, and they have the potential to address some of the issues of the textile-based strain transducers previously reported. If compared with previously developed solutions, textile goniometers provide reliable measurements of the angle between connected body segments and represent an important step forward in wearable human motion detection.

In the current chapter, Sect. 4.2 introduces the theoretical working principle of strain and angular textile sensors obtained by knitted piezoresistive fabrics. In the final part of the Sect. 4.2, a brief description of the sensor manufacturing is provided. Section 4.3 reports the characterisation of single-layer and double-layer KPF, used both as strain and as angular measurement devices. The study of the electromechanical properties was performed both in quasi-static and dynamical conditions. In Sect. 4.4, the techniques for the sensor calibration are presented, according to the outcomes of the characterisation experiments described in Sect. 4.3. Section 4.5 reports some basic applications of wearable textile sensors to give an idea of the opportunities introduced by the use of the described technology. Finally, in Sect. 4.6, new possible uses, object of future investigation, are introduced.

4.2 Textile-Based Strain and Angular Sensors

This section describes the basic theoretical principles (Sect. 4.2.1) and the manufacture (Sect. 4.2.2) of the textile-based strain and angular sensors described within this chapter.

In the *single-layer* configuration (Sect. 4.2.1.1), both CE sensors [8] and knitted piezoresistive fabrics (KPF, [20]) modify their electrical resistance when they are elongated or flexed (i.e. when the shape or dimension is modified). The main requirement for the application of the single-layer sensors is that the human movements have to produce a strain field which can be detected in terms of resistance variation. For this reason, single-layer sensors have to be integrated into adherent garments close to the human joint under investigation. If the applied strain field is uniform, as in the case a sliding joint, a simple sensor calibration allows the measurement of the elongation from the resistance value. Conversely, when the strain field is not uniform (e.g. single-layer sensor on a rotational joint), the biomechanical reconstruction can be more complex. In early works [8, 21], the authors measured the joint angles through single-layer sensors by considering the human body segment and the sensing fabric as an unique system that was calibrated through an external measurement device. The effect the calibration was that the particular body structure of the human subject relapsed into the system parameters. The main disadvantage was a too long and complex calibration of the sensing garment.

To avoid long and complex calibration procedures, a different sensor configuration consisting in coupling two sensing layers via an insulating layer was developed (the *double-layer* configuration, Sect. 4.2.1.2). The double-layer sensor is able to measure the angle between its extremities without taking into account the particular bending profile (and consequently the body structure of the subject wearing the garment). The independence on the bending profile consented to avoid the complex and time-consuming on-body identification of the anatomical parameters, and simplified the procedure of calibration of the angular sensors.

In the following part of the chapter, we will refer to the findings and results obtained for KPF sensors, given their improved performance with respect to CEs.

4.2.1 Theoretical Principles

This section summarises the theoretical principles of the single-layer and the double-layer piezoresistive fabric sensors extensively described in [24–26].

4.2.1.1 Single-Layer Configuration

The single-layer sensor was represented by a piezoresistive film (length l, width d, thickness h, resistivity ρ, volume V) attached to the textile substrate (Fig. 4.1). Under the hypothesis of isovolumetric deformation ($V = V_0$) and constant resistivity ($\rho = \rho_0$), the sample electrical resistance R was expressed as a function of the length l and flexion angle $\Delta\theta$:

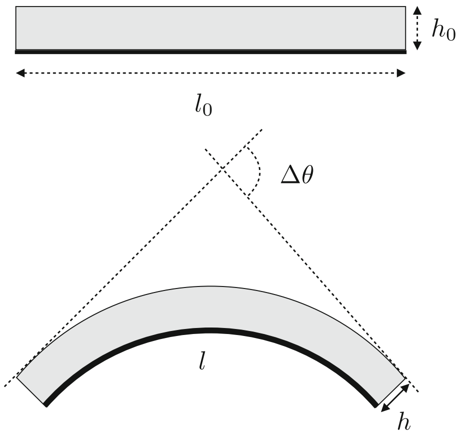

Fig. 4.1 Single-layer sensor represented by the piezoresistive fabric (*light grey*) attached to the textile substrate (*bold line*). In the *top* picture, the specimen is flat in the rest position ($\Delta\theta = 0$, length l_0, width d_0 and thickness h_0). In the *bottom* picture, the sample is both flexed ($\Delta\theta \neq 0$) and elongated ($l \neq l_0$, $h \neq h_0$). The flexion angle $\Delta\theta$ or *total curvature* represents the angle between the tangent planes to the sensor extremities

$$R = l\frac{\rho_0}{d\,h} - \frac{\rho_0}{d}\,\Delta\theta + O\left(\sup_{s\in(0,l)} k(s)^2\right) = l^2\frac{\rho_0}{V_0} - \frac{\rho_0}{d}\,\Delta\theta + O\left(\sup_{s\in(0,l)} k(s)^2\right) \tag{4.1}$$

where l was parametrised in terms of the arc length s, $\Delta\theta$ was obtained as the integral of the local curvature $k(s)$ in the interval $s \in [0, l]$ [27], and $O(sup(k(s)^2))$ is an infinitesimal function of the curvature $k(s)$ (i.e. normally negligible when applied to human body segments). It is straightforward to verify that if the textile substrate is inextensible, R depends only on $\Delta\theta$, and the single-layer device can be considered an angular sensor. By neglecting the second-order term of Eq. 4.1, the flexion angle versus electrical resistance characteristic can be expressed by:

$$\Delta\theta \simeq \frac{d\,l^2}{V_0} - \frac{d}{\rho_0}R \tag{4.2}$$

4.2.1.2 Double-Layer Configuration

The double-layer configuration was based on the measurement of the electrical resistance difference of two identical piezoresistive layers:

$$\Delta R = R_{L_1} - R_{L_2} \tag{4.3}$$

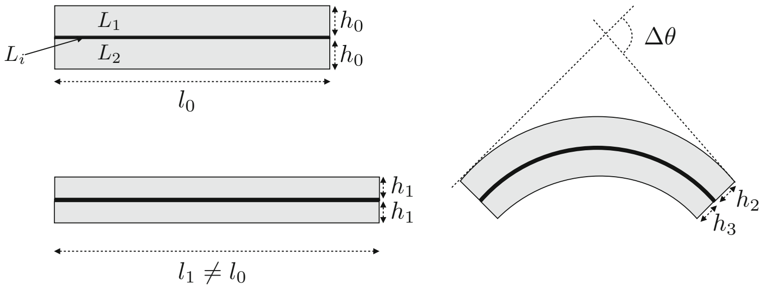

Fig. 4.2 Double-layer sensor represented by the two identical piezoresistive samples L_1 and L_2 (*light grey*) coupled through the insulating layer L_i (*bold line*). *Left-upper picture*: the sensor is at rest (initial length and thickness hold l_0 and h_0 respectively). *Left-lower picture*: the sensor is stretched ($l_1 \neq l_0$, $h_1 \neq h_0$) in the flat position ($\Delta\theta = 0$). *Right picture*: the double-layer sensor is flexed ($\Delta\theta \neq 0$)

where R_{L_1} and R_{L_2} are the electrical resistances of the two sensing layers (L_1 and L_2). The double-layer device is illustrated in Fig. 4.2. The two sensing elements—each one equivalent to the single-layer model described in Sect. 4.2.1.1—were coupled through an electrically insulating layer L_i whose thickness was negligible compared to the initial thickness of L_1 and L_2.

When the double-layer device is elongated without being flexed (bottom left of Fig. 4.2), the sensor output (ΔR) holds zero since the two sensing elements are subject to the same deformation ($R_{L_1} = R_{L_2}$). Conversely, when the sensor is flexed, the two layers undergo different deformations and the sensor output changes. Under the hypothesis of isovolumetric deformation and constant resistivity, ΔR was demonstrated to have a linear dependence on the flexion angle $\Delta\theta$:

$$\Delta R = 2\frac{\rho_0}{d}\Delta\theta + O(\sup_{s\in(0,l)} k(s)^3). \tag{4.4}$$

The dependence of ΔR on $\Delta\theta$ is not affected by the particular bending profile, as demonstrated by Lorussi et al. in [24]. It is interesting to note that the double-layer configuration reduces the error to a third-order infinitesimal function [24, 25]. In addition, the ΔR versus $\Delta\theta$ relation does not depend on the sample length, making the double-layer device an extensible angular sensor (hereinafter called *goniometer*). By neglecting the third-order term of Eq. 4.4, the flexion angle versus ΔR characteristic can be written as:

$$\Delta\theta = \frac{d}{2\rho_0}\Delta R \tag{4.5}$$

4.2.2 Sensor Manufacturing

Textile-based single- and double-layer sensors were obtained by using knitted piezoresistive fabrics, as reported in [17, 20, 25, 26]. Knitted piezoresistive fabrics were produced by Smartex [28] by combining electroconductive (Belltron® by Kanebo Ltd) and elastic (Lycra®) yarns. The Belltron® yarn is a bicomponent fibre yarn made of polyamide charged with conductive particles (i.e. carbon particles). This conductive yarn (75%) was knitted with the elastic yarn (25%) by using a circular machine.

The KPF sensors change the electrical resistance when they are mechanically stimulated due to the structural modification of the interconnection geometry. In particular, the elongation of the fabric changes both the fibres' geometry and the distance between stitches, thus affecting the carrier flow inside the fabric structure.

The single-layer sensors, described in Sect. 4.2.1.1, were produced by applying a rectangular KPF sample to an elastic fabric through a double-sided adhesive membrane. The double-layer configuration, discussed in Sect. 4.2.1.2, was obtained by coupling two identical KPF specimens on the opposite sides of an elastic fabric by using two double-sided adhesive membranes.

Figure 4.3 shows the top layer of a KPF goniometer in which the piezoresistive stratum is attached on a lycra® substrate. Each piezoresistive layer contains four semicircular pads that were specifically designed for power supplying and output reading. The electrical connections, made of the Bekinox® conductive yarn, were fixed using an ultrasonic welding machine.

Figure 4.4 reports the structure of the double-layer sensor and the schematic diagram of the front-end acquisition electronics. The insulating textile L_i is placed between the two conductive layers (L_1 and L_2). Each piezoresistive layer can be represented as a series of three resistances and has four connecting pads to minimise the effect of contact resistances (four-point resistance measurement). More specifically, a constant current I flows through the external pads while the voltages between the internal pads are measured ($V_{L1} = V_{B_1B_2}$ and $V_{L2} = V_{B_4B_3}$). V_{L1} and V_{L1} can be associated with the electrical resistances R_{L1} and R_{L2} given the knowledge of the current I. A first high-impedance input stage—instrumentation amplifiers A_1 and A_2—amplifies the voltages V_{L1} and V_{L2}. A second differential stage (the amplifier A_3) amplifies the voltage difference between the outputs of the first-stage amplifiers.

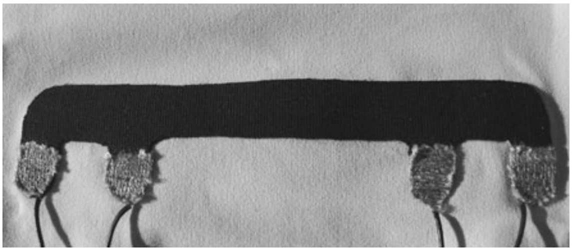

Fig. 4.3 Single-layer KPF sample attached to a lycra® substrate

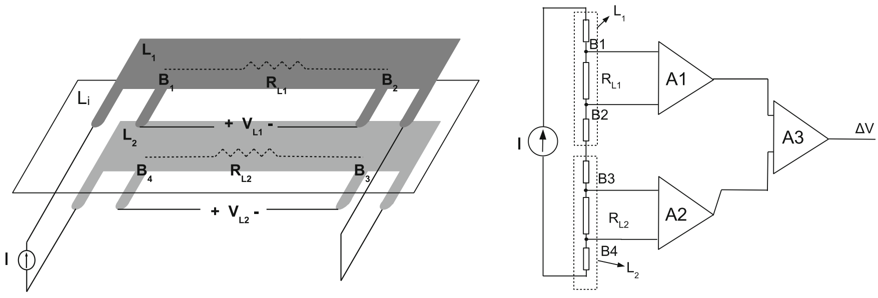

Fig. 4.4 *Left picture* functional structure of a double-layer KPF sensor. *Right picture* KPF goniometer electrical equivalent and block diagram of the acquisition electronics. The high-input impedance stage is based on two instrumentation amplifiers (A1 and A2). A3 is a differential amplifier. The output ΔV is proportional to ΔR and thus to $\Delta\theta$

Note that the final output ΔV is proportional to ΔR and thus to the flexion angle $\Delta\theta$, while the output of the first stage could be used for single-layer sensors. The KPF sample of Fig. 4.3—characterised in static and dynamic conditions as described in the next section—has total rest length of 100 mm, which corresponds to the distance between the external (i.e. current carrying) pads. The rest distances between internal pads (i.e. voltage reading) are 50 mm. The rest width and thickness are 10 and 0.5 mm, respectively.

4.3 Sensor Characteristics

This section describes the electromechanical properties of the single- and double-layer textile-based sensors described in Sect. 4.2. Quasi-static performance (sensitivity and error) was assessed for both strain and angular measurements performed by the single- and double-layer sensors. Dynamical properties are also reviewed for the considered sensor configurations. Test was performed on single- and double-layer samples whose dimensions are reported in Sect. 4.2.2.

4.3.1 Quasi-static Elongation

The single- and double-layer KPF samples were evaluated in quasi-static elongation tests to obtain their input/output characteristics: (i) R versus Δl for the single layer and (ii) ΔR versus Δl for the double layer (where $\Delta l = l - l_0$). As reported by Tognetti et al. in [25], the elongation tests were performed by applying controlled lengthening/shortening cycles by using a custom-designed electrodynamic testing instrument. The total elongation of each cycle was 5 mm divided into ten equivalent steps of 0.5 mm. Each step lasted one minute, and the sensor output was calculated from the last thirty seconds. Twenty lengthening/shortening cycles were applied. The samples were held in flat position ($\Delta\theta = 0$).

4.3.1.1 Single Layer

The mean and the standard deviation of R were computed for each elongation step over the entire set of cycles, as reported in the following relations:

$$\overline{R}_{\Delta l_i} = \frac{1}{N} \sum_j R_{\Delta l_i, j} \tag{4.6}$$

$$\sigma_{R_{\Delta l_i}} = \sqrt{\sum_j \frac{1}{N} \left(R_{\Delta l_i, j} - \overline{R}_{\Delta l_i} \right)^2} \tag{4.7}$$

where j indicates the cycle, $N = 20$ is the total number of cycles and Δl_i is the applied elongation. Figure 4.5 shows the resistance versus elongation characteristic of the single-layer sensor obtained by the mean values of Eq. 4.6 and the associated standard deviations. The characteristic of Fig. 4.5 was approximated by a linear function, and the elongation sensitivity (11950 $\frac{\Omega}{\text{mm}}$) was calculated from the slope of the linear approximation [25]. The maximum standard deviation of R was also evaluated (5603 Ω for $\Delta l = 2.8$ mm) and corresponded to an elongation uncertainty of 0.4 mm. This not negligible error (almost 10% of the measurement interval) confirms the low accuracy of textile strain transducers due to well-known hysteretic phenomena.

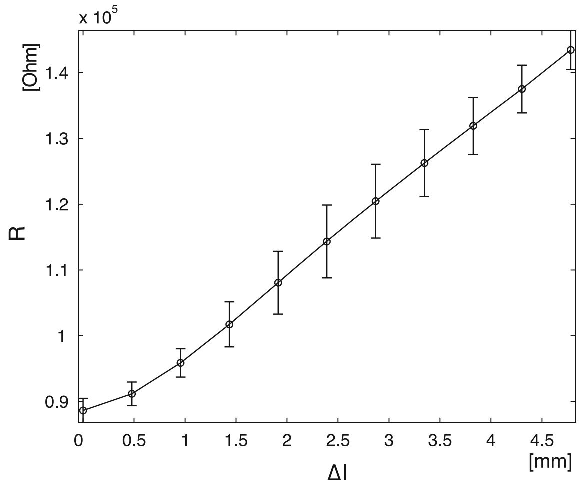

Fig. 4.5 Single-layer sensor in elongation tests: average R versus Δl for the lengthening/shortening elongation cycles. The vertical bars represent two standard deviation units in length

4.3.1.2 Double Layer

As expected by considering the Eq. 4.4, the elongation tests on the double-layer sensor confirmed the ΔR independence on elongation. However, it is interesting to underline that, in contrast to the relation Eq. 4.4, the ΔR obtained was not zero. This aspect can be explained by the difference in the geometrical and electrical properties of the two piezoresistive layers. According to this experimental finding, the ΔR versus θ relation, previously reported in Eq. 4.4, was approximated by the function:

$$\Delta R = s_{\Delta\theta}\, \Delta\theta + \Delta R_0 \tag{4.8}$$

where ΔR_0 represents the offset of the double-layer angular sensor and does not depend the sensor elongation. In the following part of Sect. 4.3, we will refer to the double-layer sensor output as the offset-compensated output:

$$\Delta R' = \Delta R - \Delta R_0 \tag{4.9}$$

4.3.2 *Quasi-static Flexion*

As reported in [25], the single-layer and double-layer KPF sensors were assessed in quasi-static flexion experiments to obtain the input/output characteristics: (i) R versus $\Delta\theta$ for the single layer and (ii) ΔR versus $\Delta\theta$ for the double layer. The flexion tests were performed applying controlled bending cycles and by associating the correspondent sensor output with the angle measured through an off-the-shelf electrogoniometer (the SG110 by Biometrics, $\pm 2°$ accuracy). Each bending cycle consisting of a flexion phase (increasing angles from 0° to 90°) followed an extension phase (decreasing angles from 90° to 0°). The $[0°,\ 90°]$ range was divided into 13 angular positions. Each angular step lasted one minute, and the sensor output was evaluated from the last thirty seconds. Ten flexion/extension cycles were applied.

4.3.2.1 Single Layer

The mean and the standard deviation of R were calculated for each angular position during the flexion/extension cycles:

$$\overline{R}_{\Delta\theta_i} = \frac{1}{K} \sum_j R_{\Delta\theta_i, j} \tag{4.10}$$

$$\sigma_{R_{\Delta\theta_i}} = \sqrt{\sum_j \frac{1}{K} \left(R_{\Delta\theta_i, j} - \overline{R}_{\Delta\theta_i}\right)^2} \tag{4.11}$$

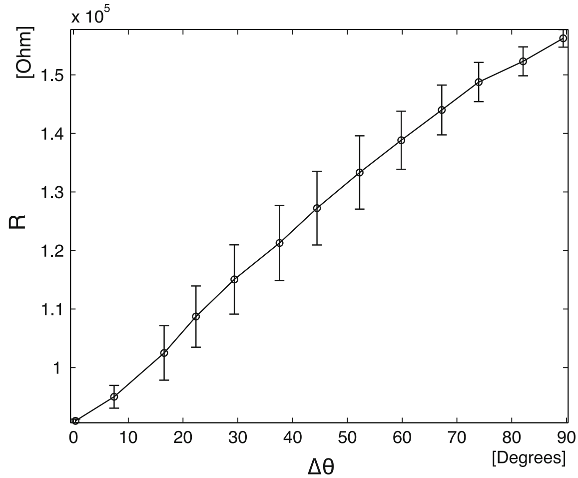

Fig. 4.6 Single-layer sensor in flexion tests: average R versus $\Delta\theta$ for the flexion and extension cycles. The vertical bars represent two standard deviation units in length

where j indicates the cycle, $K = 10$ is the total number of cycles and $\Delta\theta_i$ is the angle applied. Figure 4.6 shows the electrical resistance versus angle characteristic of the single-layer sensor obtained by the mean values of Eq. 4.10 and the associated standard deviations [25]. The angular sensitivity of the single-layer sensor (760 $\Omega/°$) was estimated by computing the slope of the linear approximation of the curve of Fig. 4.6. The maximum standard deviation of R was calculated (6405 Ω for $\Delta\theta = 37°$). The correspondent angular error was 8.3°.

4.3.2.2 Double Layer

The mean (4.12) and standard deviation (4.13) of $\Delta R'$ were calculated and plotted (Fig. 4.7) as a function of the angular position [25]:

$$\overline{\Delta R'}_{\Delta\theta_i} = \frac{1}{K}\sum_j \Delta R'_{\Delta\theta_i,j} \tag{4.12}$$

$$\sigma_{\Delta R'_{\Delta\theta_i}} = \sqrt{\frac{1}{K}\sum_j \left(\Delta R'_{\Delta\theta_i,j} - \overline{\Delta R'}_{\Delta\theta_i}\right)^2} \tag{4.13}$$

where j is the cycle, $K = 10$ is the total number of cycles and $\Delta\theta_i$ is the angle. The angular sensitivity of the double-layer sensor (955 $\Omega/°$) was estimated by the slope of the linear approximation of the curve of Fig. 4.7. The maximum standard deviation of $\Delta R'$ was calculated (5100 Ω for $\Delta\theta = 37°$). The correspondent angular error was 5.3°.

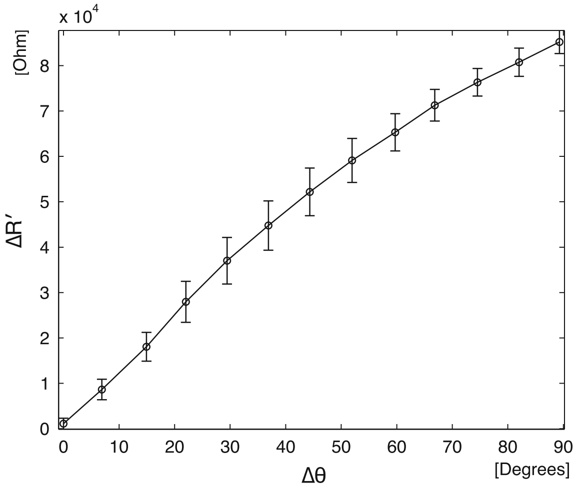

Fig. 4.7 Double-layer sensor in flexion tests: average $\Delta R'$ versus $\Delta\theta$ for the flexion and extension cycles. The vertical bars represent two standard deviation units in length

4.3.3 Dynamic Characteristics

In early works [8, 21], the dynamic response of single-layer textile-based strain sensors was analysed for CE materials, as reported in [8, 29]. CE-based sensors show a nonlinear relationship between input (strain)/output (electrical resistance) and a very slow response time [30, 31]. A nonlinear differential model fitting the CE behaviour was developed by Lorussi in [29] and took into account the following signal characteristics (highlighted in Fig. 4.8):

- Both for lengthening and shortening elongation, two local maxima—greater than both the starting and regime values—can be observed.
- The height of the overshoot peaks increases with the rate of strain.
- When the sample is relaxing after a solicitation, the resistance versus time relation can be approximated by a linear combination of exponential functions. In addition, the transient time depends on the properties of the sensor and not on the applied stimuli.

The nonlinear model, described in [8, 29], related the electrical resistance to the combination of the sensor length and the square of the length first derivative. The nonlinear behaviour entailed a complex treatment of the signal to reconstruct the strain starting from the measured resistance values (i.e. solving a nonlinear differential equation). In contrast to the previous research on CE sensors, the introduction of KPF remarkably improved the dynamic response due to the reduced output dependance on the square of the length derivative. Most importantly, the double-layer (goniometer) configuration was demonstrated to make overshoot peaks negligible. The reduced overshoot may be well explained by the relation (4.4) that was obtained by the subtraction of two instances of (4.1) that makes the dependence on the strain velocity reciprocally

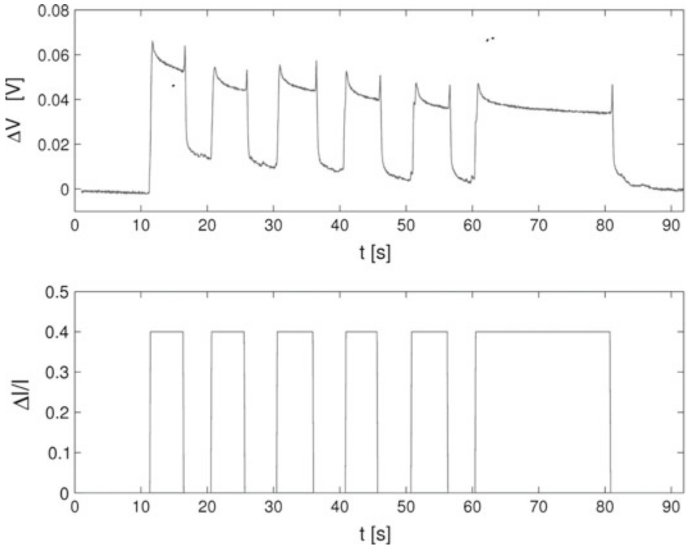

Fig. 4.8 Dynamic CE sensor output (*upper plot*) under trapezoidal strain solicitations (*lower plot*). The voltage output is proportional to the sensor electrical resistance

vanish. To demonstrate the good capabilities in following dynamic angular variations, the output of a calibrated KPF goniometer is reported in Sect. 4.4 in comparison with a standard measurement instrument.

4.4 Sensor Calibration

As already observed from the results of the double-layer sensor in quasi-static elongation (Sect. 4.3.1.2), the Eq. 4.5 is not verified, due to the differences in the electrical properties between the two piezoresistive layers. The results of quasi-static flexion on the double-layer sensor (Sect. 4.3.2.2) confirmed that the $\Delta\theta$ versus ΔR relationship can be approximated by the following linear function [25, 32]

$$\Delta R = s_{\Delta\theta}\, \Delta\theta + \Delta R_o, \tag{4.14}$$

where $s_{\Delta\theta}$ and ΔR_0 represent the goniometer sensitivity and offset, respectively. The angle values $\Delta\theta$ can be obtained by Eq. 4.14 as:

$$\Delta\theta = \frac{\Delta R - \Delta R_o}{s_\theta} = c_1\, \Delta R + c_2. \tag{4.15}$$

In Eq. 4.15, parameters c_1 and c_2 remain unknown, and it is necessary to perform an initial calibration to determine them. It is possible to compute c_1 and c_2 by acquiring ΔR_1 and ΔR_2 in two different angular positions $\Delta\theta_1$ and $\Delta\theta_2$, as

$$\begin{cases} c_1 = \frac{\Delta\theta_1 - \Delta\theta_2}{\Delta R_1 - \Delta R_2} \\ c_2 = \frac{\Delta R_1\,\Delta\theta_2 - \Delta R_2\,\Delta\theta_1}{\Delta R_1 - \Delta R_2}. \end{cases} \tag{4.16}$$

The choice of $\Delta\theta_1$ and $\Delta\theta_2$ depends on the range of measurement where the goniometer have to be employed. As described in [25], the calibration problem can be reduced by subtracting the constant offset ΔR_0 derived from a simple measurement of the sensor output in flat position ($\Delta\theta_1 = 0$), obtaining:

$$\Delta R' = \Delta R - \Delta R_0 = c_1 \Delta\theta. \tag{4.17}$$

Note that the ΔR_0 compensation can be analogically performed by simply compensating the offset of the A_3 amplifier (Fig. 4.4) when the sensor is in the flat position. The derived new output $\Delta R'$ represents a first correction to the difference in the behaviour of the two sensing layers, while the parameter c_1 remains to be computed. The reduction of the calibration problem in two subproblems having minor complexity may be useful in case we consider large networks of goniometers. In order to evaluate its performance in dynamic conditions, the double-layer KPF sensor was compared with a commercial goniometer (the SG110 by Biometrics, $\pm 2°$ accuracy) during continuous flexion/extension tasks. The KPF goniometer was previously calibrated in two angular positions ($\Delta\theta_1 = 0°$ and $\Delta\theta_2 = 90°$) to obtain the c_1 and the c_2 values, using relation 4.16. Figure 4.9 shows a representative plot of this comparison. The sensor showed reliable performance and good capability to follow dynamic variations. The maximum error is comparable with the one committed in the quasi-static case (5° in the trial of Fig. 4.9).

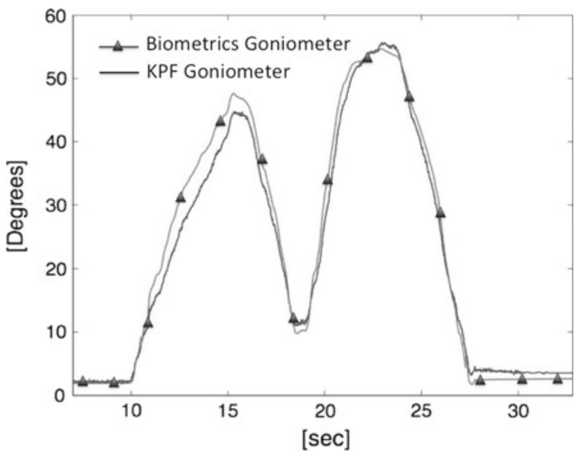

Fig. 4.9 Dynamic comparison between KPF goniometer and the reference system (Biometrics)

4.5 Applications

This section reports two practical applications of textile-based strain and angular sensors in human motion analysis, with special focus on the evaluation of daily-life performance of stroke patients performed in the frame of the Interaction EU project [33]. In Sect. 4.5.1, a single-layer sensor configuration is employed to detect the scapular movement (i.e. sliding joint). In Sect. 4.5.2, three double-layer goniometers are employed to track the finger movements (i.e. rotational joints) in order to reconstruct the hand posture.

4.5.1 Scapular Movement Detection

Revealing translational movements of human joints via ambulatory (non-optical) measurement system may be difficult. Strain sensors available on the market are conceived for measuring small amplitude strain (typically, deformation of metallic body). On the other hand, detecting joint sliding in complex kinematic chains, generally neglected, can remarkably improve the estimation of the position/orientation of the body segments. In neurological rehabilitation, this enhancement can be used to evaluate the motor performance of patients and their degree of recovery, discriminating between correct and compensatory motor schemes. The degree of stroke impairment, for example, influences the control of the upper limb muscles that can either be lost or limited by fatigue. When muscle deafferentation occurs (i.e. the incapacity of a nerve to recruit the muscle fibres), a typical body attitude is evident due to the dominance of flexor muscles together with inadequate contractions of antigravity muscles. This phenomenon may be reversible by patient training, and the use of a correct motor scheme can often be recovered. One of the most evident impairments produced by stroke on the upper limb can be the deafferentation of the deltoid muscle. In reaching movements, the arm abduction and flexion of the gleno-humeral joint (i.e. rotational movements) can be replaced by translational or spinning movements (scapular elevations and abductions). This pathological synergy may lead to a set of secondary illnesses for the shoulder (inflammation, usury illness or impingement).

The use of sensors aimed at revealing rotation movements and segment orientation cannot discriminate this pathological synergy. Indeed, it is not possible to detect this pathological synergy without taking into account the scapula movement. The following example is aimed at presenting improvement induced by the introduction of a textile-based strain sensor for pathological reaching activity discrimination. In a dedicated monitoring system [34], the textile strain sensor cooperates with inertial measurement units placed on the upper arm and electromyogram (EMG) electrodes on the deltoid. The strain sensors, positioned in the scapular region as shown in Fig. 4.10, detect the scapular movements. The inertial unit detects the arm orientation, while the EMG electrodes measure the deltoid activity. The results of [34] are presented in Fig. 4.11. On the left, when the correct abduction of the arm is

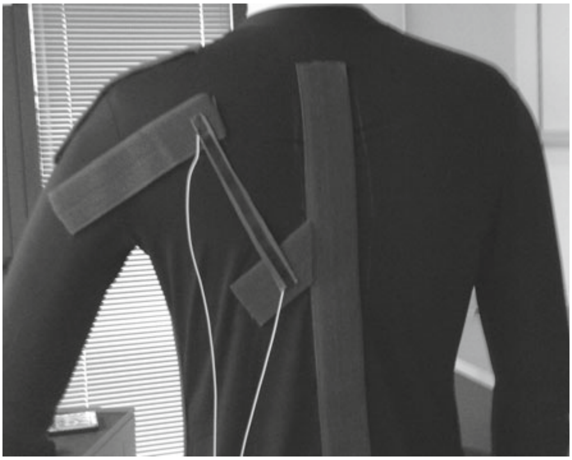

Fig. 4.10 Single-layer strain sensor is positioned in the scapular area in order to detect scapular elevations and abductions

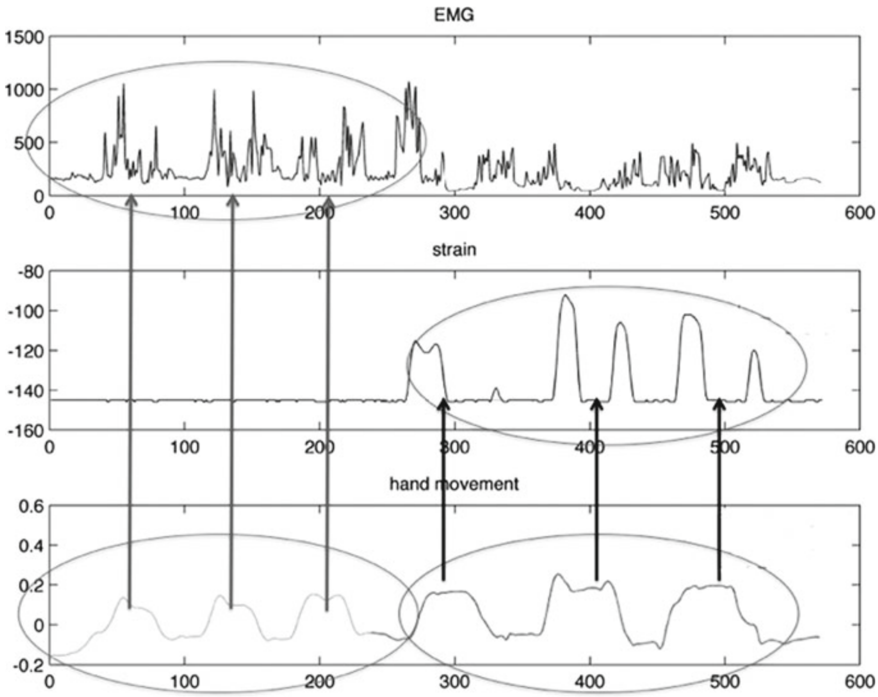

Fig. 4.11 IMU (*bottom*), strain sensor (*middle*) and EMG (*top*) outputs during reaching activity. *Left plot* data acquired during a correct reaching movement. *Right plot* data derived from a compensatory movement are plotted

executed, the IMU output (on the bottom) produces a typical wave. The strain sensor (in the middle) provides constant output, since the scapular sliding and spinning is negligible. Simultaneously, the EMG electrodes (at the top of the graph) detects an activity correlated with the correct muscle activation. On the other hand, when the compensatory movement (scapula elevation and rotation) is executed, the IMU system detects the same quantity (on the bottom, right), but the strain sensor relieves a movement of the scapula (in the middle-right of the figure). In addition, the EMG electrode does not provide any information. In summary, the use the strain sensors can allow the detection of the pathological movements (i.e. also avoiding the use of EMG electrodes).

4.5.2 Hand Motion Sensing

A kinaesthetic sensing glove was developed for the ambulatory evaluation of the residual hand function and its recovery of post-stroke patient [34]. It is devoted to assess the patient grasping activity and consists of three KPF goniometers directly integrated into the elastic lycra® fabric, shown in Fig. 4.12a. In order to detect the flexion-extension movement of index and middle fingers, two KPF goniometers were placed on the dorsal side of the hand in relation to each metacarpal–phalangeal joint. To capture the opposition of the thumb, one goniometer was placed in relation to the trapezium–metacarpal and the metacarpal–phalangeal joints. The glove goniometers were compared with an optical system as gold standard instrument (Smart DX 100 produced by BTS Bioengineering [35]) and showed angular error below five degrees [36]. This minimal sensor configuration—with a low number of monitored degrees of freedom—is a trade-off between a good grasping discrimination and design constraints typical of wearable and ambulatory applications. Indeed, small number of KPF goniometers increases user comfort and robustness of the system through a reduction in sensors integration, wiring and interconnections. Despite the low number of goniometers, the information deriving from thumb, index and medium

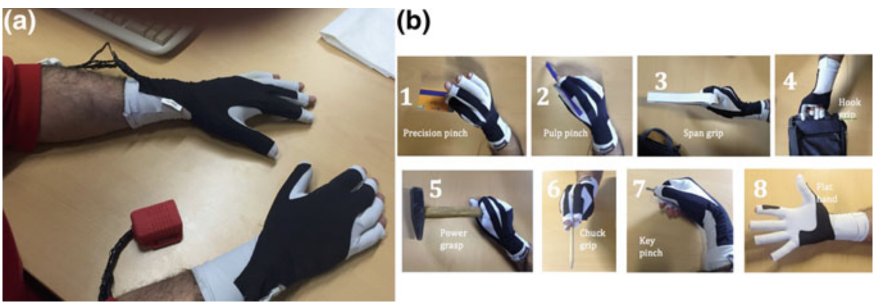

Fig. 4.12 **a** Kinaesthetic glove pair; **b** functional hand grips to be classified

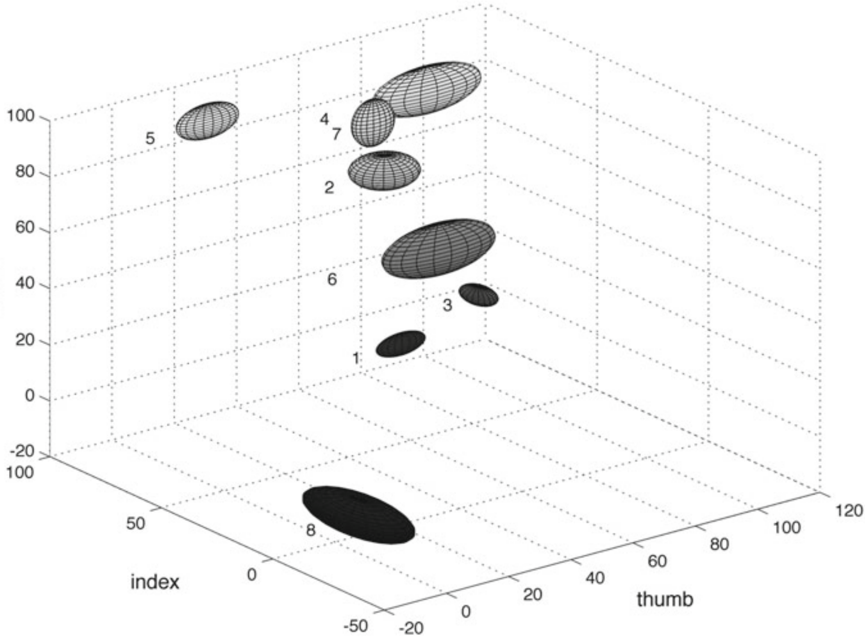

Fig. 4.13 Tridimensional representations of the acquired hand poses in the space of the goniometer outputs. For each hand pose, an ellipsoid is plotted—with the centre in the mean pose and semi-axes twice the pose standard deviation

fingers is sufficient for the recognition of functional hand positions useful to evaluate patient's daily-life performance (i.e. the eight basic hand grips [37] reported in Fig. 4.12b). In order to evaluate the ability of the glove to recognise the hand poses considered, hand positions were acquired several times from five subjects. The glove goniometers were calibrated according to the procedure described in Sect. 4.4 by reading the sensor outputs in the flat hand position and with the hand fully closed and associating 0° and 90° with these two poses. The data acquired were represented in the three-dimensional space of the goniometer outputs in order to show the data spread among the different hand poses [34], as shown in Fig. 4.13. For each position, Fig. 4.13 represents an ellipsoid with the centre in the mean angles of the pose and the lengths of the semi-axes twice the standard deviation such as if the angular measurements include the i-th ellipsoid, the pose is likely to be the i-th one. The poses are well separated via an ad hoc algorithm aimed at classifying postures was developed and tested. The i-th position is recognised if the goniometer measurement is contained in an ellipsoid with the centre in the mean pose and the semi-axes three times the standard deviations. If the angular measurements are outside each of the eight ellipsoids, no position is recognised.

4.6 Future Works

The most difficult movements to be detected in human activities are torsions. Torsions are movements which occur in the anatomical horizontal plane and around the principal inertial axis. This generally implies that the radius of rotation is small, difficult to be measured and affected by relevant errors. An example of torsion is the forearm pronosupination. A possible employment of textile goniometers to detect torsion is introduced in the following. Since a textile goniometer measures the angle between the tangent planes to its extremities and the output is invariant under twisting, the torsion can be reconstructed by applying the goniometer to a kinematic chain as in Fig. 4.14.

In other words, since the goniometer measures the angle between α and β before the movement and the angle between α' and β' after the movement, their difference is the θ required to evaluate the torsion (where α and α' are the two planes tangent to the extremity A of the goniometer and β and β' are the two tangent planes to the other extremity B, before and after the movement as reported in Fig. 4.14).

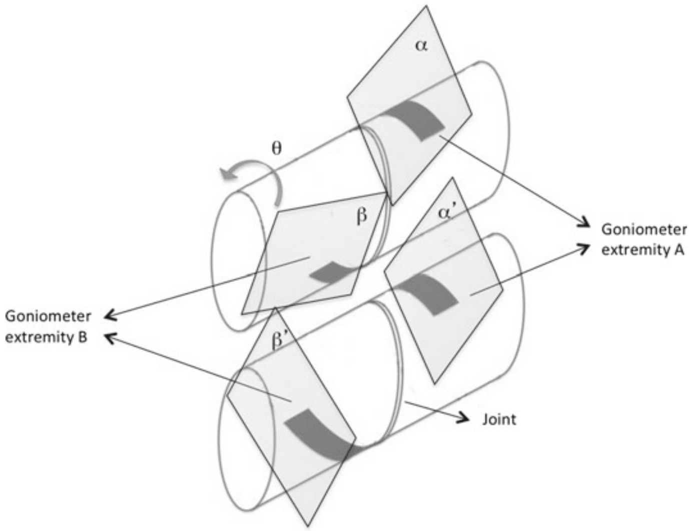

Fig. 4.14 Goniometer applied on a spinning joint which works as torsiometer. The difference between the angles measured between planes α, β and α', β' returns θ, which is the torsion angle

Summary

- Piezoresistive strain-sensing fabrics can be employed for the manufacturing of motion-sensing garments. Knitted piezoresistive fabrics (KPF) constituted an improvement with respect to previous achievements obtained with CE materials.
- Single-layer sensors can be developed by applying a KPF sample on a textile substrate. The output of the single-layer sensors depends on the elongation (Δl) and the flexion angle ($\Delta\theta$).
- Double-layer sensors or textile goniometers can be manufactured by coupling two single-layer KPFs through an electrically insulating stratum. The output of the double-layer sensor is proportional to the flexion angle $\Delta\theta$ and does not depend on the elongation and on the bending profile.
- Despite the quite low accuracy in strain detection, single-layer sensors are suitable to detect the extension of sliding joints, as demonstrated for the detection of the scapular movement.
- The textile goniometers demonstrated a good accuracy and capability to follow dynamic angle changes. They are suitable for angular measurement in rotational joints, as demonstrated in the application on the sensing glove.
- Textile goniometers can be arranged in a particular configuration in order to enable the possibility of detecting angular torsions.

Acknowledgements This research was partially supported by the EU-ICT 7th framework project FP7-ICT-2011-7-287351 INTERACTION.

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Chapter 5
Integrated Non-light-Emissive Animatable Textile Displays

Roshan Lalintha Peiris

Abstract Textile displays are a commonly investigated topic in the field of interactive textile research. Textile displays allow various display technologies to be embedded in the textile to enhance the textile to display images and animations on the textile. This work explores the development process of non-light-emissive displays using heat-sensitive thermochromic inks. In non-light-emissive textile displays, the display is more subtle and ambient, and has a natural form of color change. To actuate the thermochromic inks, we introduce the use of Peltier semiconductor elements along with a fine-tuned closed-loop temperature control system. The technology describes a robust, fast, and active controllability of the color of fabric. This controllability allows dynamic patterns to be displayed on the actual fabric in a programmable manner which is presented through a wide range of prototypes of textile displays. With the ubiquitous and subtle nature of this textile display system, we envision that it will be able to breathe life into the textiles (and even paper materials) of the future. Hence, we envision that the technology presented through this research would radically challenge the boundaries of current and future textile research and industry.

5.1 Introduction

Textiles are a common form of material we interact with daily as its recorded uses from prehistoric times textiles have become an integral part of our daily lives in the form of our clothes, home furnishing, architecture, and numerous other uses. With the introduction of new concepts and technologies, researchers have begun to embed more and more electronics in textiles [1]. This field of 'electronic textiles' or 'e-textiles' has created a vast area of research and application spanning from medical applications [2] to education [3] and even to textiles becoming a medium of expression [4].

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S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_5

With this development, a widely explored area of research in e-textiles is textile displays. Here, researchers look into embedding various forms of visual displays in textiles. From large-scale displays [5] to embedded LED (light- emitting diode) displays [6], textile displays have become a common occurrence in this field of research on household textiles, clothes, furniture, etc. Adding a visual display allows the textile to attain another dimension in time allowing its appearance to reconfigure to a certain extent making it a platform for a variety of uses such as social interaction, emotional expression [4], and gaming [7].

Currently, these displays can be categorized as *emissive*, such as embedding LEDs, electro-luminescent sheets, and wires, or *non-emissive*, such as using thermally actuated inks. However, the use of emissive technologies in conjunction with textiles renders rather an obtrusive form of a display [8]. Such displays are typically used for more specific purposes to gain people's attention positively such as in advertising or specific social contexts [5].

Alternatively, this research focuses on a ubiquitous and ambient textile display on which the technology falls to the background and lets the user to interact with the actual textile itself. This minimalism is an important characteristic in designing ubiquitous interfaces where the augmentation of technologies should not obscure the highly defined interaction modalities of the textile [9]. Hence, in this context, non-emissive display technologies have become a primary technology, in which the display does not emit any form of light. Thus, in most cases, the display is the actual fabric itself, where the animations of the display are performed as an unobtrusive and non-emissive color change of the fabric [8].

Most current such non-emissive technologies are non-animatable due to too slow color change. This is a main limitation in enhancing the textile's capabilities through a non-emissive display as it limits the display's controllability. Thus, this research explores the engineering of a non-emissive fast color-changing textile display using thermally actuated thermochromic ink and Peltier semiconductor elements as the thermal actuators (Fig. 5.1). A key goal of this research was to innovate a baseline technology that overcomes the boundaries of the current non-emissive ubiquitous displays. By applying this technology to various textile-based prototypes (and some paper scenarios) and diverse applications, we demonstrate extending the daily used textiles into subtly animated interactive textile displays by blending the display technology with fabrics in its natural form.

Fig. 5.1 Overview of the technological components used to implement non-light-emissive animatable textile displays

5.2 Related Works

Works in e-textiles have been around for a period of time. With many fields of application and research explored, these works have focused on many different aspects such as embedding components from conductive elements to sensors itself. Some of the early works in the field demonstrate the embroidery of conductive metallic fabric to form a keyboard [10]. Since then e-textiles have come a long way in enabling to integrate sensors and even switches as integrated fabrics [1, 11]. In line with these technologies, as mentioned above, fabric displays are mainly categorized as emissive and non-emissive displays.

There have been a plenty of work done in the emissive fabric display field. Lumalive by PHILIPS [6] uses LED to implement the fabric display. Here they embed multi-color LEDs in the fabric to form the display. Lumalive has been used with further interactions such as through proximity sensing [7]. Electroluminescent wires and sheets too have been used in many occasions due to its flexibility and ease of integration [12, 13]. In addition, Lumigram [14] displays the use of fiber optics woven in fabric as a display. In more recent works, Berzowska et al. [15] use photonic band gap (PBG) fibers woven in a computer-controlled Jacquard loom during the fabrication process. In 'The History Tablecloth' [16], the authors use flexible substrate screen-printed with electroluminescent material forming a grid of lace-like elements. Thus, once the objects are kept on the table, a halo effect is formed on the cloth which is retained for hours indicating the flow of the objects over the table cloth. However, the materials discussed here such as LEDs, BGFs, and electroluminescent materials are regarded as 'emissive materials' due to their emission of light [8]. Due to the nature of obtrusiveness of emissive displays, they are more useful for purposes of gaining attention. This is a clear case in Adwalker [5] where a complete display itself is embedded in the fabric.

For a more ambient and subtle approach, non-light-emissive materials such as e-inks, photochromic inks, and thermochromic inks have been used. Most of these works use these specialized inks which are actuated by an external trigger such as temperature, UV light, or force. One of the key recent non-emissive display developments include EInk. There is a work being done which attempts to merge this technology as a flexible display [17]. However, the display here features a transparent electrode layer. In addition, the display itself is attached to the textile by placing it on top of the material; thus, the interaction is not with the actual textile material. In the works of 'Information Curtain' [18], the authors use photochromic inks which actuate based on ultraviolet light. They use computer-controlled ultraviolet lights to interact with the textile. These lights create various patterns on the textile which lasts for several minutes upon removal of the light.

Further to these materials, thermochromic inks have been used as a popular material to fabricate non-emissive textile displays. Thermochromic inks too which change the color due to temperature changes are widely adopted due to their ease of use for non-light-emissive displays. In 'Shimmering Flower' [19], Bersowska uses thermochromic inks with conductive yarn woven through a Jacquard loom to construct her textile display. When powered up, the conductive yarn heats up and in turn actuates the thermochromic inks to change the color. Hence, this display animates slowly to reveal various colors and patterns on the textile. Bullseye [20] too uses thermochromic inks which are actuated by conductive yarn that is woven into the fabric. In ‘SMOKS’ [21], the jacket is printed with thermochromic ink shoulder pads which, when touched, change the color. This change gradually changes back, thus, keeping the memory of the touch for a certain time. In ‘Reach’ [4], Jacob’s et al. uses thermochromic inks printed scarfs, hats, etc., which change the color based on physical contact. Thus, the ‘SMOKS’ [21] and ‘Reach’ works use the body temperature to change the color of the thermochromic inks. In contrast, Yamada et al. uses infrared LEDs to actuate the thermochromic inks [22]. Here, they use thermochromic inks to digitally change the color of paintings. In the works of, ‘Pure Play’ of ‘Memory Rich Clothing’ [23] use Peltier semiconductor elements to present fast-changing non-light-emissive animations on textiles. Similarly, Mosaic Textile [8] uses liquid crystal inks, which change color due to temperature. This uses sewn conductive yarn to actuate the display. Here, they construct fabric elements of ‘Fabcells’ which contain this technology. These Fabcells are then used as pixels in groups to form the display on the textile.

Almost all of the above non-emissive displays have been used in an omnidirectional manner. That is, these works only use a heating source such as body heat or conductive yarn without any cooling method. Due to this reason, the absolute controllability thus the ability to animate the display is not profound.

Overcoming the above-mentioned limitations, the goal of this research was to present a comprehensive ubiquitous display technology that is embedded in fabrics. We use thermochromic inks as our display medium to achieve a non-emissive display to preserve the ambient and ubiquitous characteristics of the fabrics. In addition, the Peltier semiconductor modules used here allow the rapid heating and cooling of the fabric which allows this technology to be embedded as a ubiquitous animated display technology.

5.3 System Description

The overall system is depicted in Fig. 5.2. The textile display system uses a combination of Peltier semiconductor modules and thermochromic leuco-dye ink technologies to achieve a fast color-changing display. These two technologies are combined together using a closed-loop control system employing a PID (proportional, integral, and derivative) controller in order to accurately control the Peltier temperature and thereby control the color. Next, we describe in detail the workings of each main component of the system.

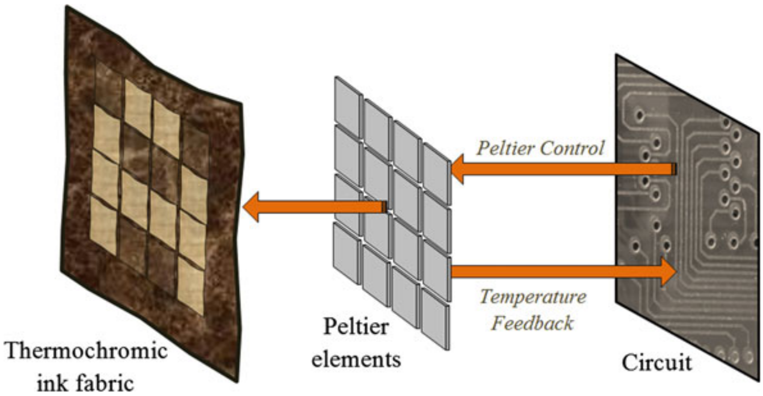


Fig. 5.2 Arrangement of the overall system of the textile display

5.3.1 Component Selection

5.3.1.1 Thermochromic Inks

The textile display system uses thermochromic leuco-dye inks as the display method due to its ease of implementation and high robustness. These inks work on the basic principle that when their temperature is raised beyond their ‘actuation temperature range,’ the inks become colorless. When the temperature is brought below the ‘actuation temperature range,’ the ink regains its original color. For example, the ink we regularly used in our experiments is of 24–32 °C actuation temperature. It becomes completely colorless at 32 °C and regains the original color approximately around 24 °C. In between are gradual shades of the original color based on the temperature. However, the color of these inks and the actuation temperature ranges can be customized for any specific requirements.

For scope of this work, we have experimented with off-the-shelf inks which are of 15, 27, and 32 °C actuation temperatures and of colors such as red, blue, green, black, and dark brown. These inks are then combined with textile binder and screen-printed, making the fabrics more robust for everyday use. Even though most of the prototypes feature single-color elements, we performed some multicolor experiments which are briefly discussed later in Sect. 5.5.1.

5.3.1.2 Semiconductor Peltier Elements

As thermochromic inks are thermally actuated, we chose the Peltier semiconductor modules due to its rapid thermal actuation capabilities within a wide range of temperatures. Peltier semiconductors use the thermoelectric effect; i.e., it creates a temperature difference across the module when a voltage is applied. Conversely, the

Table 5.1 Maximum temperature and power characteristics of Peltier elements

Peltier (mm)	Temperature Rate (°C s^{-1})	Power (W)
60 × 60	3	20
30 × 30	3	10
15 × 15	3	5
1 × 1.2	3	0.8

temperature difference is reversed when the voltage is reversed. That is, when the voltage is reversed, the heating surface becomes the cooling surface. This is a very useful feature in our work as it eliminates the requirement for bulky cooling systems as the heating and cooling occurs on the same surface of the module. Therefore, we use Peltier elements as one of our main core technologies due to its ability to rapidly heat and cool the inks with minimal space constraints.

Peltier elements come in various sizes which usually feature different operational characteristics. For the workscope of this research, we have utilized Peltier elements of sizes, 60 × 60 mm, 30 × 30 mm, and 15 × 15 mm based on the context of the application. In addition, we were able to experiment with miniature Peltier elements (1 × 1.2 mm). Table 5.1 describes the maximum specified characteristics of each Peltier element.

5.3.1.3 Controller Circuit

The basic controller circuit for one color-changing pixel is shown in Fig. 5.3. An H-bridge circuit was employed to achieve the change of direction of voltage applied on the Peltier element (Fig. 5.3). The voltage direction can be changed in the forward or reverse direction by switching on the Q1 and Q4 while Q2 and Q3 are switched off or switching on Q2 and Q3 while Q1 and Q4 are switched off, respectively. The switching on is done by a 100 Hz pulse width-modulated (PWM) signal, whose pulse width is controlled by the PID controller, in order to control the current through the Peltier element. Q1, Q2, Q3, and Q4 are MOSFETs (metal–oxide–semiconductor field-effect transistor) which have been selected based on the maximum current that is required by the Peltier module. Based on the prototype application, MOSFETs of different specifications have been used to match the specifications of the prototype's Peltier element.

To control the temperature of the Peltier element, a temperature sensor is placed on the surface of the element. This closed-loop feedback allows the controller to implement a fine-tuned PID controller. In Fig. 5.3, the labels H1, C1, and T1 are connected to the microcontroller. H1 and C1 are switched to control the Peltier element using PWM as mentioned above, and the T1 is the temperature feedback from the NTC (negative temperature coefficient) temperature sensor that is read by the microcontroller. The temperature sensor used in here is Murata NTSA0XV103FE1B0 NTC 10 kΩ thermistor.

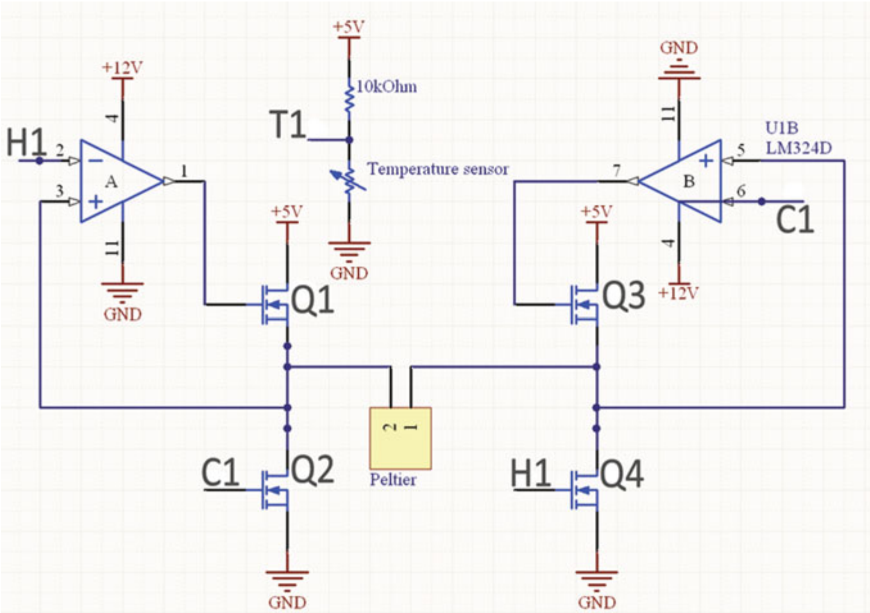


Fig. 5.3 Controller circuit schematic that consists of an H-bridge to drive the Peltier element and a temperature sensor to provide closed-loop feedback

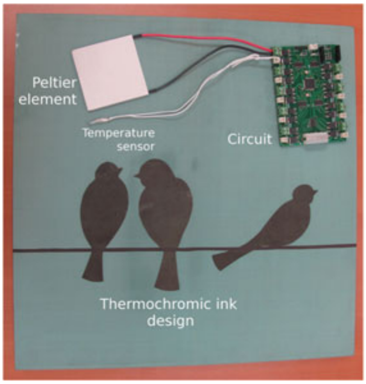
5.3.1.4 Temperature Control Algorithm

PID Algorithm: With the completion of few duty cycles, the algorithm reads temperatures of all modules. Each time all the readings are done, the controller calculates the proportional (P), integral (I), and derivative (D) terms for each of the modules using the following algorithm.

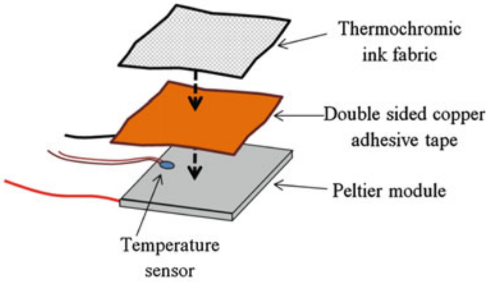
$$\begin{aligned} e &= sp - temperature \\ P &= k_p \times e \\ I &= I + (k_i \times e \times dt) \\ D &= k_p \times (e - p_e)/dt \\ p_e &= e \end{aligned} \tag{5.1}$$

where e—error, sp—set point, dt—sampling time (time interval between two samples), P_e—previous error, k_p—proportional constant, k_i—integral constant, and k_d—derivative constant.

By changing the value of the set point of a certain Peltier element, the pixel can change color to become colorless or regain the original color. For example, if the thermochromic ink with a 24–32 °C is used, the set point can be changed to 33 °C to make the pixel colorless or 23 °C to make the pixel the original thermochromic ink color. To tune the PID controller, we used a heuristic method named the



(a) Main elements of the system (one Peltier element and temperature sensor connected to the circuit).



(b) Setup of a single pixel of the system.

Fig. 5.4 Integration of the system

Ziegler–Nichols method [24]. With this method, the k_p, k_i, and k_d values are set as required.

5.3.1.5 Integration

To construct a color-changing pixel, the system contains few different elements that need to be carefully put together. The main basic elements of the system are shown in Fig. 5.4a. To integrate the system together, we initially mounted the temperature sensor on the Peltier element using a copper-adhesive tape (Fig. 5.4b). The copper-adhesive tape allows efficient heat transfer between the Peltier element, temperature senor, and the fabric in that area. The Peltier elements are attached to the fabric by a thermally conductive adhesive which allows efficient heat transfer between the fabric and the element (Fig. 5.4b). We have tested this implementation setup on several different types of fabric ranging from silk to cotton which produce similar results. This is the most common technique that has been utilized for all the prototypes discussed in the Sect. 5.5.

5.4 Technical Analysis

The temperature and color results of the system were observed with the use of one of the temperature sensors of the circuit and an external industrial color sensor. As the color-changing fabric, a prototype of a wall-hanging art that was printed with thermochromic ink was used. The system testing setup is shown in Fig. 5.5. The following are the main characteristics of the tested system

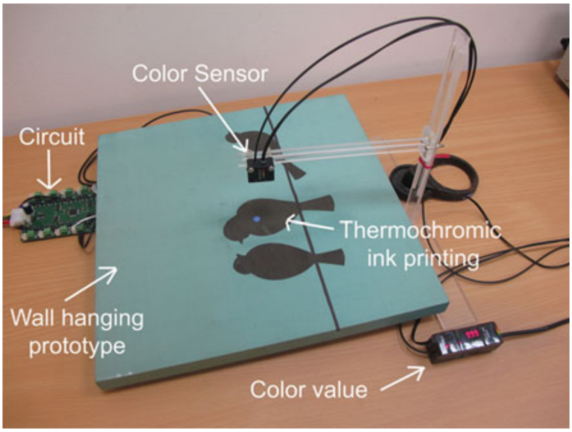


Fig. 5.5 Setup of the system for testing using a wall-hanging prototype

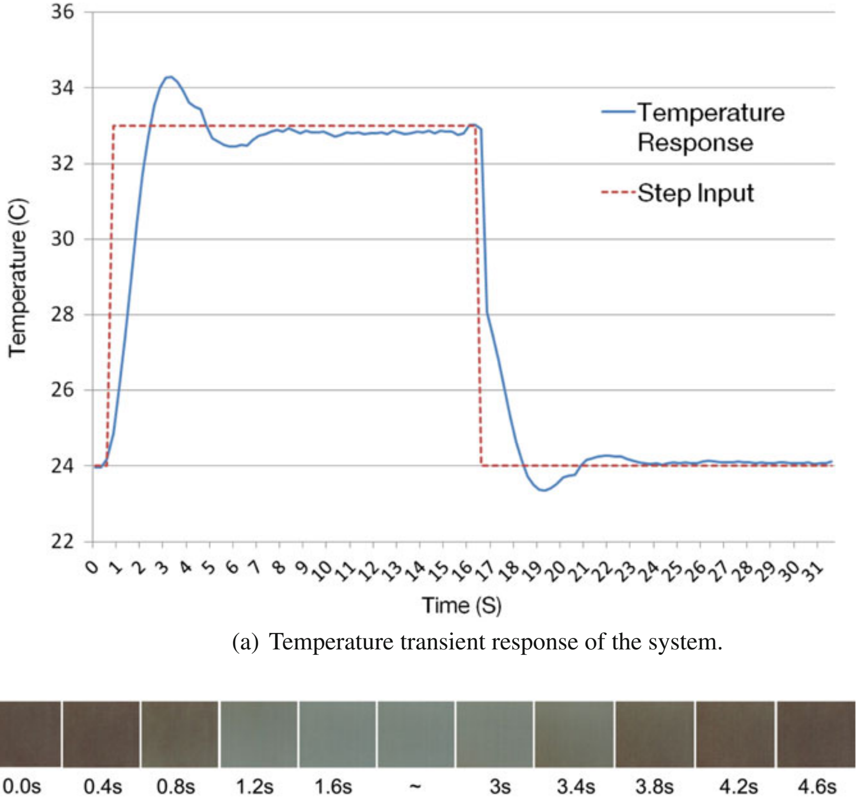
- The thermochromic ink used here has an actuation temperature range of 24–32 °C. In addition, most of the results focus only on single-color display.
- The fabric used in this analysis is the common taffeta silk fabric and the ink was screen-printed on to the fabric. (The birds have been printed in brown-color thermochromic ink on the light blue fabric).
- The Peltier modules used in this case are of 60×60 mm, 30×30 mm, 15×15 mm, 1×1.2 mm (miniature Peltier element) size. The results have been averaged, since all Peltier elements show similar results for the temperature and color controllability results. However, we have compared each Peltier module individually for the power characteristics analysis.

It should be noted that all the experiments carried out are focused on the current implementation of the system. That is, the temperature ranges of the system are essentially to match the actuation temperatures of the thermochromic ink that is commonly used in most of our prototypes, thus, approximately between 20 and 35 °C.

5.4.1 System Evaluation

5.4.1.1 Temperature Controllability

The transient response of the implemented PID controller is shown in Fig. 5.6a. As observed, the rise time of the system is approximately 2 s (to reach from ambient temperature of 24–32 °C). In addition, the fall time of the system too approximates to 2 s which is an important characteristic. This ability of the system to rapidly cool-down the fabric allows the thermochromic ink to rapidly regain the original color, hence allow subtle bidirectional animations on fabric. Figure 5.6b indicates the color change during this process.



(a) Temperature transient response of the system.

(b) Resulting color change of the (when triggered from 'color' to 'colorless' state and back).

Fig. 5.6 Color transient response of the system

The curve in Fig. 5.7 depicts the steady-state errors of the system. As observed here, the temperature controller is able to control the temperature within an accuracy of approximately 2% ($\pm 0.3\,°C$) for the given temperature range. This is an acceptable indication of the controllability of the temperature and hence the controllability of the color.

5.4.1.2 Color Controllability

Just as Figs. 5.6a and 5.7 are evidence of the accurate temperature controllability of the system, we conducted experiments to check the actual color controllability of the system. For this purpose, we used a KEYENCE(R) CZ-H32 color sensor with its CZ-V21A amplifier. This sensor unit displays the degree of correspondence between the target color calibrated as a reference and the target color currently being

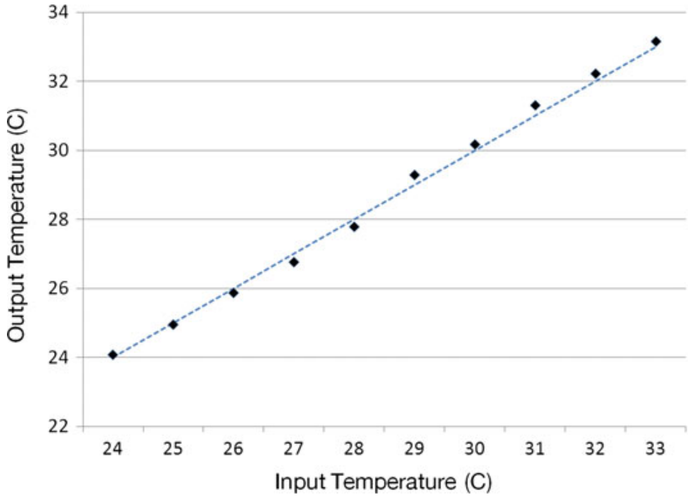


Fig. 5.7 Static temperature response of the system that displays the accurate temperature controllability

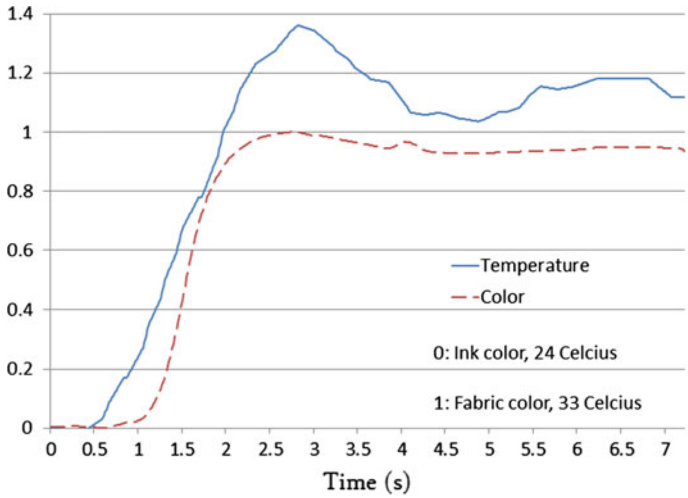


Fig. 5.8 Temperature transient of the system and the color change occurs as a response

detected. The value read as a result is the reflected light intensity effected by the target color. For our purpose, we calibrated the reference color to be the color of the thermochromic ink. For readability, the values are displayed in a normalized form where 0 is the color of the thermochromic ink and 1 is the color of the fabric.

Figure 5.6 depicts the color change resulted by the temperature change of the Peltier element. The normalized temperature values of Fig. 5.8 indicate 0 as the temperature at which the ink regains its full color, i.e., 24 °C, and 1 as the actuation

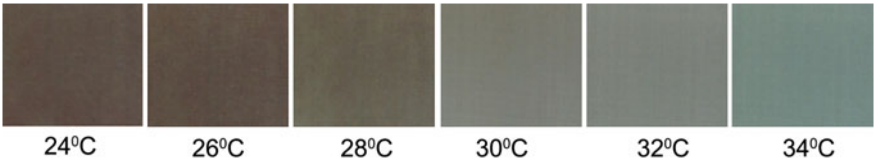


Fig. 5.9 Actual color output against various temperature settings

temperature, i.e., 33 °C. As expected, the temperature curve leads the color curve which is an indication that the color change is triggered by the temperature. The temperature curve settles slightly higher than 1 since the target temperature has been set to slightly above 32 °C at 33 °C to ensure the color change. In addition, once the ink becomes completely colorless, it still leaves a small quantity of 'colorless' residue of the ink behind which could be observed upon close inspection. Hence, it could be observed from Fig. 5.8 that the color curve settles slightly below 1 (1 is the fabric color).

Figure 5.9 indicates the actuated color of the fabric for the respective temperature settings. This is indicative of the color controllability. It should also be noted that this may change across various colors or across various manufacturers of the ink.

5.4.1.3 Power Characteristics of the System

Figure 5.10 details the different levels of power required for maintenance of the different temperatures for an area of 1 cm^2. This is a clear indication that if the

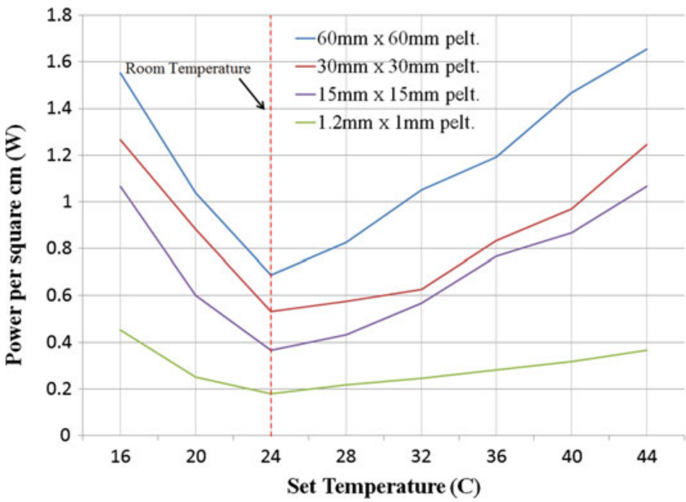


Fig. 5.10 Steady-state power requirements for 1 cm^2

actuation temperature of the thermochromic ink is closer to the room temperature, the power required is less. In this case, the lowest point was recorded at 24 °C for all Peltier elements. In addition, the miniature Peltier element has the lowest power consumption out of all the used Peltier elements.

5.4.2 *Experimenting with Different Temperature Ranges*

As we have seen here, the temperature controller can actuate the temperature relatively fast due to the introduction of active cooling as compared to the previous systems (which did not have active cooling mechanisms). As mentioned before, the temperature range was selected based on the off-the-shelf inks that were used for the experiment. However, to extend this experiment further, we analyze the speed and power characteristics for different temperature ranges. Having this knowledge would be helpful in customizing the thermochromic ink actuation temperature ranges to achieve specific speeds of color changes and limit power requirements.

To conduct this experiment, we selected a midpoint temperature and the two set points for colored and colorless states were set in multiples of 2 °C equally above and below the midpoint (for example, if the midpoint was 25 °C, then the first set of set points 23–27 °C, next 21–29 °C, followed by 18–31 °C). Next, we observed the transient and settling times and the power characteristics for each of these systems for heating and cooling. Then, we repeated these results for midpoint temperatures of 20, 25, 30, and 35 °C. Table 5.2 shows the used temperature details. The Peltier modules used in this case were 15 mm × 15 mm only. This was since the main goal of this experiment was to identify the characteristic behavior for different selected

Table 5.2 Temperature specifications for temperature range experiment

Midpoint	ΔT	Low set point	High set point
20	4	18	22
20	8	16	24
20	12	14	26
25	4	23	25
25	8	21	27
25	12	19	29
30	4	28	32
30	8	26	34
30	12	24	36
35	4	33	37
35	8	31	39
35	12	29	41

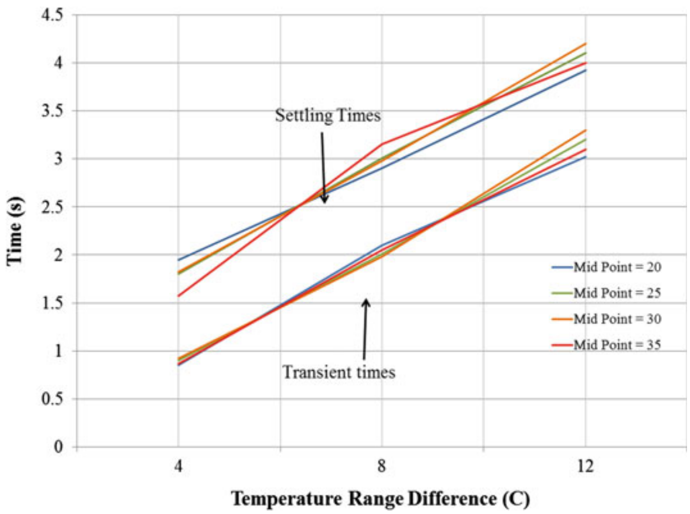


Fig. 5.11 Transient and settling times for different temperature ranges

temperature ranges. Therefore, through our experience from the previous results, we can extrapolate these results to the other Peltier modules.

5.4.2.1 Speed of Color Change

Figure 5.11 shows the speeds of transient and settling times. As observed, the transient times are faster for smaller temperature ranges. This is also true for the settling times which are slightly higher than the transient times but settle faster for smaller temperature ranges. In addition, one of the key characteristics that can be observed through this study is that the transient and settling times are similar to same temperature ranges irrespective of the midpoint temperature. This is an indication of the PID controller in effect. The controller attempts to reach the set temperature soonest possible based on the tuned parameters. As such, similar temperature differences denote similar transient and settling times.

5.4.2.2 Power Characteristics

Figure 5.12 shows the power characteristics for power requirements for continuously transient states between the two set points for different temperature ranges. As it can be observed, the required power is higher when the temperature difference between the set points is higher. However, the steady-state power for each of the temperatures can be inferred from Fig. 5.10.

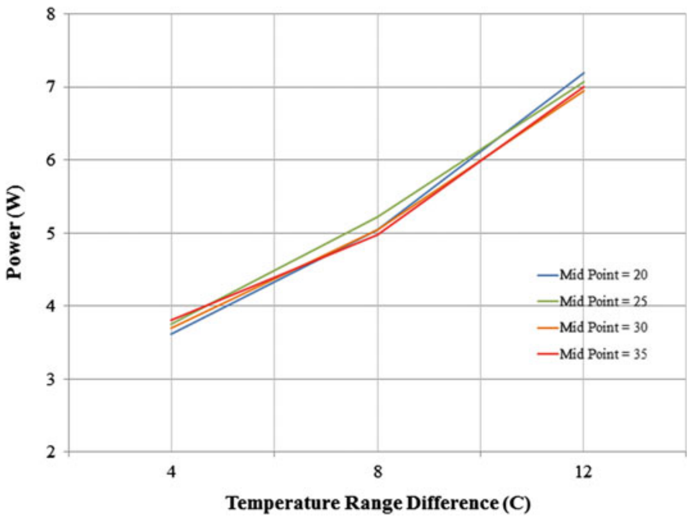


Fig. 5.12 Power requirements for continuously transient states between two temperatures

5.5 Prototypes and Applications

This section presents some of the initial work and applications that can use our textile display system. We built a range of prototypes as summarized in Fig. 5.13. The initial prototypes looked to explore characteristics such programmability, animateability, and ubiquity of the textile display system in various contexts. With the miniature Peltier elements, we explored the flexibility and wearability introduced by a microscale integration. The diverse applications were an attempt to identify the system's usability in a range of ubiquitous applications.

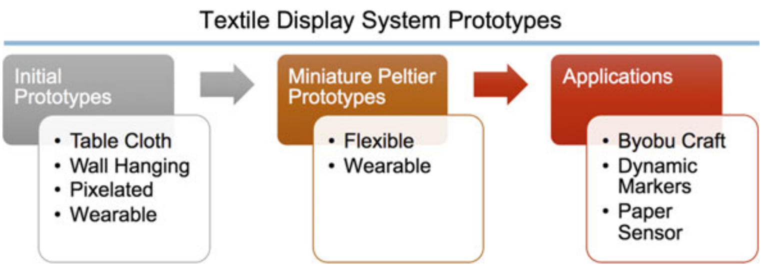


Fig. 5.13 Summary of implemented prototypes

5.5.1 Initial Prototypes

Several prototypes were designed and implemented to explore the capabilities of the textile display system. For these prototypes, a range of Peltier elements from 60 mm × 60 mm down to 15 mm × 15 mm have been used. The selection of Peltier elements for these prototypes was based on the context and the application of use: In certain applications, larger Peltier elements up to the size of 60 mm × 60 mm were used to actuate whole images as pixels, while smaller elements were used to formulate single pixels for pixelated displays and improve the flexibility of the textile. The following are some of such application prototypes.

5.5.1.1 Furniture Garments Using Textile Display

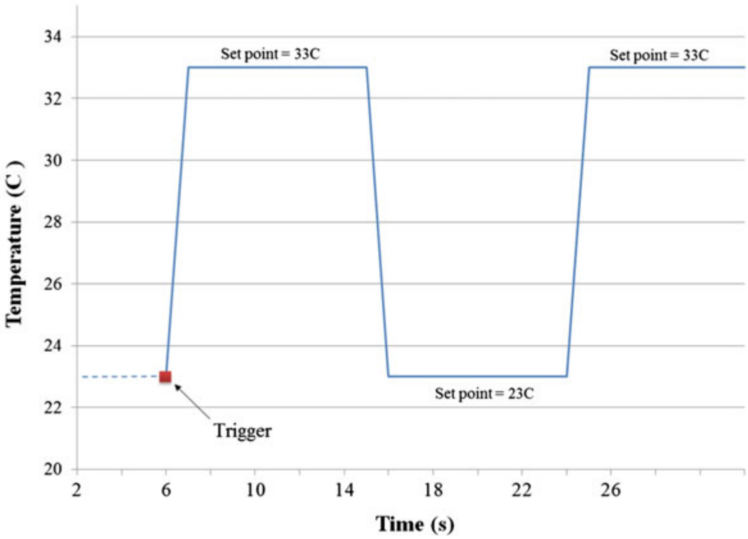
As a decorative piece, we initially created a wall-hanging painting that would animate a bird on the painting once a person steps closer to it. The bird in the middle is printed with thermochromic ink and two 60 mm × 60 mm modules are attached behind it. Using an infrared proximity sensor, a person's presence is detected and the animation is triggered to change the set point as indicated in Fig. 5.14b. This would make the bird in the middle to appear and disappear in a subtle manner.

Next, we implemented an animated table cloth that which has a subtle animation of a bird flying across the table when activated (Fig. 5.15). This work used 60 mm×60 mm Peltier elements embedded behind each bird as seen in Fig. 5.15a(iii). The Fig. 5.15a(ii) indicates the table cloth when de-activated with all the birds appearing and Fig. 5.15a(i) shows the animation in progress. The Fig. 5.15b shows the programming the set point to display the animation. As observed, the subtle animation is achieved by carefully starting each Peltier is set to turn on as the Peltier before it is turning off. Both prototypes used thermochromic inks of 24–32 °C actuation temperature range.

5.5.1.2 Pixelated Displays

Figure 5.16 shows a multicolored pixelated display. This 5 × 5 pixel display currently shows an animated clock using 30 mm × 30 mm Peltier elements and a multicolor display which uses a combination of green (37 °C) and red (15 °C) inks on a white fabric base. This 5 × 5 pixelated display currently shows an animated clock using 30 mm × 30 mm Peltier elements and a multicolor display which uses a combination of green (37 °C) and red (15 °C) inks on a white fabric base.

(a) Image sequence of an animated wall hanging painting using the textile display system



(b) Programming the set points for the wall painting animation

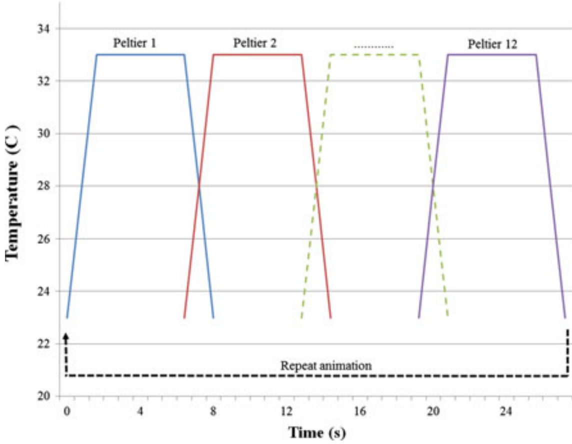
Fig. 5.14 Wall painting that animates the *bird* in the *middle* when a person moves closer

5.5.1.3 Wearable Displays

Figure 5.17a, b depicts the time-lapsed images of some early versions of wearable applications as a single-pixel display and a pixelated display, respectively. In the single-pixel display, the heart image is animated to turn on and off randomly. The pixelated display depicts various animations such as the hearts moving in circles from the center to the boundary of the display. Figure 5.17c indicates few different scenarios we envisioned such as identifying the context and displaying appropriate messages such as 'Hi' or smiley faces.

(i) (ii) (iii)

(a) Animated table runner (i) Animation of the flying bird (ii) Table runner switched off displaying all the birds (iii) Setup of the table runner



(b) Programming the set points for the table runner animation

Fig. 5.15 Table runner that animates a bird flying across on the cloth

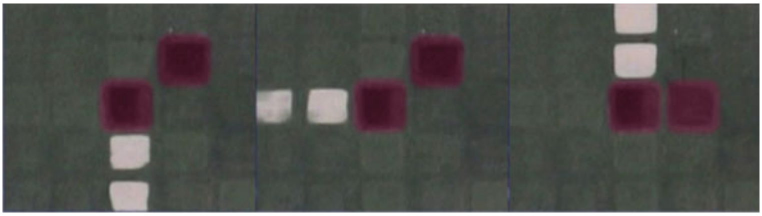


Fig. 5.16 Animating a clock using a low-resolution display with a 5 × 5 pixel arrangement

5.5.2 *Prototypes with Miniature Peltier Elements*

The miniature Peltier elements (MPEs) gave us the opportunity to identify the challenges and advantages of integrating microscale Peltier elements. The scale of these

(a) Tshirt with an animated heart using a single wearable animated pixel.

(b) Tshirt with a pixelated wearable display.

(c) Scenarios of the wearable system.

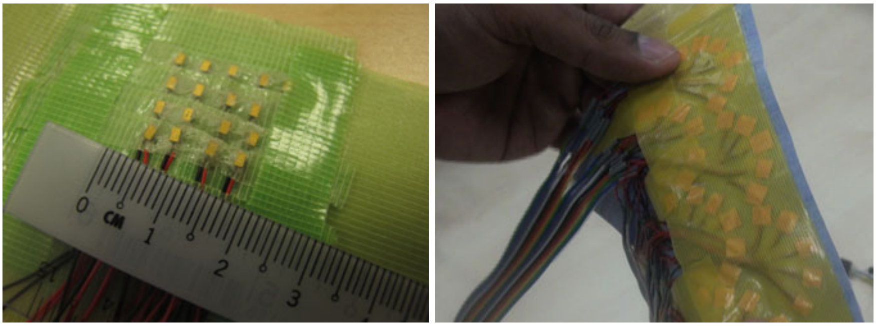
Fig. 5.17 Wearable applications of the textile display

elements and the lower power requirement enabled us to explore improving the flexibility and wearability (mobility) as demonstrated next.

5.5.2.1 Flexible Displays

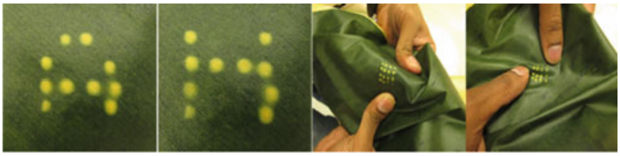
As an initial prototype (Fig. 5.18a), a pixelated display was implemented on the fabric. For this purpose, each pixel was placed 5 mm apart from each other. Figure 5.18b depicts another prototype with the Peltier modules arranged in a wavy pattern.

Figure 5.19a, b indicates some of the prototypes that utilize the MPEs. As observed, the use of MPEs have significantly improved the flexibility of the display.

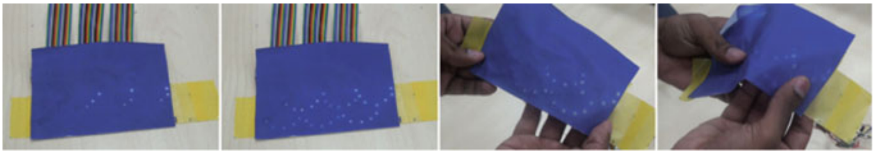


(a) MPEs of the pixelated display (b) MPEs arranged in a wavy pattern

Fig. 5.18 Context-specific attaching of MPEs to the fabric



(a) 4x4 pixelated display



(b) Wave pattern textile display

Fig. 5.19 Prototypes of textile displays with the MPEs

5.5.2.2 Wearable Display

Figure 5.20 depicts a dress fitted with the miniature Peltier elements that display 'necklace' patterns on the dress. In addition, the dress was completely battery operated with two AAA-type batteries allowing it to be operated continuously for approximately 4 h.

5.5.3 Applications

The above prototypes helped us observe and explore the capabilities of this technology. Upon these observations, next, we briefly introduce three diverse areas where the technology was applied. The diversity of these areas demonstrates the ubiquity of the technology.

Fig. 5.20 Wearable dress with miniature Peltier element textile display

5.5.3.1 Merging Textile Display Technology with Byobu

Byobu is a traditional textile craft that features textile room divider screens from Japan. Our technology leverages on current trends in ubiquitous and pervasive computing. In the case of technology, change occurs in the very fabric itself, and in terms of the color of the ink. Thus it enables smooth color changes on the fabric depicting subtle animations on the fabric surface. In this application, we were able to merge a traditional byobu screen with our technology [25], where the screen becomes active as a person moves closer to it and subtly animates flowers on the central portion of the screen (Fig. 5.21).

5.5.3.2 dMarkers: Ubiquitous Dynamic Markers for Augmented Reality

This work helped us extend our technology in to paper material that created dynamic markers for Augmented Reality applications [26]. 'dMarkers' is a concept of 'dynamic markers' or markers that can change for marker technologies for Augmented Reality (AR) technologies. Here, by dynamic we mean markers that can change or morph into different markers which could open up various new possibilities through technologies such as AR. We use our technology to achieve subtly changing animated dMarkers for paper and fabric materials. The key feature of this technology lies within its ability to animate the material itself without embedding any separate displays. Thus, this technology is used to subtly animate various patterns for markers to be used as dynamic markers. As a proof of concept, we implement the dMarkers for Quick Response (QR) codes (Fig. 5.22). In our implementation, we were able to

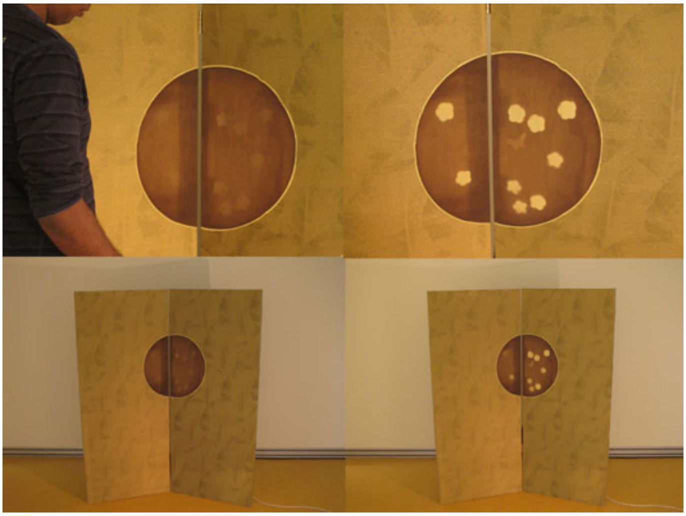


Fig. 5.21 Byobu installation where the *brown circle* in the *middle* is animated to display birds and butterflies interactively

Fig. 5.22 Detecting the dynamic dMarker QR tag with the QR application

generate various QR codes for paper and fabric-based materials that were detected through third-party QR code apps. Fabric was used in this case to explore the future possibility of implementing the dMarkers with clothes.

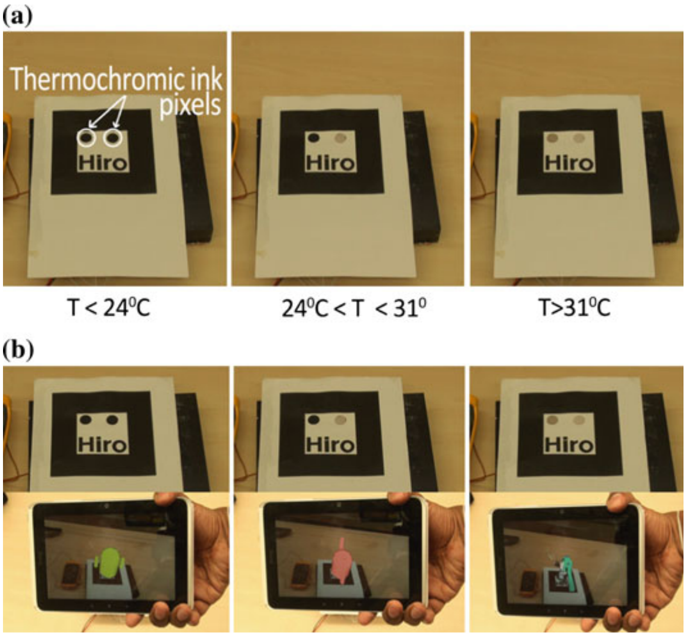


Fig. 5.23 Paper-based temperature sensor. **a** Thermochromic ink pixels disappearing as the temperature increases. **b** Detecting different markers at different temperatures

5.5.3.3 A dynamic AR marker for a paper-based temperature sensor

Based on some of the potentials identified from the previous application, this work explores the altering of the textile display technology into developing a paper-based temperature sensor that can be read digitally [27]. To achieve this, we printed patterns on an AR marker using thermochromic inks of various actuation temperatures (Fig. 5.23). Thus, as the temperature gradually changes, the marker morphs into new marker for each temperature range. As such, the simple piece of paper with the thermochromic AR pattern and the smartphone becomes the paper-based temperature sensor.

5.6 Discussion

5.6.1 Discussion on the System

One of the main goals of this research was to identify key technologies that would enable a fully controllable, programmable non-emissive textile display. As such, we used thermochromic inks and with Peltier semiconductor elements combined with a tuned PID controller to achieve this goal. The Peltier elements' ability to rapidly heat and cool the thermochromic ink-printed textile gives our system the advantage in producing subtle, yet controllable and programmable animations on the textile.

We have presented the use of few different types of Peltier elements with the systems. These Peltier elements were selected based on the application context where the Peltier elements were chosen based on parameters such as the pixel size and power requirements. With our detailed technical analysis of the system, we presented critical results to analyze the performance of the system. In addition, with the introduction of the new custom-made miniature Peltier elements, the results indicated significant improvements over the previous parameters. Thus, here, we summarize some of our results.

5.6.1.1 Speed of Color Change

Through the observed systems, the color change was relatively fast due to the introduction of active cooling as compared to previous systems (which did not have active cooling mechanisms). In addition, the results indicated that there was no significant difference in the speed of temperature change for different Peltier elements. However, the temperature ranges' experiments described in Sect. 5.4.2 show how the animation speed can be improved by customizing the actuation range of the thermochromic ink. These results are averaged and summarized in Fig. 5.24. Through observation we can see that for the tested results, the color change can be triggered within approximately 0.8 s which can increase the frame rate of the animations on the textile up to about 1.5 FPS. Since the transient time refers to appearance of a single pixel of a single frame

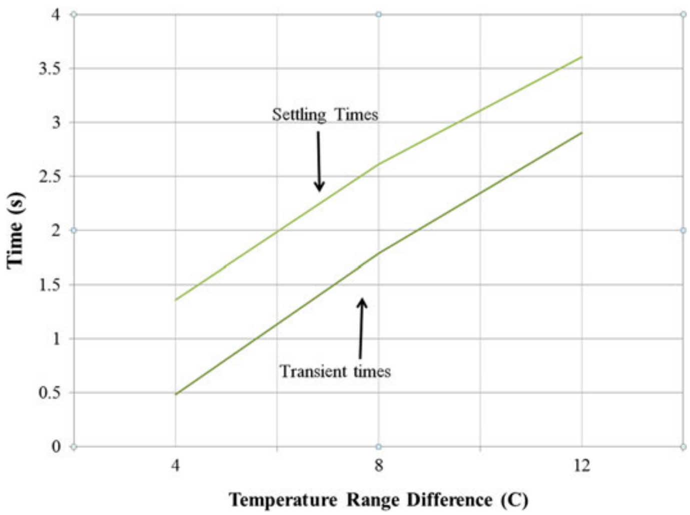


Fig. 5.24 Summary of timing characteristics for temperature ranges

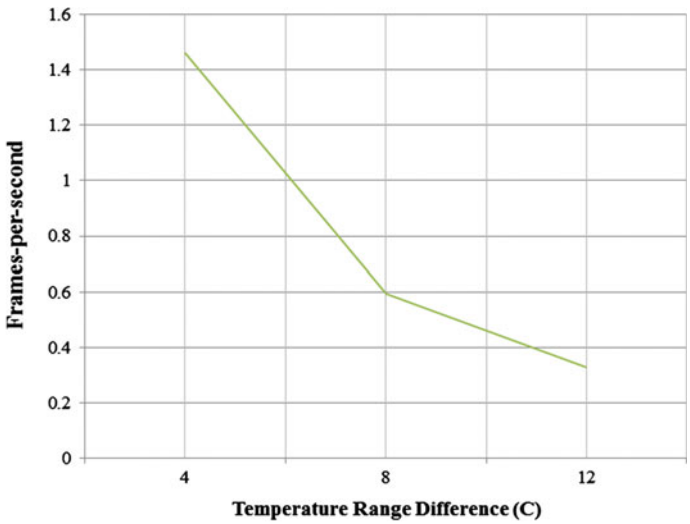


Fig. 5.25 Frame rate of the textile display for different temperature ranges

of the animation, the frames-per-second animation can be determined by the inverse of the transient time. As such, the derived frames-per-second graph is depicted in Fig. 5.25.

5.6.1.2 Power Requirement

As the display system uses thermal actuation as the main enabling technology, power consumption is often a critical design factor. To address this, we have done a number of power consumption analysis to identify optimal parameters for the system's use. These results are summarized in Fig. 5.10. Figure 5.12 shows the temperature range test for the Peltier elements. For ease of reference, the results are calculated for the actuation of a 1 cm^2 area on the textile. These figures show a few interesting characteristics of the power consumption of the system.

- When the Peltier elements differ in size, their characteristics change with larger Peltier elements using the highest amount of power (Fig. 5.10).
- The power consumption is minimal around the room temperature (Fig. 5.10).
- The power consumption is minimal when the temperature range between the color and the colorless temperatures is minimal (Fig. 5.12).
- We observed that the power consumption would be higher for continuous animations on the textile. This is because, at steady state, power is required only to maintain the required temperature. Conversely, in transient states or when the animation is occurring, power is continuously used at a higher rate to achieve the required temperature soonest possible.

- Results indicate that the miniature Peltier elements possess the best power consumption characteristics for a non-emissive textile display. But in the case of stationary and flat displays with larger pixels, the use of larger Peltier elements could be suitable to ease the process of integration. For mobile displays, the use of miniature Peltier elements would be the best choice (Figs. 5.10 and 5.12).

5.6.2 Prototypes and Applications

We presented some of the initial prototypes and three diverse applications that were implemented using the textile display system. The main motivation behind these works was to identify the applicability of the textile display system in the real world. As observed, we present some key points identified with the system.

Material: The system was implemented in two main types of materials, textiles, and paper (dMarkers and paper-based sensor). These materials are two of the widely used materials in everyday scenarios. These materials can be easily used in such applications due to thermochromic inks' ability to be screen-printed onto textiles or papers. As such, any material that can withstand thermochromic inks and have enough thermal conductivity can be converted to a non-emissive display.

Ubiquity: Similarly, the usability of widely used materials such as paper or textiles makes the system suitable for a wide range of daily objects such as furniture, wall papers, and calendars. One of the main characteristics of the system, non-emissivity, would enable merging of the technology and material seamlessly.

Wide area of application: Combining the summary of above results, it is evident that the system can be used in many different areas of applications. For example, we illustrated the merging of this technology from merging with traditional crafts to enhancing Augmented Reality applications to fabricating a new type of temperature sensor.

5.7 Design Methodology

This section lays out a methodology for designing non-light-emissive textile displays as a final conclusion to the work described in this chapter. The methodology was developed based on the design processes and the above discussion points we experienced from the development of the prototypes.

Figure 5.26 summarizes the design methodology of non-light-emissive textile display systems. We identified four key steps for the process of designing a non-emissive textile display system. They are as follows:

- Thermochromic ink selection
- Peltier selection

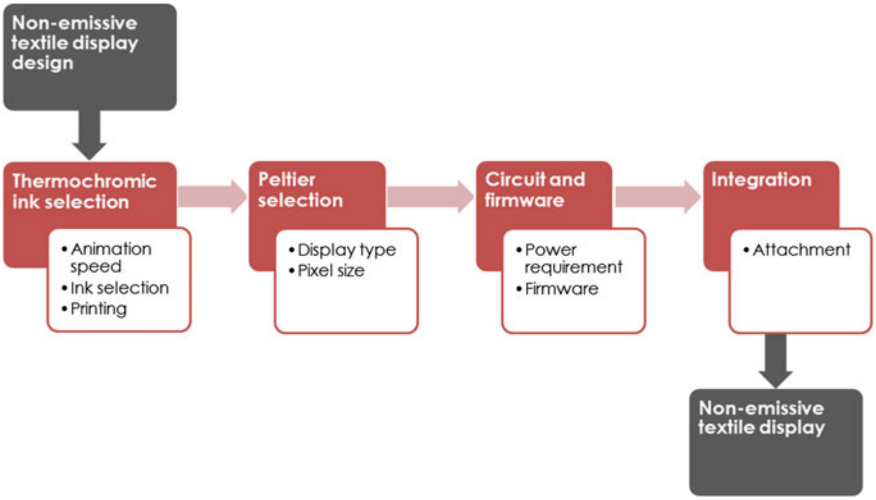


Fig. 5.26 Design Methodology for a non-emissive textile display

- Circuit and firmware design/implementation
- Integration

Next, we discuss the process of each of these steps.

5.7.1 Thermochromic Inks

Thermochromic ink selection is the first step of this design process. This step consists of two substeps: identifying the animation speed (which is useful for the next steps), ink selection, and the printing.

- Animation speed

Animation speed is critical in identifying the thermochromic inks for the system. Based on the animation speed in frames-per-second rate, we can determine the customization of the actuation temperature ranges for the thermochromic inks. By referring to Fig. 5.25, we can estimate the actuation range of the thermochromic inks. Through our observed results, if the animation speed is to be 1 FPS, the suitable temperature difference should be approximately 6 °C for the thermochromic ink.

- Thermochromic ink selection

Once the thermochromic ink actuation range is selected, the color can be customized to the requirement of the system. It should be noted that once the thermochromic ink is heated, the base fabric would appear. Thus, the color selection should be according to the requirement and such that there is enough color difference between the ink and the base fabric for the animation to be visible. In certain cases, the color change might be to a different color (instead of colorless). In such cases, the user can customize these colors according to the base fabric.

- Printing

The most common method used for printing thermochromic inks is screen printing. Generally, most such thermochromic inks require mixing the ink with a textile binder solvent which is usually provided by the supplier. Please refer to the supplier for the mixing details. According to the requirement, either the full fabric or individual pixel patterns (as seen in Sect. 5.5.1.1) can be printed with thermochromic inks.

5.7.2 *Peltier Selection*

- Display type

The type of display could be flat and stationary, mobile or flexible. Ideally, even though miniature Peltier elements would be the best choice for any display, in some cases due to ease of integration, larger Peltier elements are suggested. However, this selection can be extrapolated into any type of Peltier element available in the market since, here, we only use the Peltier elements that were used in this research as a guide.

- Pixel size

If the user decide to use a Peltier other than a miniature Peltier element, the pixel size could be the main factor to determine the selection of the Peltier element. Other than for mobile displays, larger Peltier elements, according to their size, are suitable for flat and stationary displays. As we have demonstrated in our prototypes, the use of Peltier size can be dependent on the kind of image the user wishes to animate.

5.7.3 *Circuit and Firmware*

This step is mainly dependant on the selected temperature range of the thermochromic inks and the selected Peltier elements.

- Circuit design

The basic circuit design for a single Peltier element is as described in Sect. 5.3.1.3. For multiple Peltier elements, this circuit can be repeated. The main factors in this step is the determination of the parameters of the MOSFET modules. Based on the parameters of the selected Peltier module, the maximum current required per module can be identified. Using these data, the MOSFET modules can be selected such that the maximum current of the Peltier module is less than the maximum drain current rating of the MOSFET module.

- Firmware design

Upon the design of the circuit, the firmware for the PID controller can be programmed as explained in Sect. 5.3.1.4.

5.7.4 Integration

The basic integration layout is as described in Sect. 5.3.1.5. The key element here is making sure of efficient heat transfer through all the layers from the Peltier element to the fabric. In addition, careful attention must be paid to placing the temperature sensor on the Peltier element. The sensor must be placed directly on the surface of the Peltier element be covered by copper-adhesive tape.

5.8 Conclusion

The development of non-light-emissive textile displays introduces a plethora of design and technical parameters such as colors, activation temperature ranges, and power requirements as seen through this work. However, above all, the technology has an immense potential as a ubiquitous display as it can blend with many other technologies as well as crafts. The presented design methodology briefly summarizes and discusses the guidelines for implementing non-light-emissive textile displays. This methodology carefully details all the factors that should be taken into consideration during the process as experienced by the authors. As such, we envision this technology can be utilized by any practitioners in the future to implement novel ubiquitous textile displays.

Summary

This chapter discusses a non-emissive textile display system. The current implementation of the system consists of thermochromic inks, Peltier semiconductor elements, and a fine-tuned PI controller system. We present a detailed technical analysis of this system and its results. With this integration of technology, the controller is able to control the color of the fabric accurately and with a fast heating or cooling rate. Many ubiquitous fabric display prototypes and applications of the system are presented. These demonstrate the ubiquity

of our system and its seamless integratability to our environment. As such our main contributions are as follows:

- Detailed implementation components of the system.
- A comprehensive technical analysis of the system.
- Wide range of prototypes and diverse applications that demonstrates the system's usability in real life.
- A step-by-step design methodology for implementing a non-emissive textile display system.

Due to the calm and subtle nature of this animated fabric display, we envision that this non-emissive textile display system will be able to breathe life into the textiles of the future.

Acknowledgements The author wishes to acknowledge Mili John Tharakan, Owen Noel Newton Fernando, Kouta Minamizawa, Ardian David Cheok, and Ryohei Nakatsu for their contributions during the lifespan of this work. The work was partially supported by CUTE Project No. WBS R-7050000-100-279 partially funded by a grant from the National Research Foundation (NRF) administered by the Media Development Authority (MDA) of Singapore and the JST-ACCEL 'Embodied Media' project.

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Chapter 6
Haptic Feedback for Wearables and Textiles Based on Electrical Muscle Stimulation

Max Pfeiffer and Michael Rohs

Abstract Electrical muscle stimulation (EMS)—also known as functional electrical stimulation (FES)—has the potential to miniaturize haptic feedback technology and to integrate it into wearables and textiles. EMS offers a wide variety of haptic feedback, ranging from a small tingle to strong force feedback. In contrast to stationary force feedback systems and exoskeletons, EMS technology can easily be miniaturized as it does not require moving mechanical parts. Instead, EMS activates the user's muscles. Textiles with embedded EMS technology offer the opportunity of *ubiquitous haptic feedback*. This kind of feedback is always available and can be applied to the whole body. In this chapter, we present the potential and limitations of EMS as a haptic feedback technology in wearable and textile-based computing. We begin with an in-depth literature review of haptic feedback and the design space of haptic feedback in general. Then, we describe the fundamentals of EMS, including typical placements of surface electrodes and specifics of textile EMS electrodes. This is followed by usage characteristics and safety issues of EMS feedback. Then, we present various application scenarios and introduce two research examples in depth, namely freehand interaction and pedestrian navigation with EMS feedback. Finally, we introduce a toolkit for haptic feedback prototyping and show how to apply it in different sample scenarios. We conclude this chapter with a discussion of research challenges and limitations, regarding EMS and textiles.

6.1 Introduction

Input and output devices have followed the general trend of miniaturization and have become integrated into mobiles and wearables. They will likely also become parts of textiles. Not all output devices have achieved miniaturization [1]. Visual output is already possible [2, 3]. Haptic output devices are hard to reduce in size and weight

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S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_6

because of mechanic parts, such as motors, membranes, or hinges, and they have high power consumption. Current haptic output devices have a limited feedback range in terms of intensity and scope, such as vibration, or they are bulky machines that are designed for special application areas, such as in surgery.

Electrical muscle stimulation (EMS) can generate a large range of haptic feedback. EMS has been used for miniaturizing and simplifying haptic devices [4–10]. EMS output ranges from a tactile tingling feeling [11] to force feedback. Stronger EMS signals achieve the movement of joints [12] and whole-body parts [13] or produce a counterforce to voluntary movements [6, 14]. We believe that this technology can close the gap between vibration feedback and force feedback as produced by exoskeletons. EMS does not require mechanical actuators and generates a considerable range of feedback. EMS stimulates the sensory and motor nerves and activates the user's muscles. The stimulation operates at low currents from 10 to 30 mA. EMS feedback is applied on the user's skin, where it is usually covered by clothes through surface electrodes. Textile electrodes are washable and can be embroidered on the surface of other textiles or integrated (waved, warp-knitted, or braid) in clothes [1, 15]. Since textile electrodes are flat on the skin and flexible, they are comfortable. Unlike vibration motors, they do not need rigid cases at the point at which the feedback is applied.

Regarding form factor, power consumption, and feedback range, EMS has a huge potential in textile computing. Furthermore, when EMS is integrated into clothes, such as sportswear or everyday clothing, a large range of haptic feedback is always available. The integration of EMS feedback in textiles may play a central role in achieving *ubiquitous haptic feedback*. We envision that this opens up further use cases for haptic feedback. For example, a future scenario could be as follows: A cook wears EMS-based clothing. The cook's hand is automatically guided to a pot when a sauce needs stirring or the hand is pushed away before touching a hot plate.

However, this technology also comes with disadvantages and challenges that need to be solved. Specific user groups such as people with certain diseases cannot use EMS for safety reasons. Also, the placement of the electrodes and the calibration process of the EMS signal parameters are challenging.

In this chapter, we give an overview of existing feedback technologies and discuss them in contrast to the potential and the limitations of EMS as a wearable output technology. In different application scenarios, we show how EMS can be applied and investigated as haptic feedback in a mobile, wearable, and textile context. We give a detailed literature review on haptic and EMS feedback in human–computer interaction. We discuss how existing textile sensing electrodes are used and present an overview of projects that use textiles for EMS output. Then, we present a design space for applying haptic feedback. We discuss important parameters and settings that need be taken into account when designing whole-body haptic feedback. These parameters and settings can easily be mapped to the context of wearable and textile computing. Then, we focus on EMS specifics and basics. There, we look at typical parameters that are used for EMS in physiotherapy and that work reliably for generating haptic feedback. Afterward, we give a number of examples of electrode placements for force feedback. We describe a set of muscles that are easy to actuate and the resulting movements.

In the section on application scenarios, we first envision possible examples of ubiquitous haptic feedback. Then, we present two research projects that use EMS as a haptic feedback technology: In “freehand interaction,” we compare vibrotactile feedback with EMS feedback in its simplest form and show that EMS is a reasonable alternative to vibration feedback. In “cruise control for pedestrians,” we intervene with the human locomotor system and change the walking direction of pedestrians. We steer them successfully through a public park with a minimum of distraction.

Finally, we introduce the *Let your Body Move Toolkit* for fast haptic prototyping with EMS. First, we present a general prototyping process for designers of haptic feedback. Then, we consider the toolkit’s hardware and software components and show how it can be wirelessly connected to other devices. Afterward, we give further application scenarios of the toolkit for EMS prototyping in wearable contexts. Finally, we present the challenges and limitations of EMS feedback, discuss the potential of EMS in textiles, and summarize the lessons learned on using EMS in human–computer interaction.

6.2 Background

Haptic feedback uses an additional output channel beyond visual and auditory feedback. Several research projects have looked at providing haptic feedback for interacting with remote systems and in virtual environments [16–18]. Mobile input devices are already minimized in size and integrated into textiles such as touch input with textile keyboards or circuits that are mounted on textiles [19]. Textile input goes further than simple touch input or applying sensors on the surface of the textile material. In medical contexts, textiles are used for measuring biofeedback such as blood pressure, heart rate, muscle activity, skin resistance, EMG, ECG, or EEG [1]. Therefore, textile electrodes are integrated in clothing. Textile electronics are either embroidered on the surface of the textiles or integrated (woven, warp-knitted, or braided) into the textiles [15]. They are placed flat on the skin. Textile electronics are flexible and comfortable to wear and barely noticeable when they are integrated in normal clothing.

Textile output has been investigated less. Visual output is possible with textile displays [2, 3]. Haptic feedback technology is hard to shrink haptic feedback technology or to reduce its power consumption to follow the trend of miniaturization. For example, thermo-therapeutic appliances for heating or cooling have already reduced in size and have been integrated into textiles, but still require significant amounts of power.

In the following, we review related work that concerns haptic feedback. First, we look into how haptic feedback can stimulate different senses. Then, we consider technologies to create haptic feedback. Afterward, we discuss electrical feedback and how it is used for interactive systems. Finally, we focus on textile electrodes for measuring biofeedback and how similar electrodes are used for applying EMS output.

6.2.1 Haptic Feedback

The haptic sense provides a rich and versatile feedback channel. Haptic feedback can stimulate a number of different receptors in the skin, including free and sensory hair nerves and receptors for temperature, touch, pressure, and pain, and also the receptors in the muscles and joins for contraction, stretching, and the speed and change of the stimuli [20]. Prior work has looked at providing haptic feedback through water, air, pressure, motors, vibration, temperature, and electric currents [12, 17, 21–23]. Stimulating particular receptors opens a new feedback channel that induce perceptions related to, for example, certain properties of virtual objects, such as size or mass. Furthermore, prior work shows that haptic feedback can improve the recognition of similar objects, the efficiency of task solving, as well as the user experience while interacting with these virtual objects [20, 24–29].

Haptic stimuli are used in research and commercial products for feedback. The most common haptic feedback technology generates vibration feedback, and it can be reduced in size to fit in mobiles and and wearables. The size of a vibration feedback device correlates with the maximum strength of the vibration, because the vibration is typically generated by an unbalanced weight on a motor. This limits the maximum strength of vibration feedback and does not allow for generating substantial force feedback. Force feedback is required to simulate certain properties of virtual or remote objects (e.g., CyberGrasp [30] and Phantom [31]). Force feedback can make interaction with a system more realistically [18]. In most cases, force feedback is used in desktop systems or in specialized environments but sometimes also in mobile systems. For example, Nitzsche et al. [32] present a mobile haptic system moving in front of the user during interaction. For motion-intensive interaction techniques (e.g., gestures), small, portable devices can be used that require the user to wear gloves or markers [17, 24]. However, force feedback systems usually obstruct hand and forearm and restrict both the tactile sense and the mobility of the hand. Hence, such systems are usually cumbersome to wear for a long period of time. There is still a gap between weak tactile feedback technology and precision force feedback technology that could be narrowed by electrical feedback.

6.2.2 Electrical Output

Electrical stimulation has been investigated since the eighteenth century. In its current form, EMS goes back to the 1970s, where, for example, Strojnik et. al. used it for rehabilitation therapies [10]. They investigated how complex muscle movements can be supported through muscle stimulation. Gillert [33] describes different application areas. Porcari et al. investigated how EMS impacts on different human body parts [9].

Table 6.1 Projects using as EMS output

Project	Description	Actuated muscles
NESS H200 [34]	Rehabilitation device that helps stroke patients to grasp objects	In the lower arm to enhance the grasping strength
L300 [35]	Rehabilitation device to support patients with the foot drop problem while walking	In the lower leg to lift the foot tip in the swinging phase
UnlimitedHand [38]	Force feedback gaming bracelet	In the lower arm for force feedback in the hand
ARTIFACIAL [42]	Art project to actuate facial expressions	In the face to change facial expressions
DUTY [40]	Art performance that lets people play bells	In the arms to lift up and shake the bell
GAME ON [41]	Art performance in which the audience controls two boxers	In the arm and shoulder to perform punches

Besides research projects, EMS output is already used commercially in products and art performance as shown in Table 6.1. In rehabilitation, wearable systems support stroke patients in grasping (NESS H200 [34]) and in walking (L300 [35]). Portable EMS devices were developed by Brewing [36] and Miha Bodytec [37], mainly for fitness training. UnlimitedHand [38] is a haptic game device. That haptic feedback bracelet generates hand movements with EMS electrodes on the lower arm. Moreover, artists have used EMS as an output technology to manipulate facial expressions [39] and to let a group of people perform music (DUTY [40]) or even let people fight (GAME ON [41]).

In the field of human–computer interaction (HCI), using EMS to provide feedback has received considerable attention. PossessedHand [12, 43] is a device for controlling finger joints by EMS. The authors show that electrical feedback is suitable for mixed reality, navigation, and learning to play instruments. Further, EMS was tested as a feedback method for a 3D computer game [5]. Farbiz et al. [4] investigate mixed reality EMS feedback for visualizing a ball that can be hit by a real racket. Lopes and Baudisch [14, 44] use EMS in a mobile game as force feedback. They investigate the strength of EMS signals and test the amount of force a user can provide. Pfeiffer et al. [8] use EMS for interacting with large displays in public space and provide EMS feedback in a Kinect-based interactive game. They show that EMS feedback works in 3D virtual hand selection as suitable alternative to visual highlighting [45, 46]. In addition, haptic feedback for flat surfaces, such as touch display or tracked paper maps, was investigated [7]. In cruise control for pedestrians, EMS was used to manipulate the walking direction of pedestrians [13] to reduce the amount of visual and mental distraction. Finally, hidden affordances were communicated with EMS gestures to the user [47].

6.2.3 Textile Electrodes

The EMS signal for haptic force feedback is usually applied with self-sticky electrodes. These electrodes can be only used a limited number of times, and they are not washable. Textile sensor electrodes are already well investigated to measure body feedback such as skin resistance, EMG, ECG, or EEG. They are used in sports, fitness, medical care, and physiotherapy [1]. To measure the electrocardiogram (ECG) [48], electromyography (EMG) [49], or electroencephalography (EEG) [50], sensor electrodes are mounted on the skin surface and made of conductive materials. Note that we are only focusing on surface electrodes and exclude implanted electrodes. The textile electrodes can be made of metal, conductive plastic, or silicone. In contrast to self-sticky electrodes, they can be washable and integrated in the textiles. Such textile electrodes can have different forms so as to cover specific muscles [15]. These electrodes are designated to be comfortable to wear in long-term monitoring. Hoffman and Ruff present flexible dry-surface electrodes for long-term ECGs [51]. Other textile sensor electrodes need salt solution, sweat, or conductive gel for an optimal conductibility between electrode and skin.

In contrast to other haptic feedback methods, EMS is lightweight and has a relatively low power consumption. The EMS signal can be applied to the user's body though flexible conductive materials similar to textile sensor electrodes. Rotsch et. al. [15] discuss how to use textile sensor electrodes for EMS output. They tested these electrodes with common textile test methods such as washing against abrasion and sanitizing ability. The authors used typical EMS parameters and concluded that the perceived EMS stimulus does not change after running these test methods compared to new textile electrodes. EMS technology is well fitting for textiles since the current is applied to the muscles over the skin, usually at the places that are covered by clothes, such as arms or legs. Similar to textile sensor electrodes, EMS electrodes always need a conductive path to the user's skin [48]. This can be achieved with tight clothing such as functional underwear, vests, or bandages.

Commercial projects use textile electrodes in the context of sports or gaming (an overview is shown in Table 6.2). EMS gyms like Miha Bodytec [37] or XBody [52] use wet textile electrode bands and electrodes that are integrated into vests to apply EMS current during fitness exercises (Fig. 6.1). Antelope [53] is a full suit with integrated textile electrodes to enhance sports such as running and cycling and to make the exercises more exhausting. This suit is connected wirelessly and controlled via an mobile application. ARAIG [54] and Teslasuit [55] are start-ups that build force feedback gaming suits. These suits apply feedback depending on the gaming situation, such as when an explosion happens or the player gets shot. These projects show a general trend, namely that EMS feedback is likely to enter the mass marked.

Table 6.2 Projects using textiles for EMS output

Project	Description	Electrodes
Miha Bodytec [37]	Gym suit for EMS-based training	Wet electrodes to actuate large body parts
XBody [52]	Gym suit for EMS-based training	Wet electrodes to actuate large body parts
Antelope [53]	Sports suit to intensify exercise with EMS	Silicone electrodes on sweat basis
ARAIG [54]	Sound, vibration, and EMS gaming suit	6 speakers, 40 vibration motors, 4 electrodes
Teslasuit [55]	Force feedback gaming suite	Up to 56 electrodes, type of electrodes is not clear specified

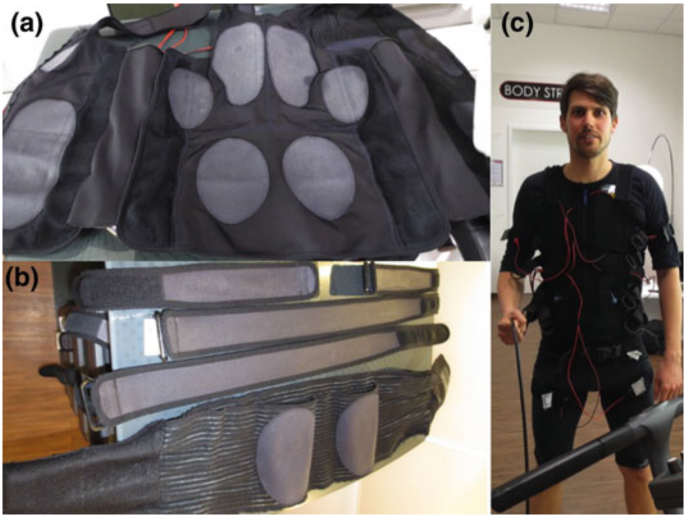


Fig. 6.1 EMS training suit with textile electrodes: **a** EMS vest for breast, abdomen, shoulder, and back muscle; **b** EMS bands for arm, leg, and gluteal muscle; and **c** a user wearing the suit

6.3 EMS for Haptic Feedback

In this section, we focus first on the basics of EMS for generating haptic feedback such as important stimulus parameters and waveforms. After that, we consider sample placements of electrodes for applying EMS-based force feedback. Then, we discuss how EMS electrodes can be integrated into clothes and textiles. Afterward, we look at EMS specifics that we need to keep in mind when applying EMS to users. Finally, we discuss important safety aspects that have to taken care of when designing and applying EMS feedback.

6.3.1 EMS Basics

This subsection gives an overview for feedback designers who are new in using EMS as haptic feedback technology. We start with feedback modalities that can be generated with EMS followed by how the muscle contraction works, then we focus on typical strength, characteristics, and forms of the EMS stimuli, and finally, we consider different feedback patterns.

Feedback modalities: EMS and FES also known as neuromuscular electrical stimulation (NMES) or electromyostimulation activate the muscles. This results in a limb movement or is perceived as force feedback by the user. The position at which the feedback is applied usually differs from the position at which the feedback is perceived (see Sect. 6.3.3). As a side effect of EMS, tactile receptors are also stimulated. This effect is applied in transcutaneous electrical nerve stimulation (TENS). The tactile feedback ranges from a weak just noticeable tingle, which users often describe as vibration, to a strong tingle, which users often compare to pinpricks on the skin. This tactile feedback is perceived in the area that the current crosses. In this section, we focus on the muscle actuation rather than the tactile feedback.

Muscle contraction: The weak current for EMS crosses the skin from the first surface electrode, flooding though the tissue and the muscle and back to the second electrode. The motor nerves are stimulated by the current that leads to a contraction of the muscle. The contraction lets the muscle tighten and pulls the tendon of a limb, which lets the limb move. This effect can be used to support a movement, such as to amplify grasping, or as a counterforce, to stop or slow down a movement. Different elementary movements can be combined to an EMS gesture. In contrast to a natural contraction, the muscle fibers are actuated continuously, which lets the muscle exhaust faster [56].

EMS feedback strength: The strength of the electrical impulses (current) depend on the skin resistance and the voltage that is applied. The skin resistance can be influenced by hairs and skin hydration, as well as the thickness and characteristics of the underlining tissues. For electrical impulses of a duration longer than 10 ms, a current of 10–20 mA stimulates only the sensory nerve fibers, a current of 20–40 mA in addition stimulates the motor nerve fibers, and a current of more than 40 mA also stimulates the pain nerve fibers [57] as shown in Fig. 6.2. Which nerves are stimulated depends on many factors of individual users. Therefore, the strength of the current needs to be calibrated for each muscle and user individually.

Impulse characteristics: The electrical impulses can follow different characteristics as shown in Fig. 6.3. Off-the-shelf devices typically generate signals with a pulse width of 50–300 μs and a pulse frequency of 1–150 Hz. The pulse intensity as discussed before depends also on the pulse width and pulse frequency. For very low frequencies (1–30 Hz), the muscle ticks for each pulse, and for higher frequencies (30–60 Hz), users can still differentiate each pulse. From our experience, a frequency between 70 and 100 Hz and a pulse width of 50 μs work well for a wide range of users.

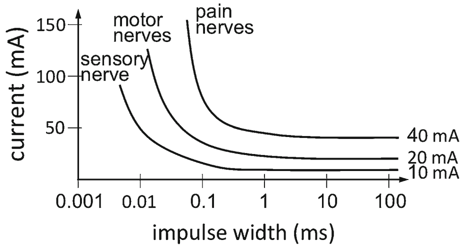


Fig. 6.2 Gradient of the nerve stimulation over time [57]

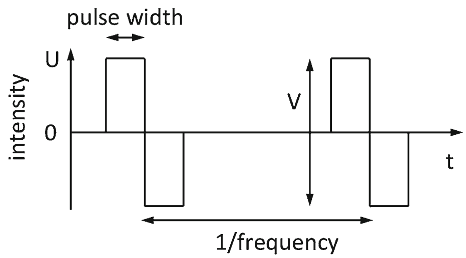


Fig. 6.3 Impulse characteristics for designing EMS feedback

EMS signal forms: The most common EMS impulse form is the square wave as shown in Fig. 6.4. This waveform is easy to generate and works well in many cases. Most off-the-shelf EMS devices generate a square wave by default. They are typically also able to generate saw or sine waves as shown in Fig. 6.4. The waveform should always have a positive and negative signal parts, so that the current flows bidirectionally though the tissue.

Feedback patterns: Complex signal patterns can be generated from this basic impulse shape. The simplest possibility is to switch the impulse on and off over the time. The generated pattern can encode information to be transmitted haptically to the user. It may also be used to combine elementary movements to gestures. For example, actuating the muscle that pulls the hand up in alternation with the muscle that pushes the hand down lets the user perform a wave gesture. The signal strength may also change over time. As patterns, the signal strength can be increased slower to smooth the actuated movements. Or the signal intensity can follow specific functions such as the sine or triangle function.

With this background knowledge, we can design the EMS output signal.

6.3.2 Textile EMS Electrodes

As discussed before, there are different types of electrodes to apply the EMS stimuli. Self-sticky electrodes are the most common and simplest to use. Other electrodes are suck electrodes and plate electrodes. Such electrodes are made of metal (textiles or plates), conductive plastic, or silicone. They are either inelastic or flexible. The electrodes need a good conductivity to the skin. To reduce the resistance of dry or

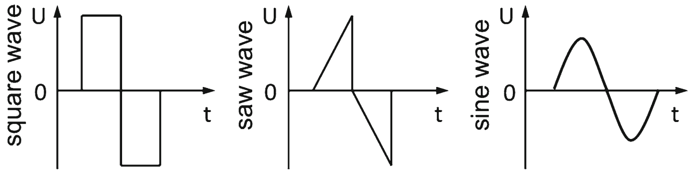


Fig. 6.4 Typical EMS impulse forms that are generated by off-the-shelf devices

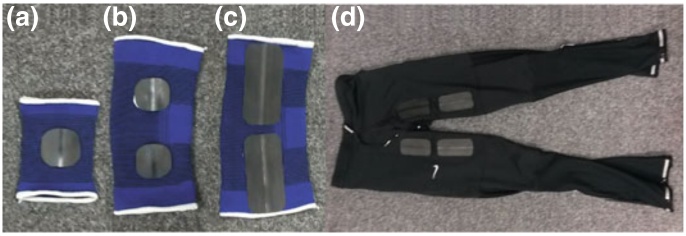
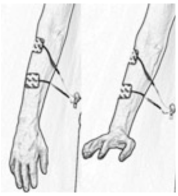


Fig. 6.5 Silicone electrodes: **a** bandage for the *upper arm* to actuate the biceps, **b** bandage for the *lower arm* to actuate extensor digitorum, **c** bandage for the *lower leg* to actuate the tibialis anterior, and **d** sports trousers to actuate the sartorius muscle

hairy skin, salt solution or conductive gel can be used. The electrodes are sucked, sticked, or wrapped to position over the muscle on the skin. Wearables electrodes could be glued or sewn on the textiles or woven into textiles. Electrodes that are integrated in clothes also need a direct contact to the user's skin or a conductive intermediate layer between the textile electrodes and the skin. These electrodes can be attached to sportswear, to underwear, or also to special bandages as shown in Fig. 6.5. Such textile electrodes are usually washable. Depending on the muscles they are applied to, the electrodes may have different shapes. However, in many cases, electrodes with a size of 40×40 mm work well. If the EMS signal is applied to a small muscle and the electrode size is adapted, then the a amount of current per area gets larger. This simulates more receptors in the skin and increases the tactile feedback at the position of the electrodes. For very small electrodes, this sensation can become uncomfortable. However, larger electrodes result in a larger dispersion of the current and other muscles may be actuated as well. There is always a trade-off between precise muscle actuation and the tactile side effects of small electrodes.

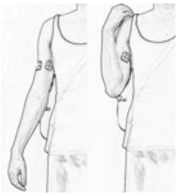
6.3.3 Electrode Placement

Not all muscles are easy to reach for EMS feedback, especially when using surface electrodes. Several muscles are very close together or even overlay other muscles. In this section, we give examples of the electrode placements on well-reachable surface muscles to achieve a set of elementary movements. One elementary movement is generated by a single contraction of a muscle or a muscle group. These elementary movements can be combined to gestures.



Hand up: The extensor digitorum muscle lifts up the hand. It is connected through a tendon to the upper side of the hand. When the electrodes are not properly placed on this muscle, the signal either actuates the extensor carpi ulnaris (lateral side) or one of the thumb extensors (medial side, extensor pollicis brevis, or extensor pollicis longus), which move the thumb inside. The muscles in the lower arm are placed very tightly together, and an exact placement is difficult. The effect also depends on the rotation and posture of the hand.

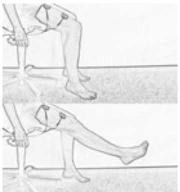
Hand down: The electrodes need to be placed over the flexor digitorum profundus, as this muscle pulls the wrist down. An imprecise placement also activates flexor digitorum superficialis, which bends the proximal interphalangeal (PIP) joints; i.e., it lets the upper finger segments claw. The flexor digitorum profundus does not actuate the thumb. To bring the thumb inside during this movement, the thumb muscle (flexor pollicis longus) also needs to be activated. Activating these muscles together results in the user making a fist.



Lower arm up: To lift the lower arm up, the biceps brachii muscles (caput longum and caput breve) need to be actuated. On this larger muscle, the electrodes may be placed vertically (proximal–distal) or horizontally (lateral–medial). The image shows the horizontal placement. With the horizontal placement, we achieved better actuation results, because the current crosses the whole muscle. However, the horizontal placement may lead to a tingle in the palm of the hand, in which case the vertical placement should be chosen.

Arm up: The arm is primarily lifted up by the deltoid muscle. When actuating it together with the biceps brachii muscles, the arm moves a bit forward. To avoid this, the shoulder muscles (infraspinatus and teres minor) can be actuated to pull the shoulder backward a bit.

Foot up: Activating the tibialis anterior muscle leads to lifting up the forefoot. The electrodes should be placed on the upper part of the lower leg on the front side (lateral) of the tibial bone (shinbone). The largest effect occurs, while the foot is swinging in the air.



Leg up: When sitting, the lower leg can be lifted up (ventral) by actuating the quadriceps muscle of the thigh. The quadriceps is a large muscle that can be reached easily by surface electrodes. This large muscle requires a relatively large current and larger dispersion of the current. Therefore, a larger electrode (40×80 mm) should be used. Care should be taken when actuating this muscle while walking, as it easily blocks the leg, which may cause the user to stumble.

The above represent only a subset of the elementary movements that can be achieved with EMS. There are several other muscles that are easy to reach and can be actuated in a safe way. These elementary movements can be combined to simple but also to complex gestures.

6.3.4 EMS Usage

Every user is different! Because of anatomical idiosyncrasies, a user-dependent placement of the electrodes is necessary for each muscle and user. The perception of the signal strength, the maximum comfortable signal level, and the minimum level at which actuation starts all differ considerably across users. The skin resistance differs depending on tissue sickness, body fat percentage, skin moisture, and hair. Moreover, the resistance changes over time, e.g., when sweating.

Typically, users do not have any prior experiences using EMS. In this case, all important safety aspects need to be considered and discussed with the user. In the calibration phase, the users should gently be introduced to the EMS experience step by step. Initially, a muscle should be tested that is easy to reach, such as the extensor digitorum on top of the lower arm. The expected effect should be described by the experimenter beforehand, and the user should be allowed to adjust the signal intensity on their own. This helps to determine the maximum comfortable level. After that, other muscles can be calibrated step by step.

To locate a specific muscle, the user should be asked to perform the expected movement and tense the muscle. Usually, the movement of the actuated muscle is visible. The electrodes can be placed at this position. Then, the user him- or herself should increase the current step by step.

The actuated muscle may change its form or it may move under the skin so that the surface electrode is not longer precisely placed over the muscle. If the electrode is placed on the boundary of the muscle, a periodic oscillation may occur, in which the muscle is repeatedly pushed away from the electrode while contracting, receives less current, relaxes, and moves back into the current. These effects need to be taken into account when elementary movements are combined to gestures or if force feedback should be applied during a voluntary motion of the user.

Placing the electrodes on tissues with a lower resistance than the muscle will lead to the current bypassing the muscle. This has unexpected effects such as actuating the biceps brachii muscles when one electrode is positioned on the lower arm and the other in the crook of the arm. In this case, the electrodes need to be shifted slightly.

6.3.5 Safety Issues

There are several medical risks that need to be considered when using EMS for haptic feedback. The haptic feedback designer and also the user need to consider these risks and limitations and always need to be aware of it. The user's health has the highest priority! It is strongly recommended that the feedback designer and users consult the manual of the EMS device and follow the safety recommendations.

It is crucial that electrodes should never be placed in front of the torus near the heart. EMS devices should not be used in combination with a pacemaker or by people who have any heart disease. It is recommended that pregnant woman, people with epilepsy, with cancer, after a surgery, with sensitive skin, or with a skin disease should not use EMS —or only after consulting their physician.

Furthermore, extremely high EMS signal levels stimulate the pain nerves. This threshold differs between users and the position at which the feedback is applied. Therefore, for every muscle and electrode placement, the EMS strength should be calibrated individually by the user. Reports from the domain of fitness training have shown that long activation periods with high EMS levels can result in muscle fatigue and overtraining of the actuated muscle.

Finally, running EMS experiments typically requires the approval of the local ethical board.

6.4 Application Scenarios of EMS

Apart form the safety issue and research challenges, EMS can be used in several application areas. When it is integrated in textiles, it could be available everywhere as ubiquitous haptic feedback. We envision that EMS feedback will soon be available in specific wearables, bracelets, bandages, suits, and other textiles. We see the first applications in sports and gaming and later also in larger application fields such as notifications or coding information. Other application areas are extending object properties, guidance, safety and prevention, assertive feedback, and learning movements. In this vision, we assume that research challenges related to other technologies, such as ubiquitous localization and tracking, will be solved. In the following, we discuss envisioned application areas and present several examples. Afterward, we focus on two application areas and discuss freehand interaction and pedestrian navigation with EMS feedback.

6.4.1 Envisioned Scenarios

In HCI, EMS feedback is still in its infancy and there are several research opportunities to be yet explored, such as a precise and linear actuation of muscles or performing reliable complex gestures. We envision that these challenges get solved and the following application scenarios can benefit from EMS as ubiquitous haptic feedback. Research projects are already explored some of these scenarios.

Notification and coded information: EMS can be used for new forms of notification in everyday life scenarios. Silent but immersive alarms can inform users about upcoming events or messages. The user feels the feedback or performs a movement or gesture and becomes the output device. A smartwatch that is connected to the muscles of the user's lower arm could make the user lift the hand up and then push it down, to let the hand wave (see Sect. 6.5.4: Event Triggering). Such a waving gesture could be mapped to event or message types. If it is a standard gesture, the user, but also the people around, can interpret the gesture. A new sign language for actuated output could be created. On the other hand, a private silence message could communicate to the user through tactile feedback or coded in secret gestures that only the user knows. The output device and the user could have a shared secret like pin code. In addition, the system can detect a combined authorization gesture, in which one part is performed through the device and an additional part by the user. Finally, emotions transfer through actuated postures or gestures become possible. Specific personal gestures can be copied to a close person and could decode emotions. For example, in long-distance relationships, these gestures cloud be familiar to the partner and let partner feel more strongly connected. On the other hand, a "close remote interaction" like a hug from a distant partner becomes possible. In this case, the haptic output system could trigger the hug with the user's own arms.

Extending object properties In interaction with non-physical or virtual objects in virtual or mixed realities, haptic feedback is often missing. The user interacts with midair and does not feel the object size, weight, or surface structures. In many cases, the user does not want to have the hands covered with an additional device. In case of a ubiquitous haptic feedback, such object properties can be simulated. For example, in remote interaction with public displays, the user is maybe not able to touch the surface of the display, so the user interacts in midair [8]. Simulating a response of a button or of a virtual object with EMS could make the interaction more natural. Moreover, virtual objects can be augmented with tactile and force feedback to simulate object properties such as softness and hardness, weight, or size. This could increase user experience in the virtual environment [8]. Varying strengths of EMS feedback may simulate the different properties. However, a number of physical objects have hidden or have not directly visible affordances. Such as a doorknob that needs to be turned in an unusual way (turned left instead of right) or a spray can that needs to be shaken before use. In this cases, EMS gestures could communicate this missing affordance to the user [47].

Guidance Haptic feedback can guide people to objects or points of interest in our near environment or further away. In our near environment, a hand on a paper map can be guided by EMS feedback to a point the user is searching for. In addition, the spatiality of a map can be explored by simulating the surface structure [7]. Again, a complete tracking of the environment and an automated search would be necessary. Guiding people to lost objects is still challenging [58]. It could be possible to show the direction toward the lost object with the hand [12]. The user only needs to follow the finger or hand. In this case, no audio or visual output is necessary to find the lost object. When envision that ubiquitous haptic feedback also enables pedestrian navigation, the human locomotion system can be engaged to change the walking direction of a pedestrian. The user can be guided to a particular destination with a minimal cognitive and visual distraction [13].

Safety and prevention In working environments, people are often exposed to dangerous areas or are located close to dangerous machines. Force feedback can reduce the likelihood that a worker moves toward dangerous areas. The force feedback can push the hand of the worker away from hot objects or dangerous machines when the worker is inattentive or distracted from the main working task [47]. Moreover, an accident avoidance system can prevent a person from running in front of a car. Inattentive pedestrians can automatically change the walking direction or stop before they enter a critical situation. Finally, a vestibular correction system could prevent a person from falling by automatically triggering a side step.

Assistive feedback Assistive feedback with EMS is already considered in research and in commercial products that support stroke patients while performing grasping or walking movements. In the future, with electrode grids and closed control loops, it could be possible to let the user perform more precise and more complex movements or gestures. This can support stroke or paraplegia patients in their everyday life. Blind people could be assisted while walking to let them feel obstacles in front of them. A virtual white stick could provide a haptic response and make the obstacles in the environment perceptible or automatically guided the user around them. It is possible to simulate textures of visual representations such as photographs or figures with EMS feedback [7]. This could assist a blind person to explore haptically such presentations that are only visually perceivable.

Learning movement Learning movements, movement sequences, gestures, or postures with high precision afford many training repetitions and corrections. Nowadays, teachers or trainers support people while learning. Today, most practices are done in groups, since one-to-one mentoring is costly. Yet one-to-one mentoring is often more effective. The teachers or trainers are not always around.

One of the most common health problems related to modern office jobs is spinal and back disorders that mainly result form wrong sitting postures. In back therapy, physiotherapists teach correct sitting postures and special exercises for the back muscles. When no trainer is around, sitting postures may be monitored and haptic feedback is given automatically through EMS. EMS could actuate the back muscles to help the patient move into the correct sitting posture while training the neglected muscles.

Furthermore, haptic tutorials can teach new movement sequences such as dancing steps. It is hard to control the whole locomotor system, but pushing or moving body parts into the right direction is often feasible. In addition, learning rhythms could be supported by using EMS feedback to find the right moment as well as playing music could be assisted by a system to learn sense of time [12].

There are many more examples and application scenarios that cloud benefit from ubiquitous haptic feedback that is always, or in specific situation, available.

Some of the given examples could easily be explored, and some pose enormous research challenges. In the following two subsections, we bring the ideas down to earth. Some of these ideas are already partly explored with EMS feedback in research. We are focusing on two different research projects to show the large field that can be covered by EMS feedback. We discuss how we can support freehand interaction and compare EMS feedback to vibration feedback. We also discuss how EMS is used to manipulate the walking direction of pedestrians and navigate people with a minimum of visual and mental distraction through a public park.

6.4.2 Freehand Interaction

With the advent of the Nintendo Wii controller and the Microsoft Kinect, midair interaction in front of (large) displays is becoming increasingly popular. Following the notion of Nancel et al. [59], we use the term *freehand interaction* to describe interactions based on midair gestures [60, 61] that do neither need a physical connection to the display nor a handheld controller. Freehand interactions are characterized by not limiting the degree of freedom for hand movements or the perception of tactile stimuli.

Different forms of freehand interaction have been investigated, focusing on the restriction of sensory capabilities and social acceptance. Obrist et al. [62] present ultrasound feedback, and AIREAL [22] air pulses are precisely shot toward the user. However, the approach is stationary and limited to a distance of 1 m. Today, vibration is the most popular haptic technology and is well understood for haptic feedback [27, 63]. It is integrated into many mobile and wearable devices. In this subchapter, we focus on capabilities of EMS and vibration as feedback methods for freehand interaction.

Prototype: To explore the feedback capabilities of *freehand interaction*, we developed an EMS feedback and a vibration feedback prototype. Both feedback modalities were applied on the forearm (Fig. 6.6) and can be embedded into clothing or textiles. Both prototypes together weigh about 580 g and uses a simple on/off feedback pattern of 750 ms duration.

The EMS prototype is built upon an off-the-shelf EMS massage device (Prorelax TENS+EMS DUO [64]). As signal parameters, we used a pulse width of 260 μs and a frequency of 60 Hz. The impulse-time intensity can be adjusted in 10 levels and has a range between 10 and 30 mA [57], so the feedback is perceivable but not felt as pain. For applying the feedback, two 40×40 mm self-adhesive electrodes were placed over the flexor digitorum profundus muscle (see Sect. 6.3.3) with a distance of 2 cm.

The vibration feedback prototype uses a motor with a asymmetric weight of 2 g that was scaled in 10 levels from 1390 to 7959 rpm ($SD = 0.04\%$). To make users perceive both feedback modalities in the same place, the vibration motor is located between the EMS electrodes shown in Fig. 6.6.

Study: In an initial experiment, we investigated the differences between levels of feedback strength for vibration and EMS and the corresponding strengths between both feedback modalities, with 12 participants (4 female, $M = 25.01$, $SD = 3.89$). As a result, we got that levels 5 (14.5 mA, $SD = 0.18$) and 8 (19.62 mA, $SD = 0.28$) for EMS correspond to levels 2 (2960 rpm, $SD = 0.67$) and 6 (5835 rpm, $SD = 0.59$) for vibration.

Then, we investigated how EMS and vibration feedback reflect (a) different types of interactions (touch, grasp, and punch) and (b) different materials (soft and hard). In total, we invited 20 participants (7 female) with an average age of 27.55 ($SD = 8.61$) for the experiment. In this experiment, different objects were shown and the user performed a certain freehand interaction toward the display (Fig. 6.7). We asked

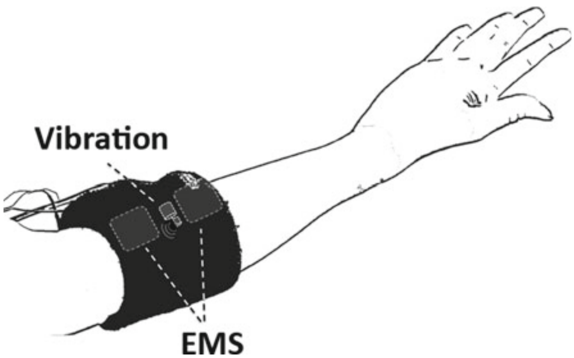


Fig. 6.6 Vibration and EMS feedback placed on the forearm

Fig. 6.7 A user receives haptic feedback when approaching an object shown on the screen

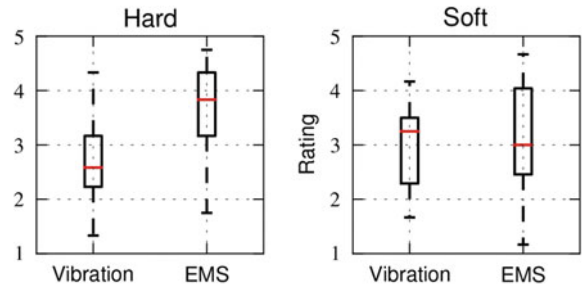


Fig. 6.8 Comparison of EMS and vibration feedback for (*left*) hard and (*right*) soft materials

the participants to stand 1.20 m in front of the display and detected the performed interaction with a Kinect. We tested two feedback methods (EMS and vibration) with all combination of two material characteristics (hard and soft) and three different gestures (“midair touch,” “midair punch,” and “midair grasp”). For EMS and vibration, the user perceives the high (EMS level 8/vibration level 6) and low (EMS level 5/vibration level 2) intensity. After performing each gesture, the users were asked to rate the fitting of the feedback for the interaction and the material on a 5-point Likert scale (1 = not fitting at all, 5 = perfect fit).

Results The 20 participants performed all 24 conditions and perceived the EMS feedback 1173 ($M = 58.65$, $SD = 19.23$) and the vibration feedback 860 ($M = 43.00$, $SD = 10.43$) times. The participants agreed that force feedback makes the interaction with virtual objects more intuitive ($Mdn = 4$, $MAD = 0$ –5-point Likert scale, 1 very bad to 5 very good). They rated EMS feedback better than vibration feedback (aggregated over all feedback strengths, interaction techniques, and interaction objects). For comparing hard and soft materials, we aggregated all gestures and strengths. As shown in Fig. 6.8 (left), EMS is perceived better than vibration for interacting with hard material. A Wilcoxon signed-rank test shows that this difference is statistically significant, $Z = -2.931$, $p = 0.003$. The comparison of EMS and vibration for soft material (Fig. 6.8, right) is not significant. The perceived feedback strength of EMS depends on the skin resistance and the user’s sensibility. Therefore, we had to divide the feedback into high and low in the second study.

The findings suggest that EMS is a particularly well-suited technology to provide haptic feedback in freehand interaction. This is also backed by the fact that it can be easily integrated in wearables and clothes. The users agreed over that all conditions the haptic feedback fits to well to the interaction with virtual objects.

6.4.3 Actuated Walking

Navigation systems have become ubiquitous. Pedestrian navigation systems require users to perceive, interpret, and react to navigation information. This can tax cognition as navigation information competes with information from the real world. In this

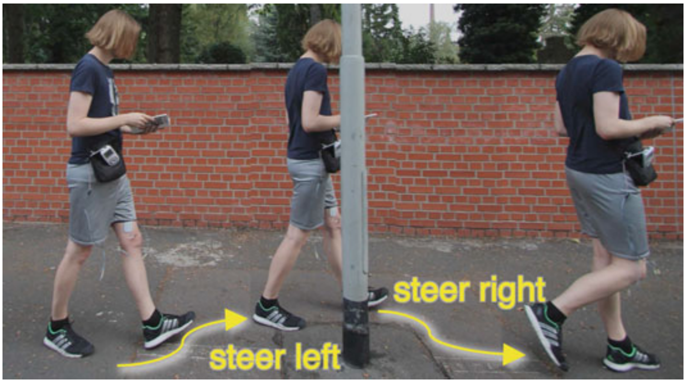


Fig. 6.9 A user is absorbed in his reading, not noticing the lamppost. Actuated navigation automatically steers him around the obstacle

subsection, we propose *actuated navigation*, a pedestrian navigation approach in that the user does not need to pay attention to the navigation task. An actuation signal is directly sent to the human motor system to influence walking direction. To achieve this, we stimulate the sartorius muscle. A rotation occurs during the swing phase of the leg that influences walking direction as shown in Fig. 6.9.

Active manipulation of walking has been explored for navigation and to enhance the walking experience. Gilded Gait [65] aims at simulating different ground textures. The user can perceive deviations from the path through modified or missing tactile feedback. CabBoots [66] is an experimental system that tilts the soles of shoes to guide the user left or right. Most closely related to actuated walking is Fitzpatrick et al. [67] and Maeda et al. [68] who manipulate the user's sense of balance through galvanic vestibular stimulation (GVS) to change the walking direction.

Approach: Common navigation systems use *visual and auditory* output (Fig. 6.10a). Here, symbolic information, such as arrows overlaid on a map or verbal instructions, are presented to the user. This information has to be perceived and interpreted before the appropriate motor commands can be issued. Interpretation often involves mapping the symbolic instructions to the real world that may goes wrong, although the visual and auditory senses are engaged by the additional navigation information that may overlay real-world information.

The *actuated walking* approach based on EMS is depicted in Fig. 6.10b. In this way, we convey navigation information through *actuation* rather than through communicating a direction. We apply an EMS signal in such a way as to slightly modify the user's walking direction toward the target direction. Our approach directly manipulates the locomotion system of the user. The signal is weak enough that the user can override it and walk in a different direction if desired. The navigation signal cannot be observed by others as it is delivered privately to the user. This approach frees the sensory channels and cognitive capacity of the user and reduces mapping errors. The user may be engaged in a conversation, observe the surrounding environment during

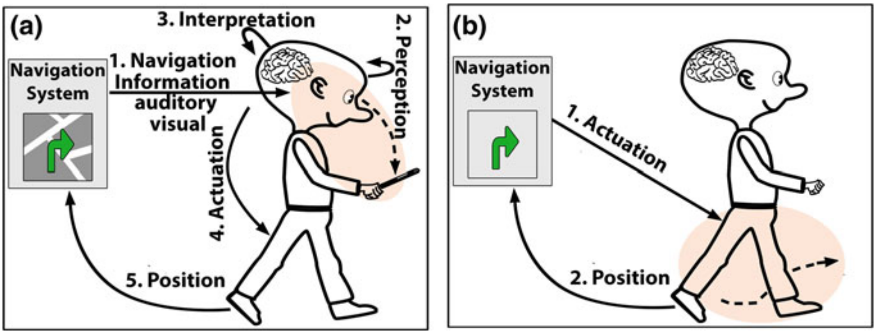


Fig. 6.10 Pedestrian navigation using **a** visual or auditory output and **b** direct modification of walking direction

Fig. 6.11 Placing the electrodes on the musculus sartorius (*left*) and measuring the angle of deflection corresponding to EMS intensity (*right*)

sightseeing, or even writes an SMS, and is automatically guided by the EMS-based navigation system.

Prototype: To achieve the actuated walking approach, we build a wearable and mobile prototype based on a off-the-shelf EMS device (Sanitas SEM 43 [69], program 8 TENS with pulse width100 μs and pulse frequency 120 Hz). The prototype consists of an Arduino Uno to control the EMS signal with a digital potentiometers (41HV31-5K) and to communicate with a Bluetooth module to a mobile. The prototype can change EMS signal intensity in 172 steps and runs on a 9 V battery. A control app that runs on a Samsung Galaxy S3 Mini to modify the signal intensity is connected to the hardware prototype.

We changed the walking direction by stimulating the sartorius muscle that is relevant for leg rotation. For the right stimulation, the optimal position of the EMS electrodes and strength of stimuli need to be calibrated as in Fig. 6.11.

Studies: The goal of our user study was to understand how to control walking direction using EMS. We recruited 18 participants (13 male, 5 female) aged between 18 and 27 ($M = 22.1$, $SD = 2.3$). The study was designed as a repeated measure experiment. The independent variables were the intensity level of the EMS actuation (strong, medium, weak, and off) and the starting position of the user (left, middle, and right Fig. 6.11, right). Users starting from the left position were guided to walk right and vice versa to encase the tracked walking area. The conditions were counter-balanced and repeated 5 times each, resulting in 40 trials per user. As the dependent variable, we measured the user's head trajectory (position and orientation). Trajectory was traced with 10 OptiTrack cameras in a area of 4×6 m.

After an introduction of the study and EMS, the participants got quipped with the prototype and the sartorius muscle was calibrated as shown in Fig. 6.11, left. When both legs were successful calibrated, the maximum angle was messaged with the OptiTrack system. The angle was divided into 2/3 and 1/3, and the corresponding EMS intensity was calibrated to achieve the three actuation levels (strong, medium, and weak).

For the walking trails, the users were blindfolded to avoid that they steer to a certain point against the contraction. The signal was applied in the swinging phases of the third step.

Results: The walking direction was clearly manipulated. Figure 6.12 shows the directional change in degrees per meter. The left graph shows an overview. The strong, medium, and weak actuation conditions have been combined for left and right, respectively. First, the median change within each user was computed and then the mean across users. The mean change is 15.8°/m to the left and 15.9°/m to the right. There is a relatively wide spread, and the data are skewed toward 0°/m stemming from the fact that the actuation showed only a small effect for some of the participants. A Friedman test shows that the differences between left actuation, no actuation, and right actuation are significant on the 5% level ($\chi^2(2) = 24.571$, $p < 0.001$). A post hoc test with Bonferroni correction shows that left, off, and right are pairwise significantly different.

The center of Fig. 6.12 shows the directional change for each condition separately. There is a tendency of stronger actuation showing larger directional change. Again, the variation between the users is strong and does not precisely follow the calibrated values for the angles (which aimed for full angle at strong actuation and 2/3 and 1/3 of full angle at medium and weak actuations).

Finally, for steering pedestrians around corners, the turning radius is relevant. While actuation is active, users move on a circular path. If the tracking area had been large enough and the actuation had continued, the participants moved in circles. The above results relate a length of 1 m on the circle arc to a rotation of $\alpha°$. This translates into a radius $r = \frac{180}{\alpha\pi}$. The radii associated with the above directional changes are shown in Fig. 6.12-right. As expected, the smallest turning radii of 3.18 m for left turns and 2.51 m for right turns are associated with strong actuation. These radii are sufficient for navigation in public spaces, such as streets and parks, and even in indoor spaces, such as shopping malls.

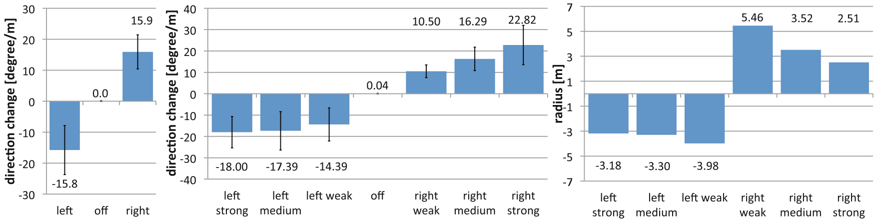


Fig. 6.12 Directional change in degrees per meter of the overall direction (*left*) and divided into the different EMS level (*center*) as well as the respective radii (*right*). Error bars show standard error

As final step, we set up a Wizard-of-Oz study to evaluate our finding in a real-world scenario and to navigate users with actuated walking though a park. We selected two routes (First: 991 m with 7 right and 9 left turns and Second: 552 m with 8 left and 4 right turns) in an area of around 380 × 400 m. The first route followed existing trails and the second mainly across lawn. We invited four male participants ($M = 25.3$, $SD = 1.3$), calibrate them in our laboratory, and let them walk both routes while video recoded them. After the trails, we conducted a semi-structured interview.

As a result, we found no navigation error (such as left instead right or straight ahead instead half right). Overall, the feedback on the navigation task was very positive. All participants stated that they were quite surprised that the system works that well. We ask them how they felt about steering and directional change of the approach. They replied that most of the directional change was caused by the actuation and a minimal may cause by the tactile feeling. We were interested in mental load as well. The participants stated that in the beginning they were consciously aware of the feedback, but after a while, they could easily focus on their surroundings.

The application scenarios show how EMS can be applied in different fields and the potential of this feedback technology. The envisioned scenarios give an impression of where ESM can used in future. The two presented research projects considered concrete application areas. For each project, we developed an individual EMS prototype. The development of the prototypes was a relevant part of the projects. Overall, the scenarios are examples of ubiquitous haptic feedback, which can be achieved with textile electrodes that are integrated in clothes.

6.5 Let Your Body Move Toolkit

Investigating new application scenarios or technologies usually starts with prototyping. In other domains, such as cross-device interfaces, toolkits and frameworks like [70, 71] help to reduce the initial effort and enable researchers to quickly focus on HCI-related questions, e.g., evaluation of approaches or interaction techniques. To simplify the use of EMS in research, we introduce in this section the “Let Your

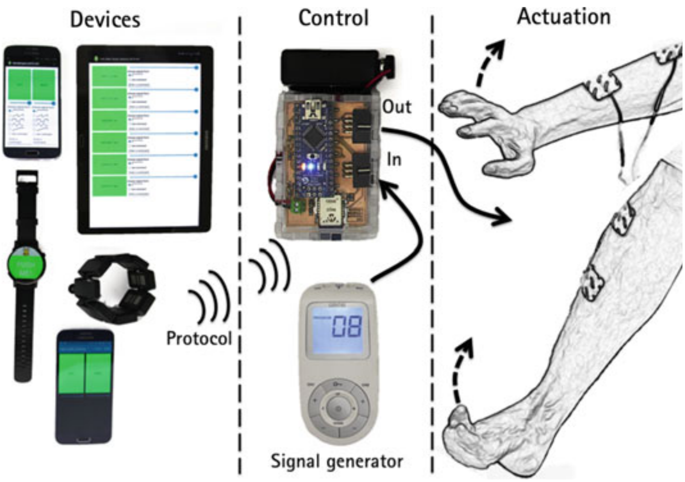


Fig. 6.13 Overview of the EMS toolkit. *Left* mobile and wearable devices that connect to the EMS control module; *middle* custom control module and off-the-shelf EMS generator; and *right* actuation of muscles

Body Move"[1] EMS prototyping toolkit (Fig. 6.13). It comprises the schematics of a EMS hardware control module, software modules, sample applications, and a robust communications protocol for EMS parameters.

We believe that this toolkit simplifies the investigation of EMS-based haptic feedback for wearables and textiles. The toolkit can help to understand this complex feedback technology and to prototype and evaluate initial ideas. New textile electrodes could be designed, integrated into clothes, and evaluated with the toolkit. Finally, it can be combined with other textile technologies such as textile displays or sensors.

As discussed before, a major concern with EMS research is safety. An important decision regarding the toolkit was to design it around existing massage/EMS/TENS devices as EMS signal generators. The toolkit was tested with four different commercial devices. A second fundamental aspect was to make the system as small and unobtrusive as possible to be able to use it in wearable applications. Moreover, the system is designed to easily connect to a wide range of mobile and wearable devices, such as tablets, mobile phones, and smartwatches (Fig. 6.13). This is achieved by wireless communication over Bluetooth LE.

First, we give a brief overview of existing wearable and haptic toolkits. Then, we present a prototyping process that can be followed when investigating EMS as a haptic feedback technology. This is followed by a detailed description of the toolkit components. Finally, we present four application scenarios in which we used the toolkit to generate haptic feedback.

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[1]Let Your Body Move Toolkit https://bitbucket.org/MaxPfeiffer/letyourbodymove.

6.5.1 HCI and Haptic Prototyping Toolkits

Prototyping toolkits help to make new technologies accessible and to focus on investigating new concepts and interaction techniques. Houben and Marquardt [71] present *WatchConnect*, a prototyping platform for smartwatch cross-device applications. It simplifies investigating cross-device interaction between watches and desktop systems.

FeelSleeve [72] are tactile gloves that are attached to the back of a tablet to provide vibration effects based on the story the user is reading. Yannier et al. [72] show that tactile feedback increases comprehension and memorization. Ledo et al. [73] present the *Haptic Tabletop Puck*, which simulates haptic feedback by changing the friction of the device. They simulate different properties, such as softness, depending on the underlying texture. Similar, but device-free, feedback is generated by *TeslaTouch* [74] and *FingerFlux* [75].

On the haptic and force feedback side, Brave and Dahley [76] present a device for haptic remote communication. Ha et al. [77] describe a haptic prototyping system for a single dial. The hardware prototype provides several patterns to turn the dial. They conclude that the system can be used for haptic prototyping automotive, medical, and gaming contexts. *WoodenHaptics* [70] is a toolkit that implements a device similar to the Phantom Desktop device. It is an open-source hard and software toolkit that allows designers to investigate high-fidelity haptic feedback. They demonstrate that their toolkit can be used for haptic prototyping with a broad range of users. However, this device cannot be used in mobile contexts and has a very limited interaction range.

Most current haptic toolkits focus on very specific forms of haptic or tactile feedback, focus on specific interactions, such as dials [77], rolls [76], or sliders [78], or are stationary [70].

"Let Your Body Move" is available in open-source form. It is suitable for mobile, wearable, and textile interactions, can easily be connected to typical mobile devices, and is able to deliver a wide range of haptic feedback—from light tingle to moderately strong movements.

6.5.2 EMS Prototyping Process

Before considering to use the EMS prototyping toolkit in a particular project, it is important to clarify whether EMS fits the requirements for an envisioned scenario. The specific capabilities (Sect. 6.3) and limitations (Sect. 6.6) of EMS have to be considered. The design space of EMS is large, both in terms of the kind and range of effects it can create.

Using the toolkit requires an initial one-time effort, consisting of building the EMS control module (using the given schematic Fig. 6.14) and installing the control software on the Arduino. Each control board can handle two EMS channels. If more channels are needed, multiple instances of the control module have to be built.

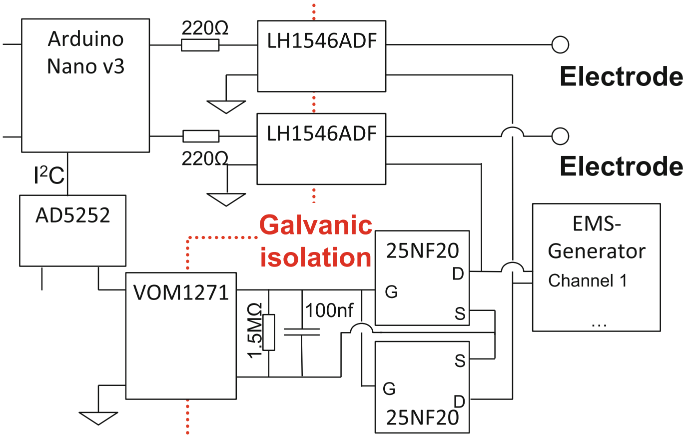

Fig. 6.14 EMS control module: Circuit for one EMS channel

For the actual design process, we recommend the following steps. This process is based on our own experience in prototyping EMS-based haptic feedback. We assume that the design starts with an initial idea regarding an application scenario, such as a mobile application giving haptic feedback to runners, or regarding an interaction technique, such as giving haptic feedback in response to grasping virtual objects in a VR environment. The steps are as follows:

1. Refine the role of haptic feedback in the application scenario or interaction technique.
2. Determine the parameters of the EMS design space (Sect. 6.3) to achieve the intended effects (EMS parameters, electrode placement, and calibration requirements).
3. Install the Wizard-of-Oz control app (Sect. 6.5.4) on the experimenter's device (e.g., a tablet) and conduct a Wizard-of-Oz study.
4. Taking into account the lessons learned in the Wizard-of-Oz study, implement a custom prototype on the user's device that communicates with the EMS control module and log events, and run a detailed study to evaluate the desired phenomena.
5. Iterate (refined prototype, Wizard-of-Oz study on specific aspects, EMS parameters, and electrode types, sizes, and placements).

The toolkit may, of course, also be used as is in brainstorming sessions in order to inspire Wizard-of-Oz prototypes. The toolkit helps in the quick production of working prototypes. We used this approach in a workshop setting, but consider it the less common prototyping variant [79].

When the details of the role of haptic feedback in the envisioned scenario or technique have been clarified, the EMS design space in Sect. 6.3 needs to be considered for typical EMS characteristics. An example scenario would be a wearable application for joggers that actuate the runner's hand left or right to indicate directional turns. Important aspects to achieve the desired haptic effects concern the required EMS signal parameters, the placement and size of the electrodes, and user-specific calibration. The signal parameters include required and acceptable intensity levels and signal patterns (e.g., rhythms to communicate a certain kind of information). These steps are in many cases sufficient prerequisites for an initial Wizard-of-Oz study that helps to validate the feedback concept or to quickly try out different feedback design ideas. The Wizard-of-Oz study can easily be controlled from the experimenter's Android phone or tablet in Bluetooth range of the user. However, this initial study already requires careful calibration of signal strength and electrode placement, as EMS strongly depends on the physiological characteristics of individual users. The lessons learned in the initial study can then be incorporated in the design of a custom software prototype for the user's device (e.g., the smartwatch of a jogger). A number of existing applications of custom prototypes may serve as a starting point for new software prototypes. The sensors of the user's device may be used to log specific events and reactions to haptic feedback. This setup can then be the basis of a more extensive user study that aims to evaluate specific phenomena. Of course, the design process allows for iterating on the prototype, specific aspects, or new ideas for haptic feedback, as well as the modification of EMS parameters and electrode placement.

New constraints or requirements may arise, such as the need for another form factor or additional EMS output channels. While additional channels can easily achieved by adding an additional EMS control module and EMS signal source, changing the form factor may call for deeper modification of the hardware. We focused on simplifying the design process for HCI researchers. We also chose a form factor that does not constrain the user severely. For example, as the system uses Bluetooth LE, it can communicate wirelessly with an smartwatch.

6.5.3 EMS Prototyping Toolkit

The EMS prototyping toolkit is a composition of hardware, software, and methods to enable prototyping with EMS as shown in Fig. 6.13. On the hardware side, we provide a circuit to manipulate EMS signals from off-the-shelf EMS devices (Fig. 6.13, middle). The EMS control module is easy to build. The components are controlled by an Arduino Nano over I^2C (Fig. 6.14). We developed a simple ASCII-based protocol to modify the signal parameters. The toolkit uses Bluetooth low energy (BLE). On the software side, we present four simple prototyping apps that communicate with the EMS module (Fig. 6.13, left). The schematics, part list, the Arduino source code, and the source code of the apps are available online.[2]

[2] Let Your Body Move Toolkit https://bitbucket.org/MaxPfeiffer/letyourbodymove.

6.5.3.1 Toolkit Hardware

We typically use the Breuer Sanitas SEM 43 as the signal generator. However, we tested the system with three other EMS devices. The control module reduces the signal intensity of the EMS device. Therefore, the EMS device is calibrated with the maximum acceptable intensity for a particular user. For safety reasons, we designed two galvanically isolated circuits, the EMS circuit and the control circuit. The control circuit is connected to the BLE module, the Arduino, and a 9 V or USB power supply. The EMS circuit is connected to the signal lines of the EMS device and the human body, as shown in Fig. 6.14. To implement the galvanic isolation, we used an optically isolated MOSFET driver (VOM1271[3]). It generates a current to drive two MOSFETs (25NF20[4]) in the EMS circuit, which reduce the signal intensity. One MOSFET is used for the positive and one for the negative half wave of the EMS signal. The resistance of the MOSFETs should be between 100 Ω and 10 kΩ, because otherwise the EMS device switches off automatically. For safety reasons, we also included two photograph relays (LH1546ADF[5]) to instantly cut off the EMS circuit when switching the module off.

In the control circuit, the input of the MOSFET driver is leveled by a 1 kΩ I^2C digital potentiometer (AD5252[6]). For Bluetooth communication, we used a standard BLE chip.[7] For the BLE module and for each EMS channel, we added a control LED. When the Bluetooth connection fails, the EMS switches off automatically.

6.5.3.2 Protocol of the Toolkit

As long as the EMS modules are not connected, they announce their Bluetooth name. Based on the name, the prototyping apps can find the device and connect to the "EMS-Service-BLE1" service. The service accepts ASCII strings to change the EMS parameters. The protocol of the service is shown in Table 6.3.

For example, if the message "C0I100T1000G" is sent to the service, channel 0 will be activated at full intensity for 1000 ms. Resending "G" activates the same channel with the previous parameters again. Each parameter can be changed individually. If a new "on-time" message is received while a channel is active, the new time will be updated even if it is shorter. For example, if the signal is on and the new time is set to 50 ms, it will deactivated after 50 ms.

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[3]VOM1271 www.mouser.com/ds/2/427/vom1271t-244790.pdf.

[4]STD25NF20 www.mouser.com/ds/2/389/DM00079534-470123.pdf.

[5]LH1546ADF http://www.mouser.com/ds/2/427/lh1546ad-254173.pdf.

[6]AD5252 www.mouser.com/ds/2/609/AD5251_5252-246267.pdf.

[7]RN4020 www.mouser.com/ds/2/268/50002279A-515512.pdf.

Table 6.3 EMS control protocol (ECP)

Command	Values	Sample	Description
Channel	0–1	C0	Set channel 0 or 1
Intensity	0–100	5000	Set intensity in %
On-time	1-int32	T20000	Set the on time in ms
Activate/go	G	G	Activate the command

6.5.4 Application Scenario

Since the EMS module uses standard BLE, it can connect as client to any device that supports BT 4.0 or higher. The sample apps were extensively used for prototyping and in multiple user studies. We have successfully run these apps on Android devices, such as tablets, mobile phones, and smartwatches. Below, we present four prototyping apps that can easily be extended: (1) an app for Wizard-of-Oz prototyping that can connect the EMS module and apply different parameter sets, (2) an app for connecting multiple devices to actuate a set of muscles, (3) an app that connects to a bracelet wearable device, and (4) a smartwatch app.

Wizard-of-Oz prototyping: The Wizard-of-Oz prototyping app can connect to one EMS module and activate two channels. Our EMS device can generate two independent signals. Four electrodes are needed to actuate two muscles. The app activates a channel as long as the user presses a button. The signal intensity may be adjusted with a slider. Different patterns may be chosen immediately on, square wave signal with a 1-s period, sawtooth signal (linearly increasing, then off), sine wave signal, and inverse sawtooth signal (linearly increasing, then on). We model the patterns by intensity and time, not by changing the signal form itself. Finally, there is a text field for sending custom protocol messages. Each time the button is pressed, one message is sent.

Connecting multiple devices: To actuate more muscles, multiple devices are needed. This is necessary for more complex haptic feedback, such as grasping or lifting an object. Each button activates one channel as long as it is pressed. It is also possible to change the intensity by a slider, and there is a text field for sending custom protocol messages for each channel. The app can be used as a “gesture keyboard”: Each key actuates a muscle and the gesture can be played like on a piano.

Myo remote control: The remote control app shows how to use external sensors such as the Myo[8] to control muscle activation. In this case, the mobile device serves as a gateway between the EMS module and the Myo device. A remote control of another person is possible: connecting the EMS module to the muscles of one user and using the Myo on another person. The detected movements are transmitted to the other person.

Event triggering: The smartwatch app runs on a Moto 360[9] and extends that device with force feedback. For specific notifications, such as an alarm, it can actuate a muscle. In this case, the user becomes the output device. For example, when an alarm is ringing, the user starts waving the hand. Different movements or rhythms may be used for different kind of notifications. Other sensors or devices such as distance or GPS sensors can directly connect to the Bluetooth module and trigger events.

6.5.5 Discussion: Textile Prototyping

We presented the *Let Your Body Move Toolkit* a fully working EMS-based haptic prototyping toolkit for mobile, wearable, and textile-based computing. We gave an overview how to use the toolkit for prototyping and producing a wide range of haptic feedback. For reproducing the toolkit, we provide the required information: schematics for the hardware as an Eagle design and a part list, software for the Arduino, and source code for the Android apps. Further, in different application scenarios, we show how the toolkit can be used.

The toolkit can easily connect to textile electrodes as discussed in Sect. 6.3.2. EMS feedback that is applied through textile electrodes can support interaction with haptic feedback in textile-based computing. Tactile and force feedback can be applied across the whole body. Possible positions of electrodes on the body such as on the back or the foot can easily be tested, as discussed in Sect. 6.3.3. With textile electrodes, haptic feedback can be integrated into different types of clothes, such as bandages, underwear, shoes, or sportswear. The toolkit enables fast prototyping to investigate different sizes of textile electrodes and to adjust EMS parameters (Sect. 6.3.1). With the toolkit, different material types for textile electrodes can be easily evaluated, such as metal or conductive silicone. Furthermore, new types of fabrication such as weaving, embroidering, warp knitting, or braiding [15] can be used. With large electrode grids, complex movements and gestures can be achieved. Due to the wireless communication of the toolkit, it is easy to combine it with textile input, like sensors, or output devices, such as textile displays. To investigate and evaluate these modifications, the presented prototyping process (Sect. 6.5.2) can be iterated. Since the textile electrodes are comfortable to wear for a long time, scenarios with ubiquitous haptic feedback become possible. With the toolkit application scenarios as envisioned in Sect. 6.4 could be investigated in everyday usage and in mobile contexts. Long-term studies can focus on the user perspective and explore how the interaction with the environment changes.

6.6 Challenges and Limitations

EMS as a haptic feedback technology is still in its infancy. There are several research challenges that need to be solved to realize the envisioned examples. The main challenges include the large differences in user characteristics, the calibration of the EMS strength, the electrode placements and posture dependency of the placement, the precision of actuation, and the combination with EMG. These limitations pose significant challenges. Several aspects are inherent to EMS, in particular safety issues, physiological limits, and negative experiences of some users.

As described in Sect. 6.3, EMS feedback is user dependent due to physiological differences. This makes the calibration phase and placement of the electrodes very time-consuming. In our studies, the calibration process often takes up two-thirds of the whole study time, depending on the characteristics of the used muscle.

The calibration and placement of the electrodes also depend on user's posture (Sect. 6.3.4). For example, when changing the posture of the arm, the muscles and the electrodes shift in different ways and the current may cross another muscle. Electrode grids could help to solve this problem. The shift of the muscle needs to be detected, and other electrodes are activated. A model of the skin and the underlying muscle could predict such shifts, and additional sensors could measure the movements.

The relation between the amount of current and the level of muscle contraction is not linear. Several factors influence the behavior of the muscle such as preuse, fitness of the muscle, limb orientation with respect to gravity, but also the muscle torque. Movement tracking with an advanced control loop could solve this challenge by adopting the current strength to these factors of influence.

The combination of EMG and EMS as input and output technologies is still challenging. EMG and EMS do not work simultaneously because the EMS signal overrides the EMG signal. The main challenge is to time-synchronize the input and output signals.

EMS has limitations and safety issues that designers need to consider when generating EMS feedback as discussed in Sect. 6.3.5. Continuous force feedback with EMS is not possible, and the number of repetitions is limited because of physiological limitations. Muscles fatigue after a short while of continuous actuation. Then, muscles need time to regenerate. The possible activation time and number of repetitions are different for every user and depend on the level of fitness. Finally, users experience EMS feedback differently. Some users feel the tingle that results from the current more strongly than others. Such users typically describe that they perceive the paresthesia effect such as a body part that "falls asleep" or like stitches on the skin. Others reported that they had a negative pre-experiences with an electric shock so they cannot get comfortable with feeling the current.

6.7 Discussion

Textile electrodes are already integrated into clothes for sensor input and EMS output. They can be made of different materials and adopted or integrated in different ways on and in textiles. Such textile electrodes can have also different forms and shapes. They can be placed over the whole body. Textile electrodes are comfortable to wear for longer time periods and are washable. Electrical output in textile-based computing is less well investigated than input. The skin of the human body on average has an area of $1.79\,\mathrm{m}^2$ [80]. In everyday life, most of it covered is by clothing. This is a substantial area that is potentially available for tactile feedback. There are several other surface muscles that are not discussed in this chapter, which also can easily be actuated. EMS feedback lets the user become the output device and perform movements and gestures. In the long term, comfortable textile sensors and low-power variants of this technology are likely to enable ubiquitous haptic feedback.

In this chapter, we gave an introduction on how to use EMS as a feedback technology and discussed how EMS can be integrated into textiles. We presented several examples of different application scenarios. Finally, we described the "Let Your Body Move" toolkit for haptic feedback prototyping, which is available in open-source form. This toolkit simplifies exploring, implementing, and evaluating new ideas in this area.

Summary

- EMS has considerable potential as a wearable haptic output technology for textiles.
- Textile electrodes allow for tight integration of EMS into clothing.
- EMS requires consideration of parameters, placement strategies, and safety aspects.
- We presented several scenarios and research prototypes of EMS as a haptic output technology.
- The "Let Your Body Move" EMS toolkit simplifies prototyping in mobile and wearable contexts.
- EMS poses significant challenges toward the goal of ubiquitous haptic feedback.

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Chapter 7
Textile Antennas

Andreas Mehmann

Abstract This chapter gives an overview of existing textile antennas and their applications. Issues are the trade-off between flexibility and conductivity of the textile, the influence of the body when the antenna is worn, and the bending and wrinkling of the antennas due to their textile nature.

7.1 Introduction

Mobile wireless communication has increased significantly over recent years and still does today. Smartphones not only provide traditional mobile phone service that allows transmission of voice and data, but also include other wireless systems such as wireless local area network (WLAN) or Wi-fi, Bluetooth, near-field communication (NFC), and global positioning system (GPS). In addition to smartphones, a variety of other mobile wireless devices exist, such as Bluetooth headphones, sports gadgets for monitoring heart rate and step count, and implantable medical devices to measure physiological data.

All these wireless devices need antennas to transmit and receive the data. In the course of the smart textile trend, these antennas can be included in garments. The following sections will give an overview of the research that has been done towards this goal.

A brief explanation of the antenna working principles and different antenna types is given in Sect. 7.2, and then, Sect. 7.3 will list some common materials and fabrication issues related to textile antennas. Applications where textile antennas are employed are given in Sect. 7.4. Textile antennas change their characteristics when worn, due to body proximity and bending, which is described in Sects. 7.5 and 7.6, respectively.

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S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_7

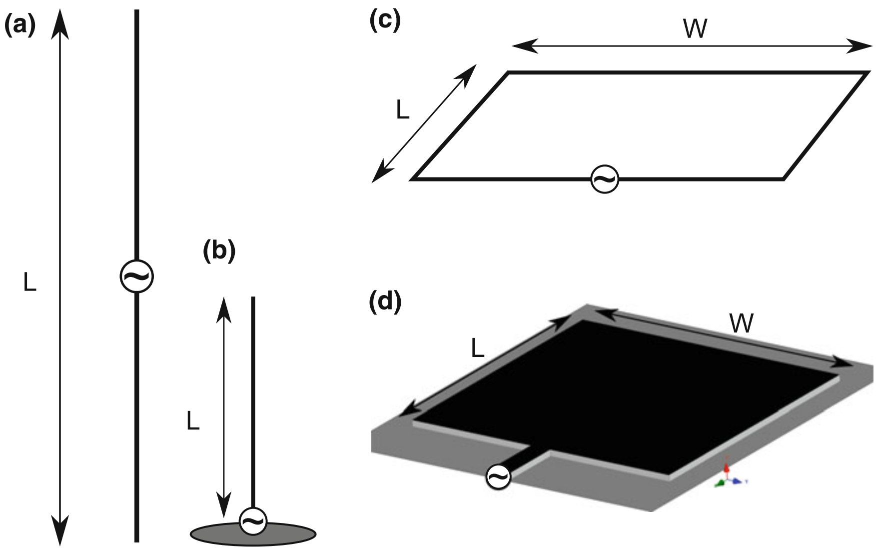

Fig. 7.1 Four different antennas: a dipole (**a**), a monopole with a ground plane (**b**), a rectangular loop antenna (**c**), and a rectangular patch antenna (**d**)

7.2 Antennas

Accelerated charges radiate electromagnetic waves [1, 2]. Acceleration can be caused by discontinuities or bends in the conductor, termination of the conductor, or by applying time harmonic voltages [3].

There are various forms of antennas, which all implement this principle of accelerated charges. Examples are wire antennas such as dipoles and loops, aperture antennas such as waveguide apertures and horns, and microstrip antennas or patch antennas, see Fig. 7.1. Monopoles, dipoles, loops, and patches shall be presented here with examples of textile versions.

7.2.1 Monopole and Dipole Antennas

Wire antennas are some of the oldest and simplest antennas [3]. They are employed for radios and television and were frequently used in cars and mobile phones as external monopole antennas, often referred to as whip antennas [4]. The downside of these external antennas is their proneness to damage. Therefore, mobile phone antennas are now built into the phone casing.

We estimate the bandwidth of a dipole antennas, to compare it to the bandwidth of a loop antenna, see Sect. 7.2.2. The radiation resistance of a half-wavelength dipole is $R_R = 73\,\Omega$ and the reactance is $X = 42.5\,\Omega$ [3]. For a small dipole with length

l less than one-tenth of the free-space wavelength λ, the radiation resistance and reactance are as follows [3]:

$$R_R = \quad 20\pi^2 \left(\frac{l}{\lambda}\right)^2 \tag{7.1}$$

$$X = -120 \frac{\log\left(\frac{l}{2a}\right) - 1}{\tan\left(\frac{kl}{2}\right)} \tag{7.2}$$

where a is the wire radius and $k = 2\pi/\lambda$. For example, a small dipole at 1 GHz with $l = \lambda/10 = 3$ cm and $a = \lambda/1000 = 0.3$ mm has a radiation resistance of $R_R = 1.97\,\Omega$ and a reactance of $X = -1076\,\Omega$.

The quality factor or Q-factor of an oscillating circuit is the ratio of the maximal instantaneous energy stored to the energy dissipated per cycle [5]. For a circuit with a resistor R, capacitor C, and an inductor L in series, the Q-factor is

$$Q = \frac{\omega L}{R} \tag{7.3}$$

where $\omega = 1/\sqrt{LC}$ is the resonance frequency. The voltage standing wave ratio (VSWR) bandwidth describes the difference between the frequencies at which the squared magnitude of the reflection coefficient is one-half. The fractional VSWR bandwidth FBW_V is the VSWR bandwidth relative to the resonance frequency. The Q-factor is related to the fractional bandwidth [6].

$$Q \approx \frac{2}{\mathrm{FBW}_V} \tag{7.4}$$

This approximation is subject to some restrictions, which are described in detail by Yaghjian et al. [6].

The quality factor of an electrically small antenna has a lower limit given by the Chu–Harrington limit [7]. The lower limit on the Q-factor corresponds to an upper limit on the bandwidth.

The small dipole introduced in the previous example has a Q-factor according to Eq. 7.3 of $Q = 546$. Thus, the fractional bandwidth of the small dipole is $\mathrm{FBW}_V = 1.8 \times 10^{-3}$. The Q-factor and fractional bandwidth of the half-wavelength dipole are $Q = 0.58$ and $\mathrm{FBW}_V = 3.44$, respectively. The lower limit according to the Chu–Harrington limit for the half-wavelength dipole is $Q \geq 0.35$.

Monopole and dipole antennas have omnidirectional radiation characteristics (see Fig. 7.4a). When incorporated in mobile phones and placed near the human head, the omnidirectional antennas induce currents in the tissue. The induced currents increase the specific absorption rate, see Sect. 7.5.1. But the simplicity and characteristics of monopoles and dipoles make these antennas good candidates for other applications, such as FM radio, television, or Wi-fi, and they are still used as internal antennas in mobile phones.

Mobile phones operate in different frequency bands, for example 900 MHz and 1800 MHz. To design wire antennas that resonate at different frequencies, branched strips of different lengths are employed. The size is reduced by meandering the strips [8].

In smart textiles, monopoles and dipoles are used for wireless communication. In particular, in on-body communication, monopoles are utilized because of their omnidirectional radiation pattern, which makes performance independent of antenna rotation. The polarization of monopole antennas oriented perpendicular to the body surface allows for on-body surface waves, which reduces the path losses [9]. However, monopoles orientated perpendicular to the body surface can be obtrusive and uncomfortable.

Examples of monopoles or dipoles in textile are as follows:

- A prototype of a wearable meander dipole with different branches of different length for tri-band communication in the frequency ranges of 915, 1575, and 2400 MHz. The dipoles are 118 and 72 mm long. As an alternative to textile integration, silicone encapsulation was employed, with higher losses due to the water content of the material [10].
- A meandered flare dipole on polyester fabric by embroidering silver-coated polymers. The size of the antenna was approximately 190 mm $\times$ 25 mm. The antenna was operated at 500 to 600 MHz, and its performance was found to be comparable to a copper antenna of identical shape [11].
- A 26.5-mm-dipole antenna for the 2.45 GHz frequency band. Nickel–copper-plated woven polyester was glued onto denim with a relative permittivity of 1.67 and thickness 0.85 mm. The antenna has a bandwidth of 430 MHz [12].
- Textile dipoles with length 57.4 mm for the 2.4 GHz frequency band, see Fig. 7.2. The conductive fabrics are woven silver-plated nylon and embroidered conductive threads. The silver-plated fabric antenna has an average gain of 1.7 dB compared to the embroidered antenna with gain -4.3 dB [13].

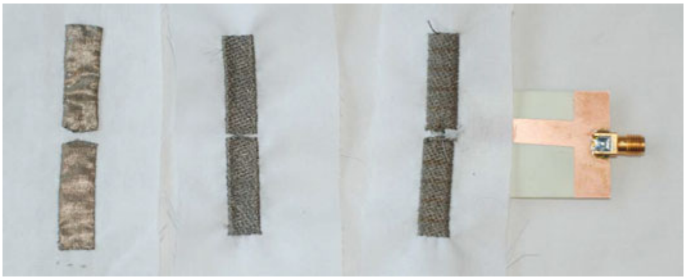

Fig. 7.2 Textile dipole antenna of length 57.4 mm from silver fabric (*left*), two embroidered antennas, and a feeding structure on the *right*. Courtesy of Kaufmann et al. [13]

7.2.2 Loop Antennas

Loop antennas can be circular, rectangular, or any other closed form. To analyse loop antennas, one has to distinguish between electrically small loops, whose circumference is less than one-tenth of a wavelength, and electrically large loops with circumference of about one wavelength [3].

The radiation resistance of small loop antennas is in the range of their loss resistance. Therefore, the radiation efficiency is only around one-half, and they are not used for transmission. However, they are employed as receiving antennas when signal-to-noise ratio is more important than absorbed power [3]. To fit an electrically large loop into a mobile device, folding techniques can be applied [14, 15]. Loop antennas are used in pager communication, for example, because the antenna only needs to receive [4]. Pagers' operation is allocated in frequencies ranging from 25 to 910 MHz.

The radiation resistance of a circular loop antenna is given by

$$R_R = 20\pi^2 \left(\frac{2\pi a}{\lambda}\right)^4 \tag{7.5}$$

where a is the radius of the loop. The inductance of a circular loop antenna with wire radius b is

$$L_A = \mu_0 a \left(\log \frac{8a}{b} - 2\right) \tag{7.6}$$

Balanis provides a detailed description of the above formulas [3]. For example, an electrically large loop antenna for 1 GHz with loop radius $a = 4.77$ cm and wire radius $b = \lambda/1000 = 0.3$ mm has radiation resistance $R_R = 197.4\,\Omega$ and inductance $L_A = 309$ nH. The resistive loss of a copper loop of this size is $R_L = 17.8\,\text{m}\Omega$. The Q-factor and fractional bandwidth of this loop antenna at 1 GHz are $Q = 9.83$ and $\text{FBW}_V = 0.203$, respectively.

The same loop antenna operated at 100 MHz is electrically small. The radiation resistance is $R_R = 19.7\,\text{m}\Omega$, which is close to the loss resistance. The sum of radiation and loss resistance results in $Q = 51680$ and $\text{FBW}_V = 3.87 \times 10^{-5}$.

The small radiation resistance compared to the loss resistance impedes the radiation efficiency given by [3]:

$$e = \frac{R_R}{R_R + R_L}. \tag{7.7}$$

The narrow bandwidth of loop antennas (cf. fractional bandwidth of dipole example in Sect. 7.2.1) makes tuning to the resonance frequency challenging.

A comparison of a textile loop antenna with a dipole antenna was given by Maleszka et al. [16]. The conducting threads are multifilaments consisting of silver-coated copper filaments combined with polyester filaments. The antenna is designed to function at 2 GHz. However, Maleszka et al. found that the non-uniform textile structure increases the actual antenna length and thus reduces the designed resonance frequency by 100 MHz.

Fig. 7.3 Reference coil on a circuit board and three stretchable coils on elastic fabric. The elastic fabric is 91% cotton and 9% polyamide. The conductors are, from *left* to *right*, copper braids of 5 mm, 7 mm with silver coating and 9 mm. © 2011, John Wiley and Sons. Reprinted with permission from [17]

7.2.2.1 MRI

In magnetic resonance imaging (MRI), loop antennas are implemented as detectors of magnetic signals. The principle of reception differs from the electromagnetic radiation detection, as magnetic near-field effects induce currents in the loop.

Wearable MRI receiver coils screen-printed on a polyimide or cut from copper foil exist [18, 19]. A stretchable coil on textile has been presented by Nordmeyer-Massner et al. [17]. The size of the rectangular coil is $50 \times 100\,\text{mm}^2$. Copper braids were stitched onto an elastic fabric, see Fig. 7.3. The coil was designed to operate in a 3-Tesla MRI machine at 128 MHz. The coils have Q-factors between 80 and 170. The changing of impedance when the coil is stretched complicates the use of these coils. Nevertheless, a textile coil MRI receiver coil can be an interesting option for an MRI solution that is more comfortable for the patient compared to rigid coil assemblies. The textile coil can be worn directly on the skin, mitigating the distance to the rigid coil and improving the sensitivity of the coil in the area of interest.

7.2.3 Patch Antennas

Patch antennas or microstrip antennas consist of a conductive patch separated by a dielectric from a ground plane. The patch is fed by a microstrip line. In a rectangular patch, the length of the patch determines the resonance frequency, while the impedance and bandwidth depend on the width of the patch [3]. The length is usually approximately $\lambda/2$, where λ is the wavelength in the dielectric. Thus, the patch size can be reduced by increasing the permittivity of the dielectric. The width is chosen in the range of L to $2L$ [20] and the height in the range of 0.003 to 0.05λ [3].

Different shapes of patch antennas exist, such as rectangular, circular, or triangular. The rectangular patch can be extended or cut by different shapes to change the polarization and achieve multiband operation. The polarization can also be chosen by selecting appropriate feed lines [20].

The small height in relation to the length and width makes patch antennas attractive to mount on surfaces where area is available but the profile should not be changed. In a mobile phone, for example, a patch antenna can cover several square centimetres without increasing the thickness of the phone by more than a few millimetres. Planar inverted-F antennas (PIFAs) are patch antennas with a shorting pin to the ground plane. They are often used in mobile phone communication. The additional shorting pin creates a loop which shifts the input impedance. Therefore, the impedance can be adjusted by changing the pin position relative to the feed line [4]. According to Fujimoto et al. [4], the typical size of a PIFA in a mobile phone is about $20 \times 40\,\mathrm{mm}^2$ with a thickness of 4 to 10 mm. Although PIFAs typically have a lower bandwidth than monopole antennas and are more affected by nearby objects, they are utilized in mobile phones because the radiation is shielded by the ground plane. Figure 7.4d shows the radiation pattern of a patch antenna. Unlike the omnidirectional radiation patterns of the wire and loop antennas, the patch antenna only radiates away from the

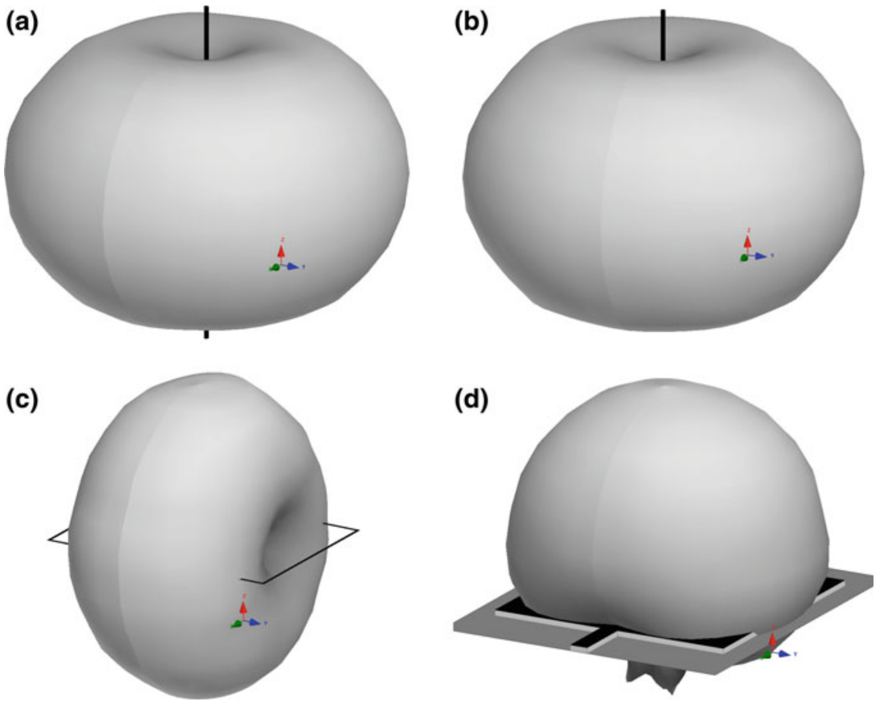

Fig. 7.4 Radiation field patterns in dB for the antennas in Fig. 7.1. The dipole antenna is of length $L = \lambda/2$, and its radiation pattern (**a**) is similar to the quarter wavelength monopole antenna $L = \lambda/2$ (**b**). The loop antenna has circumference $2(L + W) = \lambda$ and also shows omnidirectional radiation (**c**), while the patch antenna with width and length around $\lambda/2.5$ according to the calculations described by Balanis [3] radiates away from the ground plane (**d**)

ground plane. When the antenna is shielded towards the body, the power absorption in the head is reduced [21, 22], see Sect. 7.5.1.

Textile patch antennas are employed for Wi-fi, Bluetooth, or cellular communication. For more details on these applications, see Sect. 7.4. A selection of textile patch antennas is listed here:

- A wearable circular patch antenna with radius 30 mm for 2.5 GHz was built using felt as its dielectric. The felt has a thickness of 1 mm and a relative permittivity of about 1.43. A woven conductive fabric with sheet resistance less than $0.05\,\Omega/\square$ was selected for the patch and ground plane [24].
- A circular patch antenna with radius 26.3 mm was developed for WLAN in the 2.45 GHz frequency range meeting the Bluetooth specifications. The relative permittivity of the dielectric fabric (denim) is 1.67 and the thickness is 2.84 mm. The patch and ground plane were fabricated from Flectron (metalized nylon) with a surface resistivity of $0.07\,\Omega/\square$. The antenna shows similar performance to a rectangular patch antenna [25].
- Four antennas for Bluetooth in the 2.4 GHz frequency range were constructed. The conductive fabric is a silver–copper–nickel-plated woven fabric with sheet resistance $0.02\,\Omega/\square$. The conductive fabric is attached to the dielectric from felt or polyamide spacer fabric by adhesive films. The relative permittivity of the 3.5-mm-thick felt is 1.45. The spacer fabric has a thickness of 6 mm and a relative permittivity of 1.14. The patches are rectangular, while two have truncated corners that introduce circular polarization, see Fig. 7.5. Feed line insets are added to match the input impedance. The Bluetooth specifications are satisfied during the bending of radius 37.5 mm [23].
- A patch antenna for communication between firefighters was developed. The advantage of integrating antennas into protective clothing is that they can be made thicker without being obstructive. The antennas in protective clothing are also protected and less prone to wrinkling. The conductive patches were made from nickel–copper-plated polyester with sheet resistance less than $0.1\,\Omega/\square$. The length of the patch is 50 mm, and the width is 46 mm. Foam with 3.94 mm thickness was employed as a dielectric, with relative permittivity of around 1.5. The patch was designed to operate at 2.45 GHz and was circularly polarized [26].

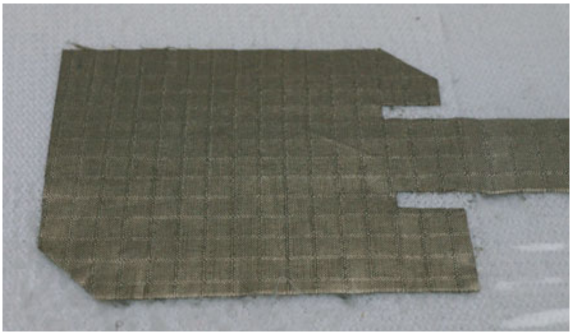

Fig. 7.5 A circularly polarized patch antenna developed by Locher et al. [23]. The antenna is 47 mm wide and 57 mm long

7.3 Materials and Fabrication

There are various ways metals can be included in textiles to achieve electrically conductive paths or patches. A trade-off between flexibility or drapability and conductivity remains. Conductive polymers can be included in textiles as alternatives to metals.

Three categories to produce conductive textiles exist.

Conductive fibres The first method uses conductive fibres that can be included into textile by textile manufacturing processes such as weaving, knitting, or embroidering [27]. Different conductive fibres exist. Metal fibres can be directly integrated in a monofilament structure or twisted with non-conductive fibres into a multifilament thread [28]. Alternatively, non-conductive fibres can be coated with conductive polymers or metals, or filled with metal powders or carbon [29, 30]. Commercially available conductive textiles at the time of editing include Shieldit Super by lessemf.com (nickel–copper-plated woven polyester) with sheet resistance $0.5\,\Omega/\square$ [31], Flectron by Laird (copper-plated woven nylon) with sheet resistance $0.07\,\Omega/\square$ [32], MedTex Balingen by Shieldex (silver-plated nylon knit) with sheet resistance $0.6\,\Omega/\square$ [33], and Eeontex 170NW-PI-15 by Eeonyx (conductive polymer-coated polyester non-woven) with sheet resistance $15\,\Omega/\square$.

Conductive ink Printing is a simple way of producing conductive structures on various substrates [34]. Ink is enriched with a conductive material and applied by screen printing or inkjet printing onto textile. Examples of conductive inks are carbon nanotubes [35], polymers [36, 37], or metallic nanoparticles [38, 39]. Conductive ink can be protected with a breathable thermoplastic to ensure stable performance after several washing cycles [40].

Miscellanious Thin films of most materials become bendable and thus can be integrated into textiles. For example, copper tape can be adhered to textiles without affecting the bendability [41]. Circuitry on flexible plastic substrates can be woven into textiles [42].

Santas et al. compare three different antennas produced according to the above-mentioned categories [43], see Fig. 7.6. The antenna patches are 34 mm long and

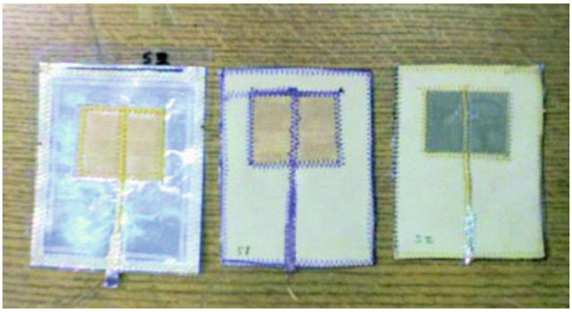

Fig. 7.6 Three textile patch antennas with different materials. From *left* to *right* copper tape, woven copper threads and conductive spray. Courtesy of Santas et al. [43]

39.5 mm wide. The dielectric substrate is leather with relative permittivity of 2 and height 1.52 mm. The resonance frequency is 3.2 GHz.

More details on the integration of conductive material in textiles can be found in the book by Dias [44] and Chap. 8.

Most textile materials used as dielectrics in patch antennas have a relative permittivity between 1 and 2. Examples are felt or spacer foam both with relative permittivity around 1.5, see Sect. 7.2.3. However, humidity can change the permittivity considerably [45].

7.4 Applications

Communication centred around the body can be classified into off-body, on-body, and in-body [46]. While mobile communication and Wi-fi are part of the first class, body area networks (BAN) and personal area networks (PAN) are part of the second class. BAN and PAN include a number of standards, mostly operating in the 2.4 GHz industrial, scientific, and medical (ISM) frequency band. The third class includes communication with medical implants.

7.4.1 Mobile Phone

A textile PIFA was developed for the 900 MHz GSM frequency band [47]. The size of the patch is $70 \times 70\,\text{mm}^2$. The conducting fabric is copper-plated nylon, and a spacer foam with 12.5 mm thickness is used as dielectric. The ground plane is a rectangle with rounded corners and side length roughly double of the patch side length. This ground plane shields the antenna radiation towards the body. A 1.2-mm-diameter miniature coaxial cable feeds the antenna. The efficiency of the antenna is 70 to 80% in free space and 50% when worn.

7.4.2 GPS

A textile circularly polarized patch antenna for GPS was developed by Salonen et al. [41]. The conductive patch was made of copper tape, while different synthetic fabrics were applied as dielectric. The dielectrics are between 0.5 and 5 mm thick and have relative permittivities in the range of 1.1 to 1.7. The patch is a square with side length 88 mm, and the ground plane is a square of 130 mm side length. The corners of the patch were cut off to introduce circular polarization.

7.4.3 Satellite

A textile square patch antenna with a polygon-shaped slot was fabricated for dual-band use with circular polarization [48]. The side length of the antenna is 65 mm. The antenna operates in 1575 MHz frequency band for GPS and in 1621 MHz to 1626.5 MHz range of the Iridium satellite constellation for satellite phones. The polygonal shape of the slot was chosen to provide circular polarization and wide band performance. Silver- and copper-coated woven nylon with sheet resistance less than $0.03\ \Omega/\square$ was used for the conductive sheets and sewed to Cordura with relative permittivity around 1.8 and thickness approximately 3 mm. The antenna efficiency is above 65% at the frequencies of interest.

7.4.4 Wi-fi

A textile dual-band monopole antenna was made from nickel–copper-plated polyester glued onto felt [49]. The felt has a relative permittivity of 1.22 and a thickness of 2 mm. The antenna covers an area of $60 \times 30\ \text{mm}^2$ and operates in the 2.5 and 5 GHz frequency bands. The antenna gain is around 1.3 dB in the lower frequency band and around 5 dB in the upper frequency band.

7.4.5 Ultra-Wideband

Ultra-wideband (UWB) transmits data over a frequency band approved by the FCC ranging from 3.1 to 10.6 GHz. Klemm et al. [50] fabricated a circular disc monopole and an annular slot antenna. The disc monopole covers an area of $20 \times 30\ \text{mm}^2$, and the slot antenna size is $30 \times 30\ \text{mm}^2$. The materials employed are metallized nylon fabric with sheet resistance $0.03\ \Omega/\square$ for the conductive surfaces and acrylic fabric of 0.5 mm thickness for the dielectric with a relative permittivity of 2.6. Performance measurements of power transfer between two antennas separated by 1 m were conducted. Up to 7 MHz, the textile antennas show performance reduction of about 1 dB compared to two reference PCB antennas of equal shape. But above 7 MHz, the performance is up to 35 dB lower for the textile antenna compared to the PCB antennas. With the transmitting antenna 2 mm away from a human body, the performance drops by 9 dB compared to free space.

7.4.6 Bluetooth

Two examples of textile patch antennas for Bluetooth were already introduced in Sect. 7.2.3. Salonen et al. developed a dual-band PIFA for Bluetooth and the Universal Mobile Telecommunications System (UMTS) [51]. The frequency bands are 1885 to 2025 MHz and 2110 to 2200 MHz for UMTS and 2.45 GHz for Bluetooth. The antenna size is 50×42 mm^2. The dielectric material has thickness 0.236 mm and relative permittivity 3.29. The return loss is less than -10 dB over the specified frequency bands.

7.5 Body Effects

Antennas in proximity to a body result in two effects. First, power is radiated into the body and absorbed, characterized by the specific absorption rate. Absorption reduces the antenna efficiency and heats the body. Second, the different electromechanical properties of the tissue change the antenna impedance. Change in antenna impedance affects the matching performance.

7.5.1 Specific Absorption Rate

The power absorbed in human tissue is quantified by the specific absorption rate (SAR). The unit of SAR is watts per kilogram. The SAR is usually averaged over 1 or 10 g of tissue.

The absorbed power heats the tissue. To maintain its temperature, the body reacts with adapting blood flow and sweating. Electromagnetic radiation can increase the tissue temperature such that these body reactions cannot dissipate the excess heat. Above 42 °C proteins begin to undergo denaturation, and cells may be irreversibly damaged.

There are two main standards that limit the SAR for hand-held and body-mounted devices. One is the standard from the International Commission on Non-Ionizing Radiation Protection (ICNIRP), which was adopted by the European Committee for Electrotechnical Standardization CENELEC. The standard limits the power per kilogram averaged over 10 g of tissue to $2\,\mathrm{W\,kg^{-1}}$ [52], which also agrees with the IEEE standard C95.1-2005 [53]. In the United States of America, the Federal Communications Commission (FCC) uses the prior IEEE standard C95.1-1992 with a limit of $1.6\,\mathrm{W\,kg^{-1}}$ over 1 g of tissue [54].

Rigid mobile phone antennas in proximity to the head or hand have been studied, for example, by Jensen et al. [55] and Bernardi et al. [56]. It was found that around one-half to two-thirds of the power transmitted by the antenna is lost in the tissue. Similar studies have been conducted with wearable antennas [57]. In the case of a textile dipole antenna on a human arm, three quarters of the transmitted power were absorbed in the tissue.

To decrease the power absorbed in the body, the transmit power can be lowered, or the distance from antenna to the body can be increased, or the radiation pattern can be optimized to minimize the back radiation into the body. Back radiation can be reduced by adding a ground plane (which is inherent to patch antennas) [3], see Fig. 7.4d, or an electromagnetic band gap (EBG) substrate [58, 59].

7.5.2 Body Effects on Antenna Characteristics

Apart from the power absorbed in the body, the antenna characteristics are changed by the different material parameters of body tissue and the distance between body and antenna [60]. While antennas with a ground plane are shielded towards the body and thus less affected by it, the distance to the body influences antennas without ground plane, such as dipoles or loops.

The impact of the body on the antenna characteristics are as follows:

- The radiation pattern is altered due to diffraction and scattering from the body [61].
- The different antenna impedance results in a shift in resonance frequency [61]. The resonance frequency is lowered in the vicinity of the body.
- A change in body posture can alter the relative polarization of the communicating antennas. Particularly, in on-body communication, body movements affect the path gain and thus the overall efficiency of the communication link [9, 62].

7.5.2.1 Adaptive Matching

The change in impedance or resonance frequency due to body proximity can be compensated by adapting the elements of a matching network [63]. First, mismatches or frequency shifts have to be detected. Then, the matching network has to be adapted accordingly. Different implementations of mismatch detectors and adaptive matching networks exist. We shall name a few to provide a starting point for the reader.

The mismatch detection can be done by measuring the reflected power using directional couplers [64]. Matching is optimized by minimizing the reflected power or the ratio of reflected power to incident power.

The matching network can be adapted by altering variable lumped elements. Examples of variable elements are varactors [65], microelectromechanical systems (MEMS) [66], or CMOS capacitor banks [67].

7.6 Bending Effects

In addition to the body effects, textile antenna characteristics vary due to their bending and wrinkling. The characteristics to be considered are the antenna impedance, which also determines the resonance frequency and the bandwidth. Previously mentioned papers on textile antennas [23, 24, 26, 48, 49] include an analysis of antenna performance under bending. These antennas were designed with wide enough bandwidth, such that the return loss remains below −10 dB at the desired frequency. In this section, we will summarize a few papers that investigate the influence of bending on antenna performance in more detail.

Three different antennas, namely a patch, a patch with an EBG layer, and slot antenna, were investigated by Salonen et al. [68] under bent conditions around a cylinder. The bending radii were chosen to be 35 and 75 mm. A cylinder of radius 35 mm approximately corresponds to the shape of an upper arm, and a cylinder of radius 75 mm approximately resembles the shape of a thigh. The antenna materials are copper tape for the conductive surfaces and felt or fleece for the dielectric. The antennas resonate at 2.5 GHz. Bending along the symmetry axis (see Fig. 7.7) increases the resonance frequency up to 5%, while bending along the orthogonal axis results in a frequency rise less than 2%. Bending along the symmetry axis reduces the effective length of the antenna and thus increases the resonance frequency. The bandwidth was altered in both bending directions, but also more in the bending along the symmetry axis. For the patch antenna, the bandwidth was increased by up to 75 MHz or 35%. For the patch antenna with EGB layer and the slot antenna, the bandwidth was reduced by 4 and 13%, respectively.

A patch antenna from polyester was bent around cylindrical PVC pipes [69]. Bending reduces the resonant length and thus increases the resonance frequency. The resonance frequency is 90 MHz or 3.7% higher for the bent antenna with radius 88.9 mm than the resonance frequency of the flat antenna (2.43 GHz). Lowering the bending radius to 50.8 mm increases the frequency by another 1.2%. The bandwidth of the flat antenna is 113 MHz, and it varies between 111 MHz for 50.8 mm bending radius and 117 MHz for 88.9 mm bending radius. The radiation patterns are changed towards a narrower beam with smaller bending radius in the azimuth plane. The 3 dB beam width decreases from 66 to 57°. In the elevation plane, the beam width is 62° for the flat antenna but increases from 51 to 57° for decreasing bending radii. The gain is reduced from 9.6 dB for the flat antenna to 8.2 dB for bending radius 50.8 mm.

An analysis of bending of patch antennas was conducted by Boeykens et al. [70]. Bending affects the textile. The textile will be stretched depending on the textile characteristics and the bending radius. Furthermore, bending compresses the dielectric and thus changes its permittivity. The permittivity of the compressed dielectric is

$$\varepsilon_{r,\mathrm{comp}} = \varepsilon_{r,\mathrm{flat}} \left(1 + \eta \frac{h(d-0.5)}{a}\right) \tag{7.8}$$

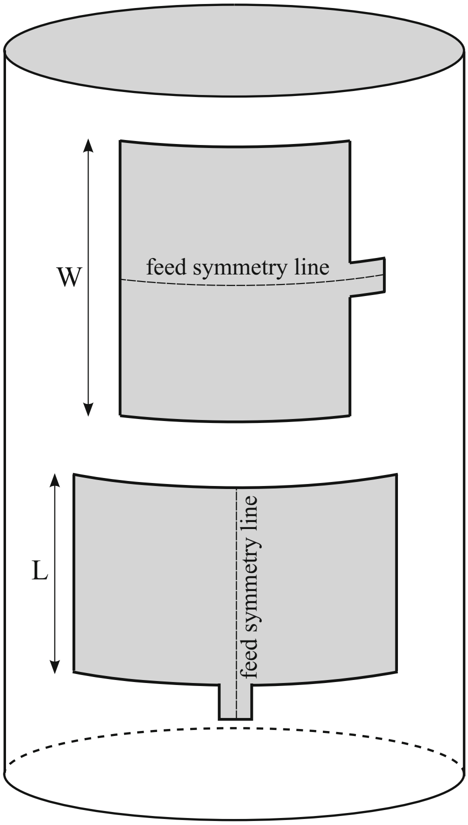

Fig. 7.7 Bending directions using the example of a patch antenna. *Top* bending along the symmetry axis (feed symmetry line); *bottom* bending along the orthogonal axis

where a is the bending radius, η is a proportionality factor, and h is the height of the dielectric. The factor d is 0.5 if the patch is stretchable and 1 if it is non-stretchable. The permittivity of the stretchable patch does not change according to the above formula. Measurements showed that antennas with stretchable patches have constant resonance frequency, whereas antennas with non-stretchable patches experience dielectric compression. The dielectric compression counteracts the effect of increasing the resonance frequency when bending along the symmetry axis. Instead of a frequency increase by 40 MHz, the frequency is 10 MHz higher for a bending radius of 3 cm compared to 1.55 GHz for a bending radius of 10 cm. When the non-stretchable patch is bent along the orthogonal axis, the resonance frequency is decreased by approximately 3 MHz due to the dielectric compression.

A coplanar waveguide-fed (CPW) antenna, which is a patch antenna with the ground plane surrounding the structure at the sides instead of facing it separated by a dielectric, was analysed by Bai et al. [71]. The antenna size is 55×55 mm^2. The

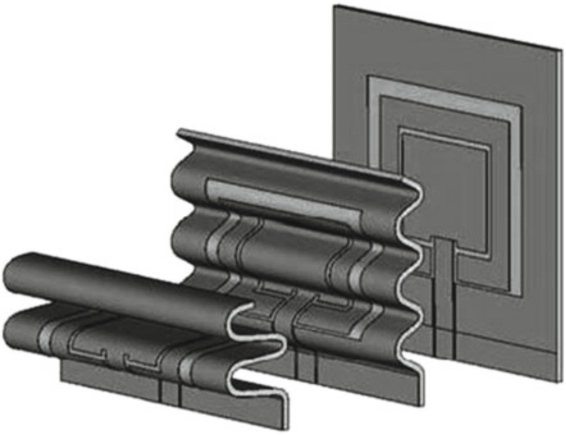

Fig. 7.8 Different crumpling shapes described by depth and aperture parameters. The antenna size is 55 × 55 mm^2. Courtesy of [72]

conductive material is a tin–copper-plated nylon, and the dielectric felt has relative permittivity 1.38 and thickness 2.4 mm. Bending the antenna along the symmetry axis has more impact than along the orthogonal. However, the resonance frequency decreases with smaller bending radii. Also, in this dual-band antenna, one resonance is more affected than the other. The same antenna was investigated under crumpling conditions [72]. The shape of the investigated crumpling is shown in Fig. 7.8. The resonance frequency at the lower band changes by less than 100 MHz, while the bandwidth is reduced from 400 to 250 MHz. At the upper band, the resonance frequency of the antenna bent with radius 38.5 mm increases by about 100 MHz. For bending radius 22 mm, the return loss at the 5.8 GHz resonance rises to −7 dB.

To counteract the mismatch and frequency shift due to bending, the same techniques as in Sect. 7.5.2.1 to adapt the matching due to body proximity can be applied.

7.7 Discussion

We have presented different antenna designs implemented in textile. Each antenna design has its advantages and disadvantages in terms of performance, mechanical flexibility, and bending and stretching characteristics. Presenting a “best” antenna is difficult. The reader should rather use the presented examples as an overview of existing technologies to help him develop his own antenna.

The majority of the presented textile antennas are patch antennas used for Wi-fi, Bluetooth, or GSM. The material of the antennas is conductive fibres or conductive ink. The material should be chosen with the trade-off between textile flexibility and electrical conduction in mind. Finally, the antenna has to be characterized, also under bending and stretching conditions. The changes in antenna characteristics under bending and stretching conditions have to be accounted for by either designing a wideband antenna or adding an adaptive matching network.

Most presented textile antennas here are designed to be wideband enough to cope with bending and stretching. In the future, more focus should be given to adaptive matching in order to increase antenna performance.

Antennas can be implemented in clothing, since a piece of garment can offer more area than a portable electronic device, such as a mobile phone. However, the circuits to control the textile antennas as well as the lumped elements such as inductors and capacitors for matching and tuning are still rigid elements. Therefore, the antenna has to be connected to an external electronic device. Alternatively, for a complete textile radio system, the rigid elements also have to be implemented in textile, which raises additional challenges and may reduce performance.

Summary

Textile antenna designs and their applications were listed:

- Monopole and dipole antennas are used in mobile phone communication, television, and radio. In textiles, they are also designed for the frequency range 100 to 800 MHz.
- Loop antennas are implemented in pagers. In textiles, loop antennas are found for special applications, such as medical applications where magnetic coupling instead of electromagnetic radiation is exploited.
- Patch antennas, used in mobile phones for telephone services, Wi-fi, and Bluetooth, are employed as textile antennas for body area networks.

Issues to be taken into account when developing textile antennas are as follows:

- the trade-off between conductivity and flexibility of the textile,
- the effect of body tissue in proximity to the antenna when the antenna is worn, and
- the influence of bending on antenna characteristics.

Acknowledgements Much of the antenna theory was adopted from the book *Antenna Theory: Analysis and Design* by Constantine A. Balanis [3].

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Chapter 8
Electronics Integration

Matija Varga

Abstract In the past two decades, wearable computing has brought together different fields of research as well as industry. The idea of wearing a computer as a part of the clothing led to an increased effort in both industry and research to seamlessly integrate electronics and textiles. Having significantly different properties, textiles and electronics pose a challenge to mechanical, material, textile and electronics engineers. To address these challenges, in this chapter, different levels of textile-electronics integration are analysed: fibre level, textile material level and garment level. At the fibre level, microelectronics (e.g. transistors and sensors) are either directly fabricated on fibres or bonded onto the fibres using a specialised fabrication process. At the level of the textile material, textile is manufactured using conventional and conductive fibres. In later steps, conductive fibres are modified and interfaced with electronics. At the garment level, textile is the substrate material and the integration happens on the surface of a garment. Embroidery technique, lamination or screen printing are used to integrate the electronics on the textile. The principles of textile-electronics integration are described using representative examples from state-of-the-art research.

8.1 Introduction

In one of the earliest works in the field of wearable computers, a term of *disappearing electronics* in textiles has been coined [1]. The *disappearing* came as a consequence of continuous miniaturisation of electronic devices. Miniaturised embedded computers, that were attached to the clothing and equipped with sensors and actuators, quickly found many applications from continuous health monitoring to human–computer interaction. Since then, researchers and industry explore various integration methods that yield wearable systems that are as light and unobtrusive as everday garments. Also, the interaction with such a device is intuitive and built on existing paradigms of

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© Springer International Publishing AG 2017
S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_8

human–computer interaction (e.g. touch input). Even though the goals are straightforward, consumer electronics in the form factor of clothing still seem futuristic.

In the current state-of-the-art research, conventional textiles and garments with additional functionalities such as heat control and light-emitting indicators are called smart textiles, smart fabrics or smart garments. In this chapter, the focus is set on textiles with integrated electronic devices; we will refer to them as smart textiles or smart garments. Often such textiles are also called the e-textiles. The reader of this chapter will gain an overview of concepts for the (seamless) integration of electronics in textiles. The focus is set on studying fundamentally different integration technologies and linking them tightly with the examples from the research. In the following sections, electronics integration is studied at three different levels: (1) Fibre level: closest to the ideal of the *disappearing electronics* at the expense of limited functionality, (2) Textile material level: electronics are integrated in the textile structure with many functionalities but at the expense of wearability of the garment, (3) Garment level: conventional and flexible electronics are laminated on a textile substrate. The integration complexity is minimised at this level but the seamless integration is compromised.

The first section on fibre level integration presents the technology for the integration of transistors, digital circuits, sensors and actuators on fibres. Two types of transistors on fibres are shown: transistors that are deposited directly on a round or flat fibres (plastic strips) and transistors that consist of two fibres. The strips with sensors and actuators can replace round fibres and can be exposed to an industrial weaving process and integrated in textile. During the manufacturing, strips are exposed to high bending radii; thus, a high strain is introduced in electronics. Therefore, the importance of encapsulation for mechanical protection of fibres is elaborated here. Additionally, as an example of crack-free metallic conductors, fibres made of elastomer and eutectic gallium alloy are presented.

The section on the integration of electronics in the textile structure describes how an intarsia knitting technique is used to seamlessly integrate conductive tracks in textile. Such a fabric is stretchable and conformable. In addition to intarsia, weaving technique can also be used to define an orthogonal grid of interconnects inside a textile material. In post-processing, conductive paths are formed by cutting the fibres in a grid and bonding them with electronics. Different bonding techniques are employed: conductive and non-conductive adhesives, crimping technology and anisotropic conductive adhesives.

The last section describes techniques where garments are only used as a substrate. The complexity of the integration is reduced. Due to simplicity and affordable materials, it can be employed by out-of-the field enthusiast (e.g. fashion designers) in their experimenting with wearable computers. Using the concepts given in this chapter, almost any miniaturised system can be integrated on the garment, but at the expense of reduced wearability. This section provides examples of techniques based on lamination and screen printing. Finally, a discussion section is followed by an overview of all techniques in a summary section.

8.2 Integration on a Fibre Level

The lessons learned from conventional silicon industry encourage us to believe that high-density integration of transistors on fibres can lead to the integration of complex electronics systems directly into the clothing. The rigidity of silicon and the fragile nature of thin films limit the direct application of the microfabrication technology on fibres. The challenges for the application of microfabrication on fibres are as follows: rounded surfaces, mechanical flexibility and exposure to stress and strain during textile manufacturing. These challenges have been tackled by the researchers and are shown in this section.

In work by Bonderover et al. [2] and Lee et al. [3], one of the first examples of transistors on fibres were presented. Logic circuits and transistors were functional and operating on both flat and round fibres. Bonderover et al. [2] fabricated the amorphous silicon transistors on a flat 50-µm-thick polyimide substrate that was cut after the fabrication in 2- mm-wide strips—fibres with transistors. To build logic circuits, i.e. inverters, perpendicular conductive fibres were woven into the fabric (Fig. 8.1). The connections between the fibres were obtained through pressure that was introduced during weaving. Authors have used high-density oxygen plasma to cut through the polyimide, which left smooth edges after the processing. Also, each fibre was curved by depositing a compressively strained layer of silicon nitride. The advantage here was that the interconnects were not bonded so they could move against each other. Nevertheless, the contacts were not characterised in a bending test. To improve the reliability of the contacts, one can fabricate conductive bumps over the contact area. In this way, the pressure increases locally around the bumps; thus, the contact is more reliable. One example of such contact structure was developed by Yamashita et al. [4] (Sect. 8.2.3).

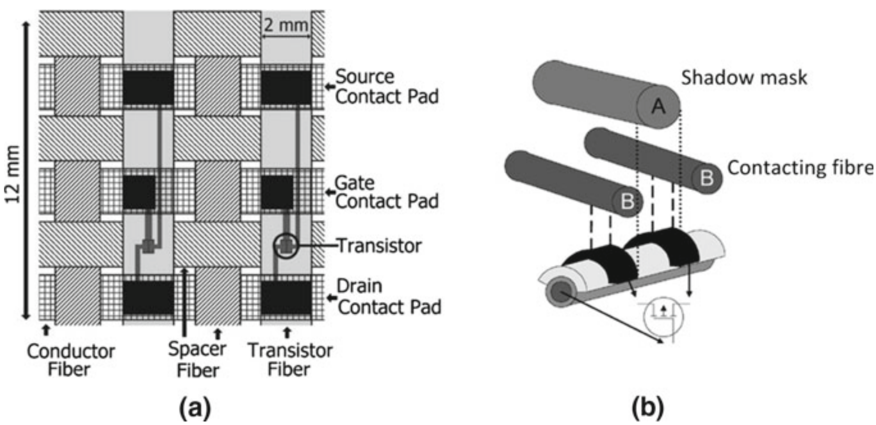


Fig. 8.1 **a** A woven textile with polyimide strips with transistors. Image courtesy of Bonderover et al. 2004 [2]. **b** A transistor on a round fibre. The core of the fibre is the gate electrode and deposited contacts are the drain and the source. Image courtesy of Lee et al. 2005 [3]

The transistors on round fibres in [3] were fabricated using a different approach. A stainless steel and an aluminium fibre with a diameter of 125–500 μm are used as a gate metal. It is first coated with a dielectric (silicon dioxide or poly-4-vinylphenol) and then with an organic semiconductor (pentacene). The coating of rounded surfaces is enabled by conformal coating techniques such as low temperature chemical vapour deposition (LTCVD) or deposition from a solution. To define a channel of the transistor, a shadow mask consisting of perpendicular fibres was used. In that way, after the physical vapour deposition (PVD) of the metal, source and drain contacts were formed. The channel length of the transistor is defined by the thickness of the shadow fibres. Since the PVD technique can only deposit on the top surface, the source and drain contacts must be correctly oriented before the integration. The end application of such transistors would be in a network of sensors where transistors can be used as switches that connect the sensor with the central processor.

In previously presented approaches, the focus of the integration was set on the fibre. After the fabrication, the fibres were mostly hand woven in a textile. In work by Cherenack and Zysset, the thin film electronics, sensors and off-the-shelf components have been exposed to a commercial weaving process. They used microfabrication technology on a polyimide substrate to fabricate the electronics and cut them in 2-mm-wide and 50-μm-thick strips using a dicing saw. In the final step, they introduced the strips in a commercial weaving machine (Fig. 8.2). When compared

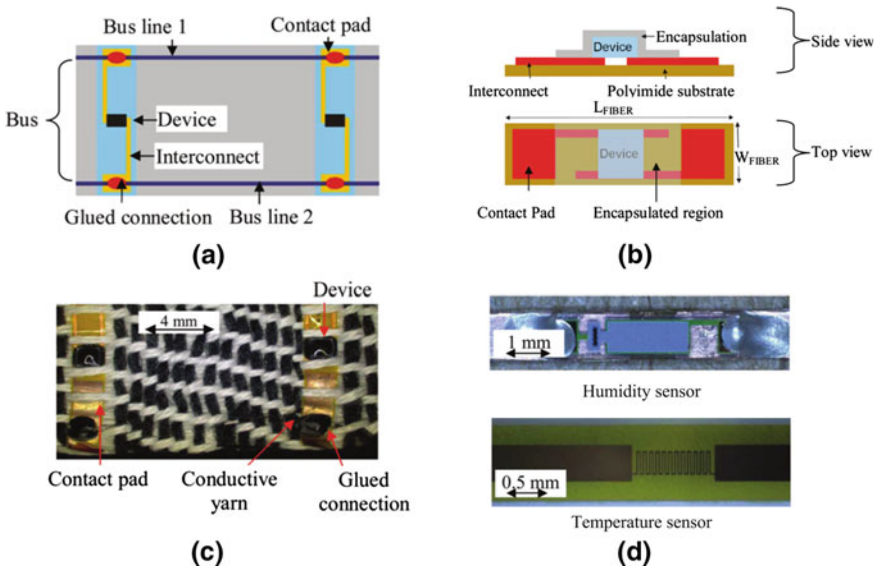


Fig. 8.2 **a** A scheme of a bus line in textile with electronics on plastic strips. **b** An illustration of a device on a strip. **c** A photograph of strips with electronics that are woven in textile. **d** Humidity and temperature sensors embedded on a strip. Image courtesy of Cherenack et al. 2010 [5]

to Bonderover et al. [2], a more costly step of high-density oxygen plasma cutting was replaced by dicing. The need for flat contact surfaces was mitigated by using conductive glue to obtain reliable contacts. The plastic strips were woven with soft conventional cotton fibres that can adapt to stiffer plastic strips. Standard conductive yarns were woven in a perpendicular direction and aligned with the contact pads on the strips. An infrared spectroscopy bandage [6] and textile for humidity and temperature monitoring [7] are the applications that used this integration technology.

To efficiently use space, the integration made use of miniature bare dies instead of packaged chips. After the bonding, the chips were mechanically stabilised and protected using a glob-top material. The encapsulation of the fibres was the enabling technology for the weaving of fibres. The fibres were exposed to mechanical stress during the weaving process as well as while the fabric was worn. To prevent cracks in thin metal films, it was vital to determine the optimal encapsulation method (Sect. 8.2.1).

In work by Zysset et al. [8], the first attempt was to integrate the electronics by using a roving machine to twist the plastic strips around the cotton fibres. The major disadvantage of this approach was the folding of the plastic strip that appeared when the twisted strip was extended. The folds introduced high strain that led to cracks in the metallic layers of the fibre.

The second approach used embroidery to integrate the plastic strips in textiles. The concept of the integration was simple—a plastic strip was sewn to the textile substrate. In this process, plastic strips, which were coated with 100 nm gold layer, are fed into the machine and bent at 90°. To measure the strain indirectly, authors bent tested strips to well-defined bending radii and measured their resistance. They used theoretical equations from Suo et al. [9] to determine the strain and link it to the measured resistance (Fig. 8.3). The same type of plastic strips were then fed into the machine and the resistance (i.e. strain) was measured. The strips in the machine experienced 2% of resistance change which corresponds to 6% of strain. For improved mechanical stability of thin metal films, encapsulation can be used.

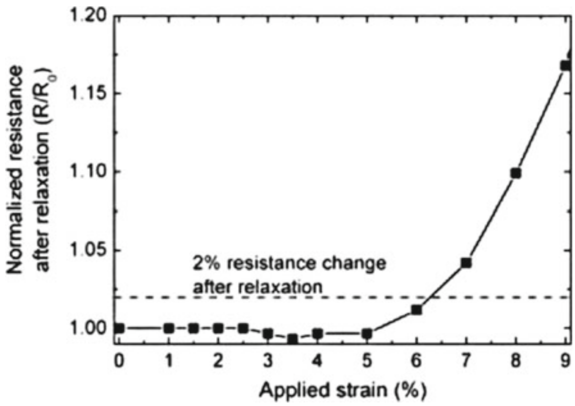


Fig. 8.3 A result of a strain measurement on a plastic strip during the embroidery process. A 2% change in resistance is measured on a conductive strip that went through the embroidery machine. It is compared to the value obtained in a separate bending test, which corresponds to 6% of strain. Image courtesy of Zysset et al. 2013 [8]

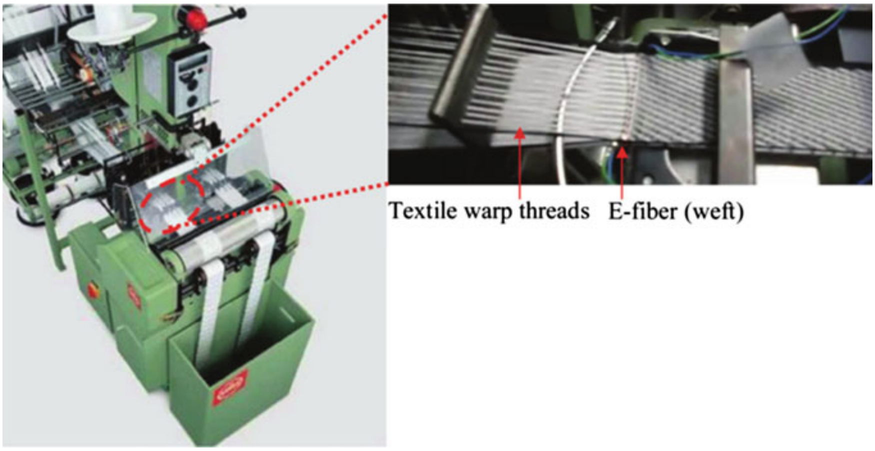


Fig. 8.4 A narrow weaving machine with a detail of the warp and weft fibres. Plastic strips are inserted in a weft direction and conductive yarns are a part of the warp thread. Image courtesy of Cherenack et al. 2010 [5]

The third approach was to weave the strips directly using the weaving machine (Fig. 8.4). The strain in strips depended on the weaving method. The advantages of using the rapier loom were as follows: 1. The loom allowed automated introduction of flexible plastic strips into the 1.6-m-wide textile and 2. The weaving method and surrounding fibres did not cause strain in plastic strips. The first point was accomplished by attaching the plastic strips to the moving rapier that pulled each strip into the textile structure. The second advantage came from the weaving with a low strain and using surrounding fibres that were more rigid. On the other hand, on a narrow weaving machine (4.5 cm), it was observed that 14% of strain was introduced. It was due to the size and higher density of surrounding fibres which eventually bent the plastic strips inside the woven material. The narrow weaving machine used cotton fibres unlike plastic fibres in the rapier loom. A 4.5-cm-wide textile patch contained four conductive yarns (Bekinox VN 14/1) in the direction of warp threads. They were connected to the plastic strips using a conductive epoxy (Epo-Tek H20E) and cured at 80 °C for 24 h.

Brun et al. [10] show a *Diabolo* technology that integrates silicon dies directly into a conductive fibre. A silicon wafer with electronics has prepatterned cuts and is enclosed with a protective wafer that is as well prepatterned. After the glueing of wafers and grinding from the back side, wafers split on the pre-cuts. On the edges of each chip, there are two grooves. A specialised machine mechanically pushes the fibres in the grooves. The strain from the side walls of the chip assures enough force for a reliable electrical contact. Finally, the fibres are mechanically fixed using a conductive glue or by the use of electroplating. Brun et al. [10] have successfully shown the integration of LEDs and RFID chips in a yarn. The limitation of this approach is the number of contact points which is usually greater than two for typical

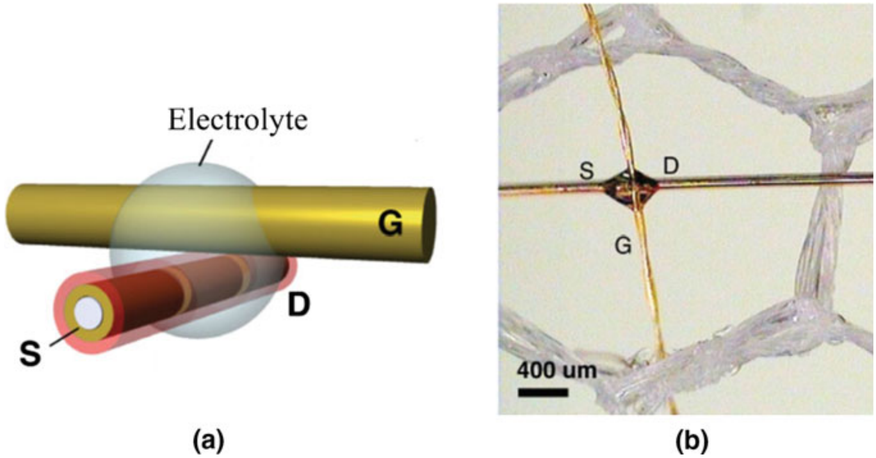


Fig. 8.5 A depletion transistor fabricated on two fibres. Source, drain and gate electrodes are marked with S, D and G, respectively. **a** A gate dielectric material is a solid-phase electrolyte that depletes the charge in the semiconductor on the second fibre. **b** At the crossings of fibres, a droplet of the electrolyte creates a transistor. Image courtesy of Hamedi et al. 2009 [11]

electronic devices. One must also consider the issue of isolated filaments, where the isolation must be removed and the chip aligned before the bonding.

Previous concepts share a common approach—a single fibre is modified by microfabrication, by bonding or by mechanical insertion of electronics in the fibre. Hamedi et al. [12] presented an approach, where a transistor consisted of two fibres (Fig. 8.5). Similar to transistors on a round fibre, fabrication process included coating with metal and patterning of source and drain contacts. Then, the process continued with a dip coat step, where a film of organic semiconductor, poly[3-hexylthiophene-2,5-diyl], was deposited on the fibre. The gate fibres were positioned above the channel and between the source and the drain. It was not necessary to precisely align the gate fibres and have thin dielectric layer since a solid-phase electrolyte was used as a gate dielectric. It is a imidazolium ionic liquid whose ions separated upon applying the gate potential. The ions around the channel affected the charges by means of the field effect and by doping/undoping. As a consequence, charge depletion occurred and current between the source and drain significantly dropped. The ratio between the on and off current in depletion transistors on a fibre is in the order of 1000 at the gate voltage of -1 V [11] (typical on/off ratios of silicon transistors are around 10^6). Conducting state was the default state of depletion transistors which may be a difficulty when designing a system. The attractive property of such concept is that the transistors can be created after the weaving process. The choice of the material at the crossing of two fibres defines whether the transistor, resistor or isolator is created.

8.2.1 Utilities: Encapsulation

Kinkeldei et al. [13] explored two different methods for the prevention of cracks in thin metal films. The first method, the crack prevention, included patterning of micro-openings in metal layers. The openings were thought to prevent the propagation of cracks through the structure of the thin film. The second strategy included the encapsulation of the thin films with a flexible material. A 50-μm-thick polyimide material was glued on the top of the electronics. The substrate and the encapsulation were of the same material and the same thickness, i.e. the thin films were positioned in a mechanically neutral bending zone, where compressive and tensile stress cancel out.

In work by Kinkeldei et al. [14], the authors applied encapsulation method to indium gallium zinc oxide thin film transistors (TFTs). They compared encapsulation using a scotch tape with the encapsulation using the substrate material. The process steps of encapsulation using the substrate material (50-μm-thick polyimide foil) were as follows: fabrication of transistors, patterning of the polyimide foil, alignment of the foil over the electronics, contacting and curing. The patterning process included the definition of contact openings using evaporated aluminium layer and dry etching in a reactive ion etching system. Finally, the mask aligner MJB3 was used to align the samples and keep them in contact for 24 h of curing at room temperature. Figure 8.6a shows the comparison of crack prevention methods during bending and Fig. 8.6b shows the effect of encapsulation during bending on properties of the TFTs. The encapsulation yields the best results since the thin films are not exposed to either tensile or compressive stress. The encapsulated TFTs were still functional at the bending radii of 125 μm, where a theoretical limit for a 50-μm-thick substrate is 100 μm.

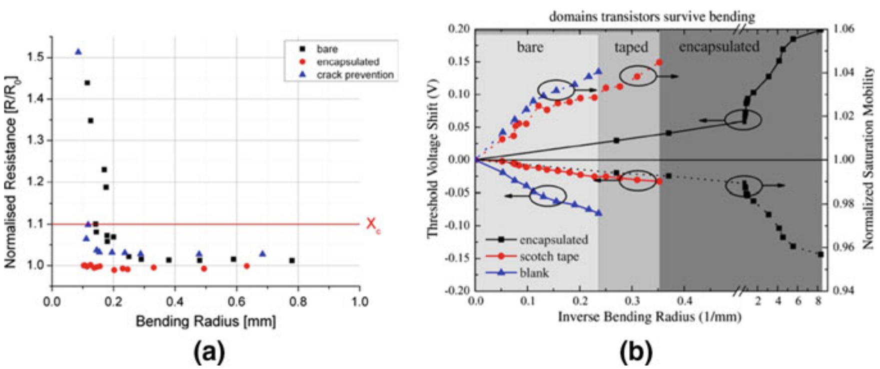


Fig. 8.6 **a** Different protection methods are applied to prevent cracks in thin metal films. Encapsulation with the substrate material (50-μm-thick polyimide) allowed highest possible bending radii [13]. **b** Properties of encapsulated and bare thin film transistors after bending [14]. Image courtesy of Kinkeldei et al. 2011 [13, 14]

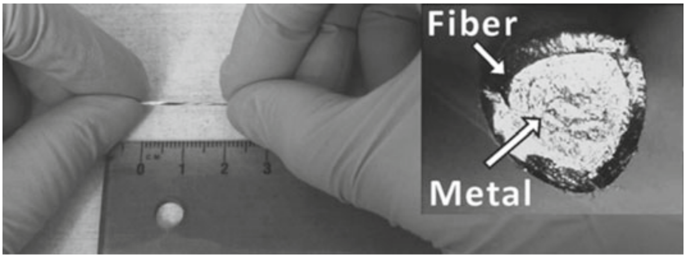


Fig. 8.7 A stretchable conductive fibre that conducts current when stretched up to 800%. A hollow elastomer fibre is filled with an alloy of gallium and indium, which is liquid at room temperature. Image courtesy of Zhu et al. [15]

8.2.2 Utilities: Stretchable Conductive Fibres

A crack-free conductive fibre can be created using a hollow stretchable material and a liquid metal alloy (Fig. 8.7). Zhu et al. [15] presented highly stretchable hollow fibres filled with eutectic alloy of gallium (75%) and indium (15%) that melts at 15.5 °C and is non-toxic (unlike mercury [16]).

The fibres were made of thermoplastic elastomer Kraton (SEBS - Poly[styrene-b -(ethylene- co -butylene)- b -styrene]) that is extruded through a slit and pulled through a water bath for cooling. The pulling speed controlled the inner diameter of the fibre, which varied between 360–1030 µm. The stretching results showed that the fibres remained conductive up to the strain of 700% with the nominal resistance increased by 50 times. The maximum strain of Kraton elastomer was 900%. They performed cycling tests at levels of strain higher than 500%, where only few tens of cycles were performed before the breakdown. At a lower strain (≈50%), there was only 5% of plastic deformation and the fibres withstood hundreds of cycles before the breakdown.

Applications that require both stretchable and reliable fibres can benefit from the fibres with a liquid metal alloy. Hurdles for the textile integration are contacting and sealing of the fibres with the liquid metal.

8.2.3 Utilities: Polymer Contact Structures

Woven fibres with integrated electronics often employ a dry contact between functional and conductive fibres (Fig. 8.8). The weaving process exerts a force between the fibres which can be used to provide an electrical contact. When the fibres bend, dry contacts can become unreliable or disconnect. Therefore, additional contact structures need to be designed.

Yamashita et al. [4] developed a surface modification on the flat PET fibres to increase the reliability between woven fibres. The interlacing of fibres during weav-

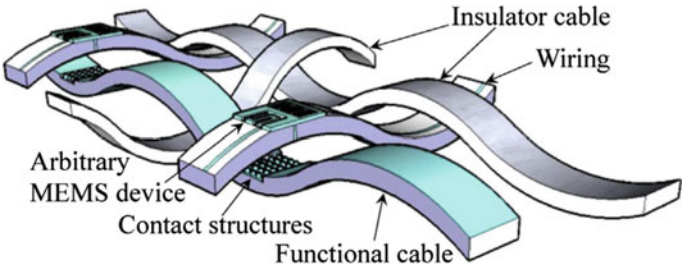


Fig. 8.8 An illustration of woven fibres (cables) with devices and polymer contact structures. Image courtesy of Yamashita et al. 2012 [4]

ing exerted the force on the contact points between the fibres. Since the fibres (i.e. cables in Fig. 8.8) were flat, the contact area reduced quickly with bending and the contact resistance rose. To increase the force at the contact points, the PET fibres were coated with a conductive polymer on the top of which contact structures were built. The coating process consisted of running a fibre through a dissolved conductive polymer (PEDOT:PSS - poly[3,4-ethylenedioxythiophene]-poly[4-styrenesulfonate]) at different speeds, which resulted in different coating thicknesses, and then applying a surface modification. On the surface of the fibre, a micropipette dispensed a silicone droplet and then the conductive polymer. After the curing process, the surface of the fibre contained 1.5-mm-high structures. The surface modification assured that two perpendicular fibres are in contact even when bent down to 1 cm radius.

In a cycling test, a load cell repetitively exerted force of 4 N on the contact of two strips. The contact resistance remained unchanged after more than 10^4 cycles. The initial force for obtaining a contact was 1 N for fibres without surface modification and 10 mN for the fibres with a contact structure. The resistance of the contact was 300 Ω, which is a typical value for the PEDOT:PSS conductive elastomer.

8.3 Integration on a Textile Level

This chapter describes the concepts that integrate the electronics on/in textiles. The textiles are fabricated using standard textile manufacturing processes and usually contain conductive fibres (metallic or coated fibres). The integration happens after the textile fabrication, usually by modifying the texture or the individual fibres.

Two different integration approaches use textiles fabricated by intarsia knitting and weaving. The first technique is similar to routing of printed circuit boards, where conductive tracks are routed on a board. In intarsia knitting, the conductive tracks are defined in a computer-aided design tool, loaded onto the machine and knitted into the textile. In later steps of fabrication, electronic components interface the conductive tracks through bonding and embroidery [17]. The weaving technique does not allow free routing but rather defines fine orthogonal grid of conductive fibres with repetitive patterns. The processing of the textile includes cutting of conductive fibres, removal of isolation and bonding of electronics to the fibres.

Both approaches can be used to build more complex systems than those built with electronics on fibres. The advantage of woven textiles is a fine pitch of fibres, which can be as small as 150 μm [18]. The intarsia-knitted textiles enable free routing of conductive tracks on a single layer; however, the pitch of fibres is limited to the size of the knitting loops (>500 μm) [19].

8.3.1 Integration with Intarsia-knitted Textiles

Figure 8.9 shows a schematic of intarsia-knitted system. The building blocks are electronic devices that contact the ends of the conductive tracks. The authors of [19] have also reported on routing methods using multiple layers of stacked textile. However, having multiple layers of textile adds other difficulties such as alignment and the implementation of textile vias. Li et al. [19] presented the state-of-the-art intarsia knitting technique with out-of-plane loops that withstand strain in both transversal and longitudinal directions. Their stretchable textile allowed building electronic systems on textile that are permeable, comfortable and stretchable. The conductive fibres were copper wires with 50 μm diameter and 3 μm polyurethane coating. Authors

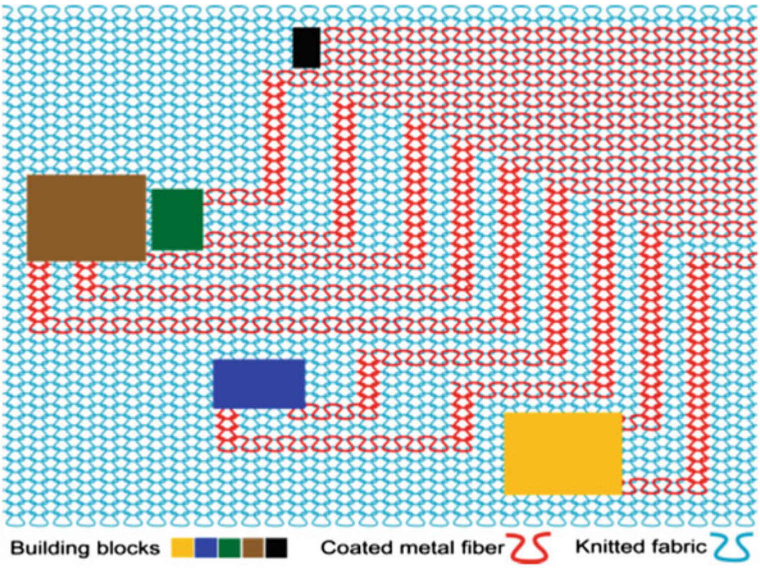


Fig. 8.9 A schematic of intarsia-knitted textile with blocks of electronics. Image courtesy of Li et al. 2014 [19]

reported that a 300% stretched textile with conductive paths exhibited less than 1% of relative change in resistance.

Figure 8.10 shows the three-dimensional loops that exit the textile structure periodically. The sketch in the same figure describes the two amplitudes incorporated into the loop. The stretching in the direction of the meandered loops straightens the meanders and thus compensates for the strain. In the perpendicular direction, strain is absorbed by the third dimension of the loops, i.e. the strain flattens the height of meanders.

The interface between a stretchable textile and a rigid component is the most vulnerable spot of the system. The interface must provide enough flexibility and a gradual transition in stiffness between a rigid component and the 50-μm-thick conductive fibres. Li et al. [19] developed an approach, where a helical structure was used to interface with a rigid sensor. The conductive fibre and the leads of the sensor were wound in a helical shape. After connecting the two helices, the contact is encapsulated in a polymer (Fig. 8.11). Other possibilities for contacting the intarsia-knitted textile are as follows: embroidery with a conductive fibre [17], conductive glue and a non-conductive adhesive [20] that is described in Sect. 8.3.3.

In the stretching tests, the helical connector preserved the stretchability and did not increase electrical resistance upon applying a strain. Moreover, the textile material withstood 30 washing cycles with 84% of specimens with no change in resistance. A repeated cycling test showed a relative 1% increase in resistivity after 1 000 000 stretching cycles.

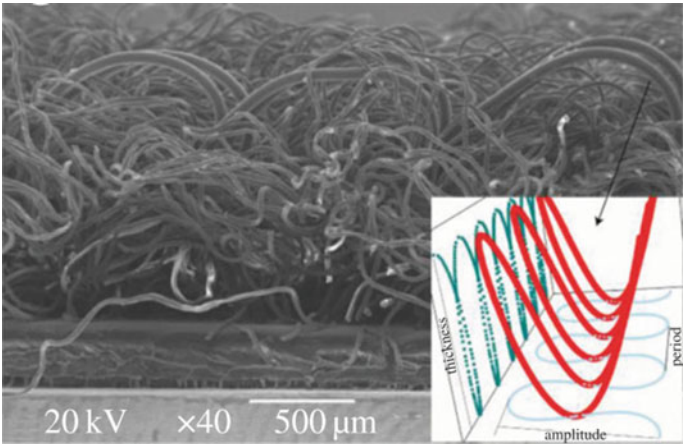


Fig. 8.10 A scanning microscope image of an intarsia-knitted textile. The three-dimensional loops of the conductive fibre exit the plane of textile. A scheme of a conductive fibre shows the three-dimensional loops which compensate up to 300% of strain in all directions. Image courtesy of Li et al. [19]

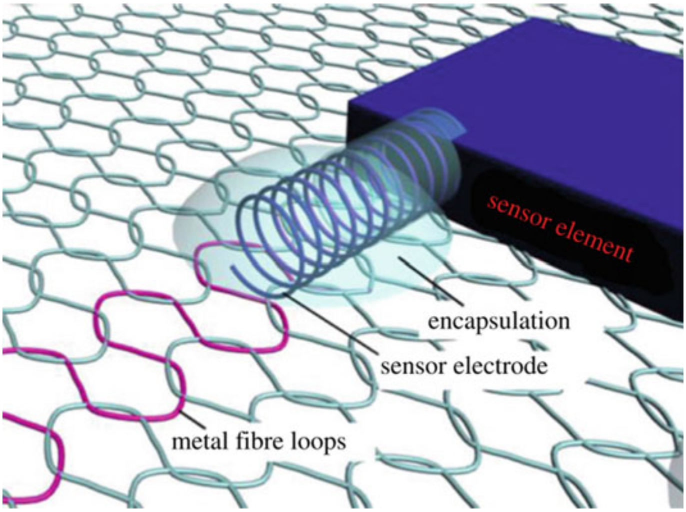


Fig. 8.11 A scheme of a helical connector for the integration of electronics in knitted textiles. A conductive fibre is pulled out of the textile and wound in a helix. A helical lead on a sensor is bonded with the textile helix and encapsulated. Image courtesy of Li et al. 2014 [19]

8.3.2 Integration with Woven Textiles

The woven textiles have a finer pitch of conductive fibres than the knitted textiles due to the necessary loop meandering in knitted textiles. On the other hand, the only parameter that can be modified in woven textiles is the repetitive pattern of conductive threads in the textile. In industrial weaving machines, the fibres that are wound on rolls in large quantity are called warp fibres and those in the perpendicular directions are weft. The system designer is also limited by the pattern of conductive threads in the warp direction since exchanging the fibres in the warp direction would be a time-consuming and costly process.

The challenges that woven textile poses on a design of system-in-textile were addressed in work by Locher et al. [18]. They used PETEX textile woven by Sefar Inc that consisted of monofilament polyester fibres and isolated copper wires (40, 8 μm) in horizontal and vertical direction (warp and weft). The spacing of wires was 0.57 mm, and the openings in textile were $95 \pm 10\,\mu$m (Fig. 8.12c). The DC resistance of woven wires is between 15.7–17.2 Ω/m. To enable free routing, authors developed a process for defining independent conductive tracks inside the predefined grid. The complete integration process consisted of the following steps: 1. Insulator removal: removing the polyurethane isolation using a laser, 2. Forming the path within the grid: wires were laser cut in warp and weft direction and separated from the rest of the grid (Fig. 8.12a), 3. Interconnecting the warp and weft wires: a conductive glue is applied at the crossing of wires (Fig. 8.12a) and 4. Protecting the interconnects: an epoxy is used to mechanically protect the interconnects and electrically insulate them

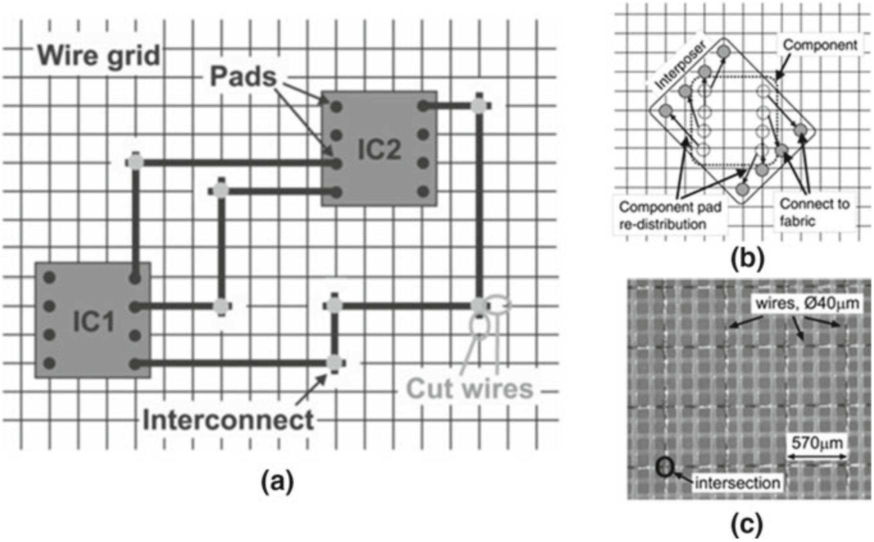


Fig. 8.12 **a** An electronic system integrated on a woven grid of conductive fibres. **b** An interposer for bonding the footprint of the electronic component and the conductive fibres. **c** A grid of woven isolated conductive fibres. Image courtesy of Locher et al. [18]

from the rest of the system. The electronic components could not be directly soldered to the conductive threads; instead, an interposer was used (Fig. 8.12b). It matched the footprint of the electronic components with the conductive fibres. Finally, a conductive glue was used to connect the pads of the interposer and the conductive fibres.

To characterise the transmission lines in textile, authors conducted a test on a wire group in a ground-signal-ground configuration. The transmission line had a bandwidth of 6 GHz when no parasitic fibres were placed around it and 500 MHz when the parasitic lines were included. The impedance of the transmission line was 250 Ω. The vias between the warp and the weft fibres are also characterised and showed a bandwidth of 500–600 MHz.

In work by Varga et al. [21], authors showed a concept of the integration that enabled signal routing on two layers of textile without modifying the textile. They used a woven textile with silver-coated copper fibres (750 μm pitch) fabricated by Sefar Inc. They built blocks of thin film electronics that contacted the textile using contact pads on the top and the bottom side of the block, as shown in Fig. 8.13. The signals between the two layers travelled through the bottom conductive fibres, anisotropic conductive tape, the thin film electronics, and through the identical 90° rotated top part into top conductive fibres (Fig. 8.13). The thin film electronics replaced the routing in textiles. In this way, the routing, that before happened inside the textile, remained in its native domain.

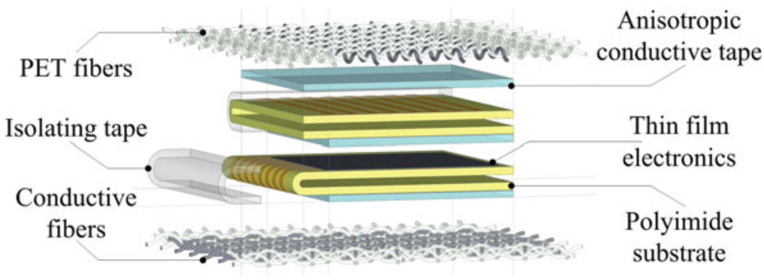


Fig. 8.13 A scheme of a composite material that consists of two polyimide substrates with electronic devices and contact pads, two layers of woven textile with conductive fibres and conductive adhesive tapes. Isolating tape is used as an encapsulation for highly bent contact pads

The conductive fibres contacted the top and bottom pads through an anisotropic conductive tape (3M 9703). The tape consisted of silver-coated nickel particles that had a nominal resistance of 50 $m\Omega/mm^2$ in the direction of the tape's thickness. Since the overlap areas between the flat contact pads and the round copper fibres (400 μm diameter) were significantly smaller than in the specifications, a contact resistance of $\approx$375 $m\Omega/mm^2$ was measured. The same tape contacted the electronics on the top with the electronics on the bottom polyimide substrate. This arrangement of substrates also served as an encapsulation layer for the thin film electronics. The isolating tape encapsulated and protected the conductive track in the bending region.

As a proof of concept, they simulated and fabricated SRAM cells and multiplexers that were used to build a look-up table as a core of a programmable textile. The indium gallium zinc oxide (IGZO) semiconductor was used to build the multiplexers, which consisted of four n-type field-effect transistors (FETs) and SRAM cells, which consisted of six n-type FETs. The SRAMs and multiplexers were then packaged in blocks (Fig. 8.14a) with contact pads covered with anisotropic conductive adhesive (Fig. 8.14b). The blocks were integrated in textile by aligning the conductive fibres to the pads and applying pressure at room temperature. For mechanical stability, such contact point must be laminated using a thermoplastic sheet.

Simon et al. [22] presented a packaging for the integration of printed circuit boards and chip dies in textiles. The electrical connection between the conductive fibres and the electronics was motivated by an established method of mechanical crimping. The name of the packaging is Crimp Flat Package (CFP) and is inspired by the Quad Flat Package (QFP) from the semiconductor industry. The die in a QFP is glued and wire bonded to a lead frame with pins. The die and the lead frame are moulded in polymer with the pins left free at the edge. Similarly, the CFP is built with the exception that the lead frame can carry a conventional printed circuit board (as well as a die) and has crimping leads instead of standard pins (Fig. 8.15). The difference between QFP and CFP is the leads of CFP that end with crimping barrels. Crimping barrels are copper leads with two wings at the ends. A conductive fibre is placed in a barrel which is then mechanically crimped, i.e. wrapped with the two wings (Fig. 8.16).

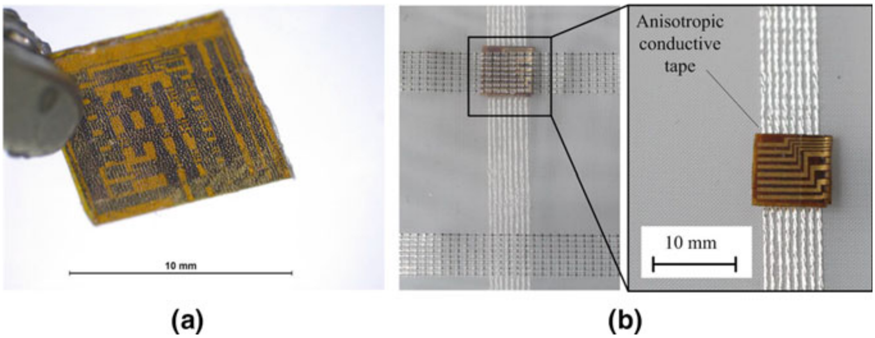


Fig. 8.14 **a** A block of electronics that consists of two bent polymer substrates. **b** A composite of textile and flexible electronics

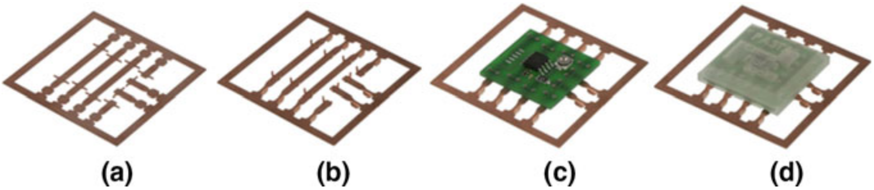
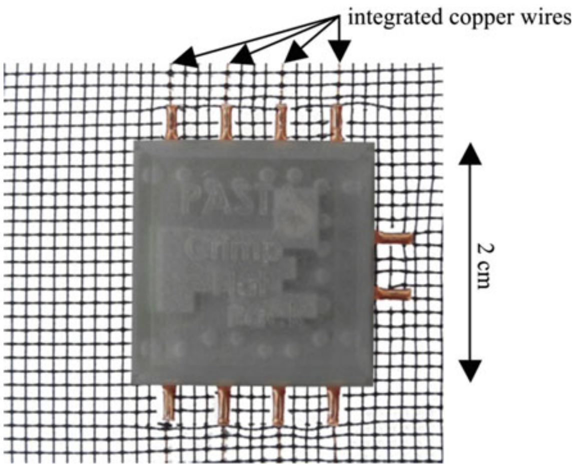


Fig. 8.15 Four fabrication steps of the Crimp Flat Package. In steps **a** and **b**, the wings for crimping are visible. After the last step, a copper frame is separated from the electronics. Image courtesy of Simon et al. [22]

Fig. 8.16 The final step of the integration using Crimp Flat Package. Encapsulated electronics are crimped to the conductive fibres. Image courtesy of Simon et al. [22]



8.3.3 Utilities: Bonding Using Non-conductive Adhesives

Electronic components, that need to be integrated on a soft material such as a knitted textile, require a reliable bonding at the interface. A gradual transition in stiffness is desirable when choosing a bonding material. Apart form conductive glues and embroidery [17], an approach that uses non-conductive adhesives can be employed. The advantage of non-conductive adhesives is that short circuit cannot come from the adhesive itself; therefore, the integration is reduced to correct alignment. Krshiwoblozki et al. [23] connected textile and a printed circuit board (PCB) both mechanically and electrically using a thermoplastic material, heat and pressure. The integration consists of three steps: 1. heating and applying pressure, 2. cooling and 3. releasing pressure. If the isolation of the fibres is also a thermoplastic material with a similar melting temperature, it will fuse with the non-conductive adhesive and leave the conductive fibres exposed. The pressure is then used to bring the pads and the fibres in contact during the curing.

Woven, knitted and non-woven textiles were proven to work with this approach. In work by Krshiwoblozki [23], authors emphasised that from mechanical point of view, using a soft adhesive (with Young's modulus from 10–50 MPa) is important since it must compensate for the shear stress between the textile and the rigid PCB. For a good electrical contact, delamination and relaxation (decreased contact force with time) of the adhesive must be avoided. A polyurethane adhesive with a high coefficient of thermal expansion was used to introduce shrinkage upon cooling and increase the contact force. A contact resistance of 2 mΩ was measured for the bond with a litz wire in a four-point resistance measurement. Similar results were obtained using a metal-coated polymer fibres but with variations in contact resistance up to 25 mΩ.

The integrated test PCBs were subjected to a standardised temperature cycling test from −45 to 85 °C. After 1000 cycles, no significant increase in contact resistance was measured on the samples with litz wires, whereas polymer-coated fibres showed 20% increase in contact resistance. The samples were exposed to relative humidity of 85% at 85 °C for 1000 h. No significant increase in the contact resistance is measured for both fibre types.

8.4 Integration on a Garment Level

In this section, the textile is used as a substrate for building electronic systems. It is not conductive and serves only as a supporting material. All methods mentioned in this section could also be applied to garments, which further emphasises that the integration and textile manufacturing are independent. The means of the integration are lamination and screen printing.

Beuchley et al. [24] described a technique of laminating conventional printed circuit boards (PCBs) onto a textile substrate. They cut a conductive textile and laminated it on a textile substrate. Off-the-shelf components were then soldered onto the conductive textile and encapsulated using epoxy. The goal in this work was to introduce a set of methods that can be used by amateurs and designers to easily create prototypes and explore possibilities of smart textiles.

In the integration process, they used a heat-activated adhesive for bonding. The conductive textile was a metallised fabric with a Sn/Cu plating and a surface resistivity of 0.1 Ω/sq. To form the conductive tracks, they attached the adhesive to the conductive textile and covered it with paper. A laser cutter was employed to pattern the conductive tracks (Fig. 8.17a). A paper backing was removed only where the bonding should occur and elsewhere it was used as a masking layer (Fig. 8.17c). An iron activated the adhesive and bonded the unmasked conductive tracks onto the textile substrate (Fig. 8.17d). The rest of the conductive textile, that was masked by the paper backing, was removed. Multilayered fabric printed circuit boards (PCBs) were created by inserting a layer of standard textile on the crossing of conductive tracks. Finally, pins of electronic components are soldered on the textile using conventional soldering tools.

Vervust et al. [25] developed a stretchable interconnect structure and a moulding procedure for rigid electronics that can be laminated on textile. The concept of the integration of rigid electronics on a stiff islands interconnected with stretchable conductors is a common approach for creating stretchable electronics [26].

In work by Vervust et al. [25], authors used a standard screen printing process for the lamination. They investigated the penetration of polydimethylsiloxane (PDMS) adhesive and the corresponding adhesion. The optimal curing temperature was found to be 100 °C in an oven, and the optimal ratio of the silicone and the curing agent was 10:1. This prevented the penetration and left the textile soft and bendable. In the printing process, a thin layer of PDMS was left on the textile by pressing a bulk amount of PDMS through a predefined stencil. The electronic modules, together with stretchable interconnects, were placed on the textile and laminated by curing in an oven (Fig. 8.18).

The stretchable and encapsulated interconnects allowed deformation of the underlying textile but also provided protection for the metal material. To test this, authors performed 50 washing cycles on test structures and reported that the visual damage was not observed. However, they did not present electrical measurements after the washing test. The compromise between the wearability and the functionality of the textile-integrated system is best depicted through the increase in density of the textile. Authors reported that a typical textile substrate had a density of 100–200 g/m^2 (polyamide–elastane mixture), whereas a 1-mm-thick sheet of PDMS had a density of 2000 g/m^2. A tenfold increase in density of the textile was traded for the ease of electronics integration. Figure 8.19 shows the impact of the lamination on the stretchability of the woven and the knitted substrate. The woven substrate is usually not stretchable, and there, a PDMS lamination does not make an impact. For the knitted textile, the lamination stiffens the textile and ruptures at 140% strain, which is a typical value for the PDMS.

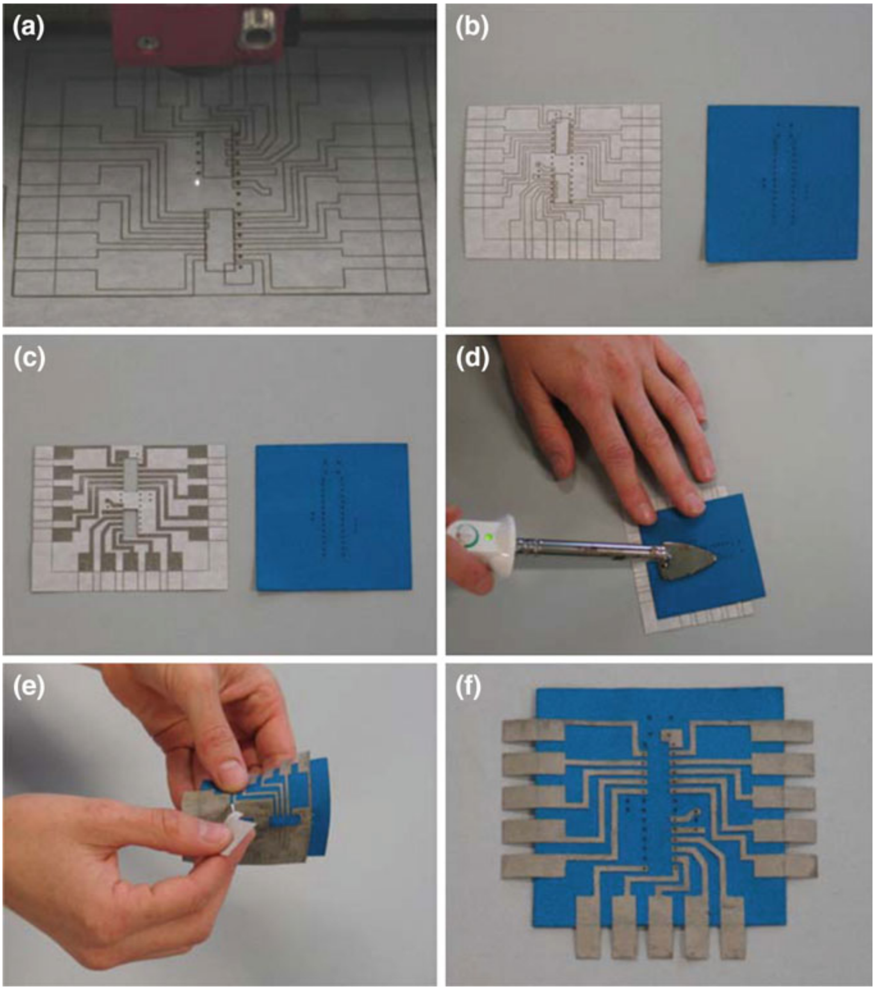


Fig. 8.17 **a** Laser cutting of the conductive textile and the paper backing. Prior to cutting, one side of the conductive textile is coated with heat-activated adhesive. **b** Holes for inserting pins of electronic components are drilled in the textile substrate. **c** A paper backing is removed where the bonding should occur. **d** An iron is used to activate the adhesive on the conductive textile. **e** The remaining textile that was masked with the paper is removed. **f** The final result of the structuring of conductive tracks on textile substrate. Image courtesy of Buechley et al. 2009 [24]

The screen printing of silver paste can be used as a cost-effective approach for the integration of conductive tracks on a textile. The pitch that can be achieved using this approach is around 0.2 mm [27]. The finer the fibres of the textile the more precise the printing can be. In work by Kim et al. [27], authors reported that the densely woven textile gives best results in terms of the mechanical stability of screen-printed

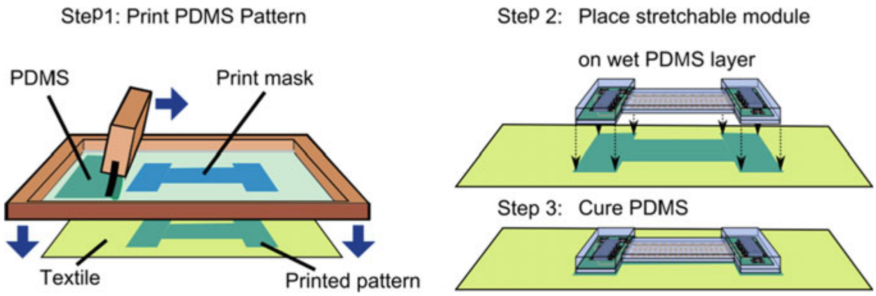


Fig. 8.18 Scheme of bonding of electronics to the textile substrate using screen printing of the PDMS. Image courtesy of Vervust et al. [25]

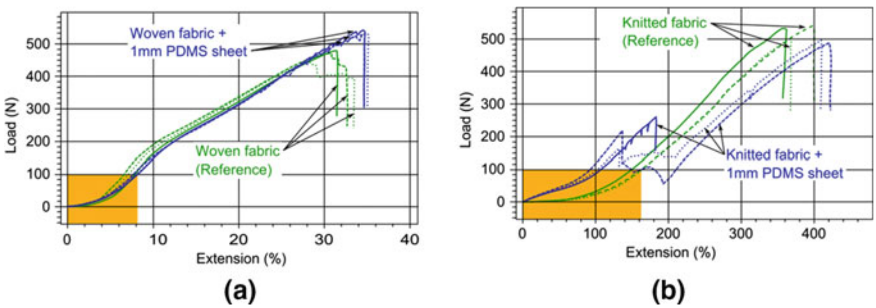


Fig. 8.19 A stretching test performed on **a** a woven textile laminated with 1-mm-thick PDMS sheet and **b** a knitted fabric with laminated 1-mm-thick PDMS sheet. The impact of PDMS on elasticity of knitted fabrics is significant. Image courtesy of Vervust et al. [25]

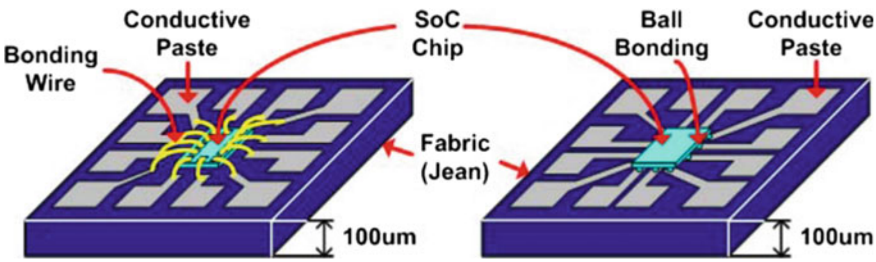


Fig. 8.20 An example of wire bonding on textile substrate. The conductive tracks are screen printed using a sliver paste. Image courtesy of Yoo et al. 2009 [28]

conductive tracks. This was due to the rigidity of both the textile substrate and the silver paste after the drying. Figures 8.20 and 8.21 show different applications of screen-printed tracks on the textile substrate.

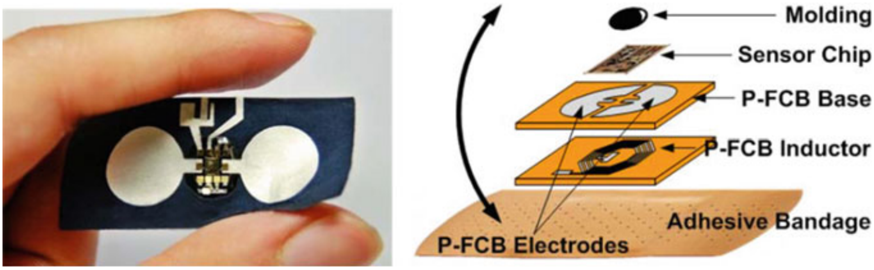


Fig. 8.21 Details of the bandage with embedded sensor on a fabric printed circuit board (P-FCB). Image courtesy of Yoo et al. 2009 [28]

Discussion

The advances in mechanical stability of thin films (e.g. protective coatings) and reliable contacting schemes can advance the integration of electronics on fibres. A straightforward solution for mechanical protection of thin films is encapsulation with the same material as the substrate. Due to low thermal conductance of most polymers, the remaining challenge is the cooling of such devices.

When comparing round fibres and flat strips, fibres require more effort during the integration (e.g. alignment), whereas the strips have less degrees of freedom, i.e. the top and the bottom side to align. Moreover, more functionalities can be integrated on strips because of the photolithography that is created for planar substrates (e.g. a silicon wafer). Nevertheless, the strips introduce stiffness into the textile.

Systems that are integrated on a fibre level typically have lower complexity than other integration methods. Transistors on fibres are limited to simple applications such as switching of elements in a grid. There, each transistor must be contacted by a fibre and thus the density of transistors per unit area is limited by the size of the fibres, e.g. one transistor per $100 \times 100\ \mu m^2$ area for 50-μm-wide fibres. In case of complex circuits on a fibre (e.g. an amplifier), another limitation is a photolithography on a curved surface. Nevertheless, by combining many simple devices, a higher complexity of the system can be achieved at the expense of increasing the textile's dimensions. The advantage of the electronics on fibres (flat and round) is the roll-to-roll manufacturing which makes it compatible with the textile manufacturing process. Joint roll-to-roll fabrication of textiles and electronics could potentially yield a high throughput and lower the fabrication costs.

In contrast to electronics on the fibre, more complex systems can be integrated in textile using intarsia-knitted or woven textiles. The advantages of woven textiles are the fine pitch and the scalability that are achieved at the expense of more complex post-processing steps (e.g. laser cutting and textile vias). The textiles fabricated using intarsia knitting are stretchable unlike the woven ones. Another advantage of intarsia-knitted textile is the computer-assisted routing which replaces the post-processing that is necessary in woven textiles. The drawbacks of intarsia are lower pitch and higher resistance of conductive tracks due to meandering fibres.

The integration on the textile level or on the garment level is best suited for general wearable applications that require wireless connectivity and high data throughput. The techniques presented in this chapter can be used to reliably integrate off-the-shelf electronics (silicon based) in the textile without the need for expensive machines and facilities (e.g. a clean room or the weaving machines). On the other hand, with the integration on the fibre level, a seamless integration and high-volume manufacturing can be achieved. Further research on high-resolution photolithography on fibres (e.g. a feature size $<20\ \mu m$) as well as encapsulation could aid the integration on fibres and lead to mass production of even smarter textiles.

Summary

In this chapter, the following textile-electronics integration concepts are shown:

- Integration of electronics on a fibre. Microfabrication and dip coating techniques are the main fabrication methods for patterning of conducting and semiconducting layers on fibres. Electronics on fibres integrate the most seamless in textiles but can implement limited functionalities. Plastic strips can integrate more functionalities and can be exposed to a standard industrial weaving process.
- Integration of off-the-shelf electronic components and printed circuit boards on woven and intarsia-knitted textiles. Conductive fibres in the textile are used for interconnecting electronic components. The concepts described here meet the trade-off between the functionality and wearability.
- Integration on a garment level by lamination or screen printing. The textile is used as a substrate for building electronic circuits. Conductive tracks can be laminated or screen printed on a textile substrate. Electronic components are bonded to the conductive tracks.

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Chapter 9
Reversible Contacting for Smart Textiles

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Abstract Smart textiles include integrated sensors and actuators, which are connected to electronics to read or control. Various ways of connecting electronics to textiles exist. In this chapter, we will give an overview of these electronics-to-textile connector prototypes. While the different connection types have advantages and disadvantages, there is a trade-off between the size and the number of connections. The electronics can be fabricated with pitches of 0.2 mm, but the textile part has lower limits on the size given by the textile fabrication processes such as stitching and weaving. The connection can be fixed, which implies better reliability and less rigid components, or removable, which allows the separation of textile and electronics for charging or washing.

9.1 Introduction

The textile sensors and actuators and their applications increase the requirements on data transmission and processing in smart textiles. The performance of processing units, such as mobile phones, has increased over recent years. Complex data analysis of sensor signals can be performed on smartphones. Meanwhile, the link from the textile sensors and actuators to the processing units has not received much attention. The processing power of smartphones also offers the possibility for applications combining different signals with simultaneous signal acquisition (see Chap. 14). Acquiring data signals from different sensors in the textile increases the number of necessary connections. Therefore, we investigate different electronics-to-textile connectors for smart textile applications.

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S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_9

The connectors are grouped into fixed and removable connections. A fixed connection cannot be disconnected without breaking the connector. A removable connection can be repeatedly disconnected and reconnected without impairing the mechanical stability of the connection. With removable connections in smart textiles, the electronic processing device can be separated from the garment. The garment can then be washed, while the electronic device is being charged.

In the following sections, different types of connections will be described. First, general requirements will be listed. Then, the different connection types will be investigated with respect to the aforementioned requirements.

9.2 Requirements for Smart Textile Connectors

The main goal of any electrical connector is to provide low ohmic and capacitive resistance and reliable electrical connection under various application scenarios. In this section, we highlight the challenges that are particularly important when choosing or designing electronics-to-textile connectors.

As mentioned before, the electrical connection should be maintained under mechanical stress. The application will determine the stress to be expected. At the same time, the connection should be easy to use, i.e. simple connecting and disconnecting for removable connectors.

Altering the shape and feel of a garment affects the wearer's comfort. Therefore, the size of the connector should be as small as possible. However, reducing the size of the connector is limited by the number of connections and the maximum density of connections. The maximum density of connections is higher in electronics than in the textile due to manufacturing processes and cumbersome alignment by the user. To ensure comfortable wear of the garment, rigid parts in the garment should be small or avoided. Also, the transition from textile to rigid parts is prone to break.

Since many steps in smart textile fabrication cannot be done by standard garment manufacturing processes, the fabrication of smart textiles is expensive and smart textiles have not yet been deployed as much as their functionality might suggest. Therefore, materials and processes from the textile industry are favoured.

9.3 Fixed Connections

Fixed connections cannot be disconnected without irreversibly breaking the connection. In this section, we describe thermal joining, mechanical fastening and adhesives used to connect electronics to textiles.

9.3.1 Thermal Joining

Under thermal joining, we subsume processes where materials are joined by the application of heat. The heat melts materials, which solidify and form bonds when cooled. The temperature to melt the material can damage the surrounding fabric. There are two main categories of thermal joining: welding and soldering.

Welding is a process where materials are joined by melting them at the joint. After the mixing of melted materials, they solidify when cooling down and thus form a bond. In the semiconductor industry, it is used for wire bonding. Copper, gold and silver melt at around 1000 °C, but localised pressure can reduce the temperature necessary to melt the metals to around 300 °C. The combination of pressure and heat for welding is called thermocompression bonding. With ultrasonic vibrations, the necessary temperature can be reduced to room temperature. In integrated circuits, wire connections are done with a combination of ultrasonic bonding and thermocompression at around 100 °C. This process is called thermosonic bonding [1].

Welding is also applied in garment fabrication [2]. It is usually referred to as thermal bonding [3]. A process for joining polyamides similar to thermosonic bonding is described by Potente et al. [4] under the name friction bonding. This process uses a lower frequency than the ultrasonic bonding, namely 240 Hz. Friction can also be generated by mechanical vibrations at ultrasonic frequencies of 20 to 40 kHz [5]. The advantage of the friction bonding compared to the thermal bonding is that the heat is generated directly at the joint. Localised heating reduces the risk of burning the surrounding fabric.

While the process of welding is well known, parameters such as material, pressure, energy and time often have to be determined empirically. Slight changes can effect the stability of the welds, and the parameters have to be re-evaluated. Also, special machinery is needed for this process.

In soldering, an additional material—called solder—bonds the substrate materials. The solder has a lower melting point than the substrate materials. By heating, the solder melts and through a wetting process attaches to the materials, before the heat is removed and the solder solidifies [6]. In this process, only the solder melts, and the other materials do not change their state of matter. However, in the case of metals, the substrate metal diffuses into the solder to form an intermetallic compound [7].

In the electronics industry, soldering is used to contact chips to circuit boards. The materials utilised in circuit boards are usually copper with gold and nickel coatings. All these materials have melting points above 1000 °C. Solder can be an alloy made from tin and lead, but due to its toxicity, the lead has been replaced by other metals.

Soldering is done at above 200 °C, although low-temperature solder with melting points as low as 50 °C exists [8]. For example, the Loctite Multicore 97SC 400 by Henkel consists of 96.5% tin, 3% silver and 0.5% copper. The solder alloy has a melting point of 217 °C [9]. MG Chemicals claim an electrical resistivity of $13 \times 10^{-8}\ \Omega\mathrm{m}$ for the same alloy [10]. An example of a low-temperature solder is tin–indium alloy with 52% indium. It has a melting temperature of 120 °C and an electrical resistivity of 14.7×10^{-8} Ωm [11]. In comparison, the resistivity of copper is 1.7×10^{-8} Ωm.

9.3.2 Mechanical Fastening

In mechanical fastening, two objects are held together by a supporting structure that holds the objects in place. Examples of supporting structures are rivets, clamps, screws, etc. We also include binding or stitching in this category. Additionally, lamination, where a polymer is glued or welded onto the fabric fixing the underlying threads can be viewed as a kind of mechanical fastening.

9.3.3 Adhesive

Three categories of adhesives exist [12]. In one, hardening is achieved by cooling the adhesive. In the second, the bonding is achieved by a chemical reaction. The reaction is induced either by the mixing of two components, by the deprivation of oxygen or by the reaction with water. In the third category, the adhesive is cured by the removal of a carrier or solvent.

In textiles, the most commonly utilised adhesives to bind synthetic fibres are polymers, where the carrier is water, which is evaporated to bond [2]. Conductive adhesives contain a conducting material, usually graphite or silver. For example, silver epoxy is applied in chip bonding. Compared to soldering, the epoxy needs lower temperatures to cure, which is advantageous if the textile material is sensitive to heat. However, resistivity is higher compared to solder, and the epoxy is more brittle. For example, Epo-Tek® H20E, a two-component silver epoxy by Epoxy Technology, has a curing time of one hour at 150 °C. The electrical resistivity is $400 \times 10^{-8}\,\Omega\,\mathrm{m}$ (c.f., 13×10^{-8} Ωm for 96.5Sn-3.0Ag-0.5Cu solder).

A method with non-conductive adhesives to bond circuit boards to textile has been proposed by Linz et al. [13]. The adhesive covering the textile is pressed aside by pressing the contact pads of the circuit board onto the conductive threads in the textile. After curing, the adhesive holds the circuit board in place to ensure contact between the pads and the threads.

9.4 Removable Connections

In this section, we give an overview of removable electronics-to-textile connections, namely hook and loop, snap fasteners, plug connectors, magnetic connections, and conductive zippers.

Fig. 9.1 Conductive hook and loop with silver coating. Image courtesy of adafruit.com

9.4.1 Hook and Loop

Hook and loop, commonly known under the trademark Velcro®, is a fastener that comprises hooks on one side of the connector, which hook into the loops on the other side of the connector. Hooks and loops are usually made of nylon and polyester. They are employed in the garment industry as replacements for zips, laces or buttons [14].

Conductive hook and loop fasteners are commercially available. For example, adafruit.com offers conductive hook and loop tape with advertised life cycles of 5000 openings and closings, and sheet resistance below $2\,\Omega/\square$ [15]. Manufacturing includes coating with conductive material such as silver. Conductive hook and loop fasteners have been patented since the 1980s. They are applied for electrostatic shielding and for electrical contacting in smart textiles. Examples of applications in smart textiles are interconnecting blocks of e-textiles [16] or connecting textile antennas [17]. Seager et al. [17] investigated the frequency dependence of the conductivity and found that after electroplating, the insertion loss of a 4-mm-long hook and loop transmission line is less than 1 dB up to 2 GHz (Fig. 9.1).

9.4.2 Snap Fasteners

Snap fasteners are utilised in garment manufacturing. The snap fasteners are attached to a fabric by riveting or sewing. When coated with conductive materials, snap fasteners can act as electrical connectors in smart textiles. Conductive threads are connected to the conductive snappers by using a fixed connection method described in Sect. 9.3, such as thermal joining, mechanical fastening or adhesives.

An advantage of snap fasteners is that they are easy to disconnect. Snap fasteners are around 1 cm in diameter. For example, Prym provides sew-on snap fasteners ranging from 6 to 11 mm in diameter [18]. Conductive snap fasteners have been

Fig. 9.2 Snap fasteners with female part on leather and male part on a PCB. Image courtesy of Linz et al. at Frauenhofer Institute [20]

used for prototypes of smart textiles. Examples can be found in the work of Lehn et al. [19], Linz et al. [20], Ngai et al. [21] and Post et al. [22]. Commercial versions of circuit boards with a microcontroller and snap fasteners are available [23] (Fig. 9.2).

9.4.3 Plug Connectors

There are a number of shapes and forms of plug connectors, each specific to a certain application. A few examples of rigid plug connectors in textiles are given here. Ohmatex advertises a washable textile connector [24] with six connection points on an area of a few square centimetres. Wilson developed a buckle-type connector [25] with five pins. The buckle size is 11.4 cm $\times$ 4.2 cm. In [26], a flexible flat cable connector was clamped to a ribbon with conductive threads. The connector has four pins and is 1.5 cm wide and 2.7 cm long, as shown in Fig. 9.3.

9.4.4 Magnetic Connections

Magnetic connectors are employed in the electronics industry, since they can be easily attached and detached. An example is the MagSafe power connector in Apples MacBook Air and MacBook Pro [27]. Magnetic power connectors were introduced as breakaway electric cords for deep fryers and hot pots [28]. The magnetic connector disconnects when the cable is pulled. This prevents the deep fryers from falling over and spilling hot oil, which can injure people standing close.

Scheulen et al. [29] used neodymium magnets for contacts in smart textiles. The electrical contact resistance between two magnets was found to be less than 0.01 Ω. The magnets were glued to the textile using conductive epoxy adhesive in parallel

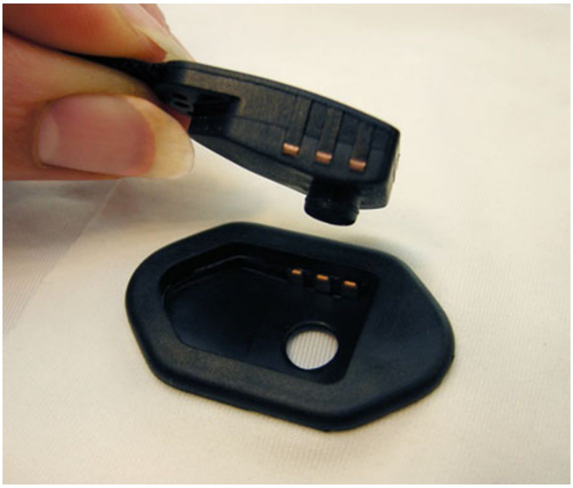

Fig. 9.3 Plug connector with female part integrated into textile. Image courtesy of Ohmatex [24]

with a non-conductive adhesive to ensure mechanical strength of the joint. The electrical resistance of the adhesive joint between the magnets and the silver-coated textile is less than 1 Ω for gold-coated magnets. The size of the magnet was about 5 mm squared.

Righetti et al. [30] developed a modular I2C-based wearable architecture. The garment provides a bus made of four litz wires. At different positions, modules can be attached to the bus via magnetic connectors. The modules are 0.4-mm-thick flexible circuit boards. The magnets were glued to the circuit board with conductive silver epoxy. Master modules are responsible for initialising the slaves and centralising the data, while different slave modules either store data or include vibration motors and accelerometers, as shown in (Fig. 9.4).

Fig. 9.4 Magnetic connectors for I2C printed circuit board. © 2010 IEEE. Reprinted with permission from [30]

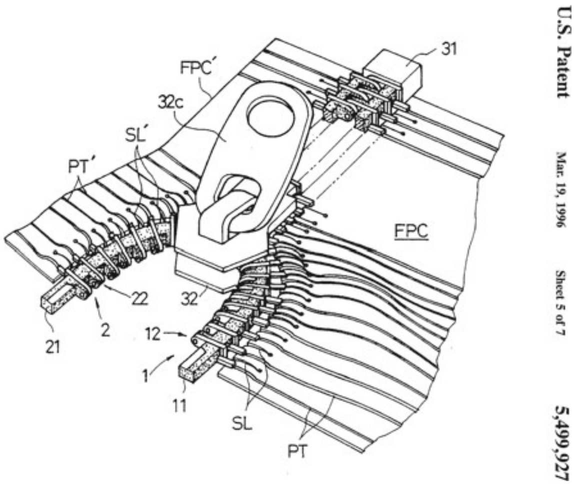

Fig. 9.5 Electrical connection through a zipper (Patent US 5499927 A)

9.4.5 Conductive Zipper

An electrical connector in the form of a zipper was proposed by Avery in 1953 (Patent US 2877439 A) and later refined by several others, e.g. Hayashi in 1994 (Patent US 5499927 A). In the latter, conductive and insulating "teeth" of the zipper alternates on each side, preventing short circuits between neighbouring lines. Each element (tooth) comprises of a conductive area, which touches the conductive area of the opposing element, while being surrounded by non-conductive material to ensure isolation between neighbouring elements, as depicted in Fig. 9.5.

9.5 Pocket Connector

A novel type of electronics-to-textile connector shall be presented in more detail. The connector was introduced by Mehmann et al. [31].

The principle of the pocket connector is depicted in Fig. 9.6. An electronic device is slid into a stretchable pocket. Similar to a ball-grid-array chip, the device has copper bumps in a matrix structure. The pocket contains conductive pads inside. When the device is inside the pocket, the copper bumps connect to the conductive pads of the pocket. Specifically, the principle with the conductive bumps is similar to zero insertion force (ZIF) ball grid arrays (BGAs) in circuit board assembly [32, 33]. When sized correctly, the stretchable pocket should keep the device in position and ensure contact and alignment. In order to distribute the pressure between all contacts, the device surface was curved.

The advantage of this design is the clear separation between textile and electronics. This facilitates the manufacturing of device and textile, as both textile and electronics

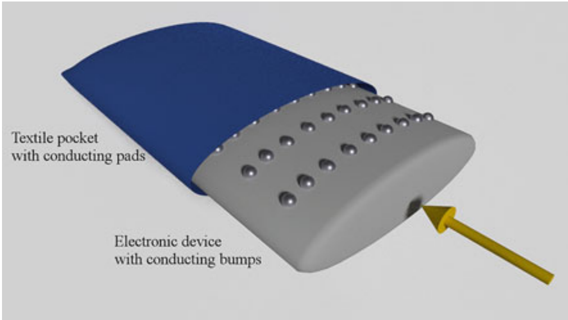

Fig. 9.6 Principle of ball-grid-array-like electronics-to-textile pocket connector. Conductive bumps are attached to the casing of the device. When slid into a pocket with conductive pads, bumps and pads align, forming electric contact ensured by the pressure caused by the stretch of the pocket

industry can apply their known fabrication processes and materials. Also, there are no rigid parts in the textile.

The device can easily be pulled out of the pocket and reinserted, enabling separate washing of the textile, charging of the battery or swapping of the device. Sliding the device in and out of the pocket conforms to common behaviour of smartphone users who carry their phone in a pocket.

9.5.1 Simulation of Contact Pressure

Electrical contact between the conductive pads on the textile and the conductive pads on the electronics device is ensured by mechanical pressure. The mechanical pressure is achieved by sliding the device into a stretchable pocket. The surface of the electronic device is curved in order to optimise contact pressure between bumps and pads in the middle of the device. To focus the pressure on the contact pads, small spherical conductive bumps were shaped on the device to contact the textile pads.

To investigate the effect of the shape on the mechanical pressure between textile and device, computer simulations based on a framework developed by Harms et al. were conducted [34]. The framework used a force-based particle model to simulate the force of a textile acting on a surface [35].

The simulations showed that the pressure between textile and device is highest along the edges. With a curved surface and bumps on the device, the pressure can be concentrated on the contact areas. With an elliptic surface and bumps of 0.7 mm, the force on the contact pads increases from 0.1 N, which is the pressure along the edges, to 0.3 N (see Fig. 9.7). When doubling the height of the solder bumps, the force also roughly doubles to 0.6 N, which is a factor of about 6 to 7 compared to the force along the edges.

To verify the simulation results, a measurement set-up with load cells was designed (see Fig. 9.8). With no bumps, there was no pressure measured. With 0.9 mm bumps, the measured force increased to 0.15 N. The deviations between measurements and simulations can be caused by a different young modulus of the neoprene, measurement uncertainties and fabrication deviations.

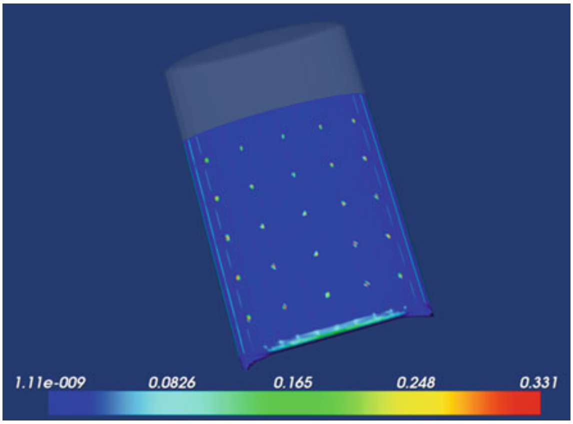

Fig. 9.7 Simulated pressure distribution on casing with bumps. The visible pressure spots are caused by the bumps

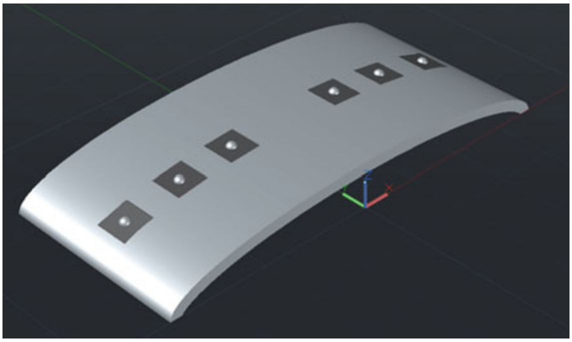

Fig. 9.8 Design model of 3D-printed casing with elliptic shape, containing load cells with 0.9 mm bumps to measure force. The casing is 35 mm long and 75 mm wide. The curvature is elliptic with 16 mm minor axis

9.5.2 Prototype

A prototype was built by Mehmann et al. with 56 connections on an area of 60×100 mm, which is roughly the size of a smartphone [31]. The device prototype is depicted in Fig. 9.9.

The pocket pads were made from woven metal threads in a polyester fabric. Stripes were separated into pads by punching holes in the fabric. The metal threads were 50-μm silver-coated copper filaments, and the polyester was a woven polyethylene

Fig. 9.9 3D-printed casing with attached flexible print with solder bumps. The casing is 100 mm long and 75 mm wide. The curvature is elliptic with 16 mm minor axis

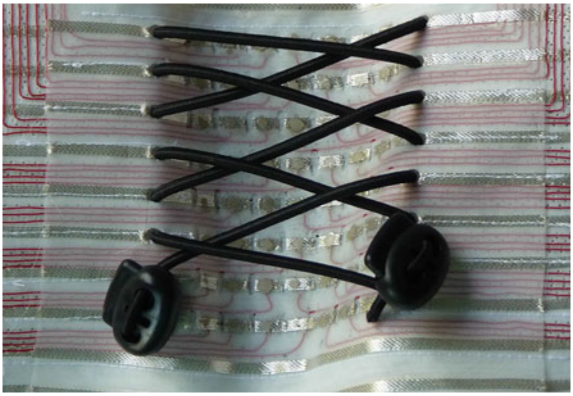

Fig. 9.10 Pocket version with elastic cords. This version allows the reader to see the conductive pads inside, while the elastic cords generate the pressure between textile and device

terephthalate (PET) from 64-μm monofilament fibres. A special weaving process was employed to ensure that the conductive threads were concentrated on one side of the fabric to improve the contacting between the textile pads and the solder bumps. The pads were connected to stitched copper cables with silver epoxy glue. The stitched copper cables are copper-stranded wires with a silver coating and 0.032 mm^2 cross section.

Figure 9.10 shows an open version of the pocket. The stretchability is achieved with elastic cords. Although the measurements were made with a closed pocket of neoprene, this version allows the reader to look inside the pocket and see the pads and the connection to the stitched wires.

While the described pocket connector design separates textile from electronics, some issues remain. During the insertion or removal of the device from the pocket, the bumps contact textile pads that are not assigned to them. This can result in damaged sensitive components when connected to the power supply. Also, the pocket can wrinkle. Two textile pads can then contact the same bump, causing a short circuit. To prevent this, software solutions to only operate the device when fully inserted can be implemented.

The durability of the fabric and device can be reduced due to sliding. The alignment and contact can be lost when using the device in harsh environments. For example, activities such as running or jumping imply higher strain and may introduce misalignment of the contact pads and solder bumps due to the shaking of the device. Furthermore, dirt and sweat can impair contacts. This can be impeded by the selection of the right textile material.

9.5.3 Measurements

After fabrication, the resistance of the prototype pocket connector was measured. The ohmic resistance of each connection at direct current was found to be less than 1.4 Ω

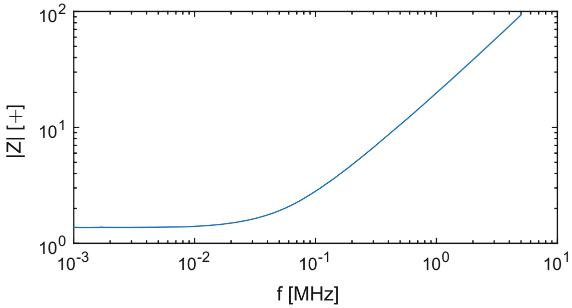

Fig. 9.11 Absolute value of impedance of connection depends on frequency. The inductive behaviour of the resistance results from the measurement set-up

and remains constant for frequencies below 10 kHz. This value is less than typically measured sensor resistances. In piezoresistive pressure sensing, the resistance is typically in the range of kΩ, and in bioimpedance sensing, the resistance is a few hundred Ω.

Figure 9.11 shows the impedance of the connection. At frequencies up to about 10 kHz, the constant 1.4 Ω can be observed. At higher frequencies, the resistance increases, which is due to the loop formed by the measurement set-up. The loop results in an inductive behaviour of the impedance measurements. Measuring only the conductive threads in the textile with the same measurement set-up gives similar results with slightly lower resistance values. The difference in resistance results mainly from the conductive epoxy.

9.6 Further Reading

A collection of do-it-yourself smart textile projects including various connectors can be found on kobakant.at/DIY.

Summary

In this chapter, various types of textile-to-electronics connectors are presented.

- Fixed connections include welding, soldering, mechanical fastening or adhesives.
- Removable connections can be done with hook and loop, snap fasteners, plug connectors, magnetic connectors or zippers.
- A pocket connector design separates textile and electronic device manufacturing.
- There is a trade-off between number of connections, size of rigid parts and ease of use.

Acknowledgements Part of this work was funded by the Simple Skin project from the European Union Seventh Framework Programme ([FP7/2007-2013]) under grant agreement no. 323849.

The pocket connector was developed in cooperation with two contributors. SEFAR, a Swiss textile company specialised in high precision fabrics for filtration, provided the fabrics, and Werner Gaschler and Peter Chabrecek provided helpful information on textile processing. Karl Gönner with the Institute of Textile Technology and Process Engineering (ITV) in Denkendorf did the textile integration.

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Chapter 10
Energy Harvesting Smart Textiles

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Abstract The ever-increasing population of the world is putting a significant demand on the need for multifunctional electronic devices and electricity to power them. This growing demand has led to an enhanced focus on the development of energy harvesting techniques based on renewable and ambient sources. Although materials having unique properties such as photovoltaic, piezoelectric and triboelectric have been known for a long time and have been utilized usually in the form of thin-film structures, their utilization in the form of textile structures for energy harvesting is a relatively new area of research. This chapter will focus on the recent advances in the area of photovoltaic, piezoelectric and triboelectric energy-generating textile structures and the fundamentals of these unique properties, production methods and textile-based energy storage. Finally, expected future trends in the fabrication and application of textile-based energy harvesting and storage will be discussed.

10.1 Introduction

The term “energy harvesting” is used to explain the derivation of energy from renewable sources present in the ambient environment including sunlight, heat, wind and vibration. Some specific materials termed as “smart materials” are designed to respond to in an unconventional manner wherein these materials when subjected to external stimuli such as sunlight, heat and vibration can convert this stimuli to

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S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_10

electrical energy. Some of the most widely studied and used materials for renewable energy applications are photovoltaic, pyroelectric, thermoelectric, piezoelectric and triboelectric materials. Particularly, photovoltaic structures also known as solar cells are a significant source of energy where the solar radiation is abundant. However, it is not possible to provide a continuous energy generation from photovoltaic materials since it is strongly dependent on the intensity of sunlight. Pyroelectric materials need to be heated or cooled to generate an instantaneous voltage across the material, and according to Warner, all pyroelectric materials are also piezoelectric [1]. Thermoelectric structures are slightly different from pyroelectric materials. For thermoelectric energy generation, temperature difference must exist between the two sides of the structure. On the other hand, piezoelectric materials can generate electrical charge as a result of applied mechanical stress caused by an external stimulus, such as wind, rainfall, waves, footsteps and body movements. Similarly, for triboelectric materials, an electrical charge is produced when two dissimilar materials come into contact with each other. The most important advantage of piezoelectric and triboelectric materials over other smart energy harvesting materials is that they can convert mechanical energy generated during human activities directly into electrical energy, thereby making them independent of the environmental requirements of sunlight, temperature difference, etc. For the sake of brevity, this chapter will focus on the recent developments in textile-based piezoelectric (PE), photovoltaic (PV) and triboelectric energy generation structures and attempts on textile-based energy storage systems.

10.1.1 Photovoltaic Energy Harvesting

The sun is the most significant and abundant source of renewable energy on earth. The solar energy that the earth receives in an hour (defined as solar flux, 1.37 kW/m^2) is far greater than the energy consumed in a year; however, most of this energy is wasted; that is, it is neither captured nor harvested. Using materials known as photovoltaic materials, the photons of the sunlight can be converted to electrical energy via the photovoltaic effect. Alexandre-Edmond Becquerel first observed the photovoltaic or PV effect in 1839 when he subjected an AgCl electrode in an electrolyte solution to light. When a PV-active material is exposed to sunlight, photons may be reflected, absorbed or transmitted. Two fundamental processes of PV effect, light absorption and charge separation, are the basis of all PV cells.

The PV devices themselves are characterized by open-circuit voltage (V_{oc}) which is the maximum voltage where the current is zero and short-circuit current (I_{sc}) which is the maximum current where the voltage is zero. The photovoltaic power conversion efficiency (η) of a solar cell can be defined by the following equation:

$$\eta = \frac{V_{oc} * I_{sc} * FF}{P_{in}} = \frac{P_{out}}{P_{in}} \tag{10.1}$$

where P_{out} is the output electrical power of the device under illumination, P_{in} is the incident solar radiation (W/m^2) and FF is the fill factor and can be defined by the following equation:

$$FF = \frac{V_{mpp} * I_{mpp}}{V_{oc} * I_{sc}} \tag{10.2}$$

where V_{mpp} is the voltage at the maximum power point and I_{mpp} is the current at the maximum power point. The term FF is one of the important parameters for power conversion efficiency of a PV structure, with the higher value of FF concurrent with higher η. Good-quality electrodes along with good contact between the layers results in higher FF, while it is lowered if the internal resistance of a PV cell is high. Usually, as compared to the thin-film-based PV structures, the FF of textile-based PV structures is generally owing to the poor electrical contact between the layers [2].

The PV cell structures can be classified into rigid and flexible PV architectures, with the flexible PV cells themselves classified further into inorganic and organic photovoltaic (OPV) cells (including dye-sensitized, tandem and hybrid PV cells). While many researchers have concentrated on increasing the efficiency and achieving maximum power, the inorganic PV structures still have higher-power conversion efficiency as compared to other PV structures. Maximum recorded efficiency for a free-standing 50-μm thin-film monocrystalline silicon solar cell is 17% [3], while that for a 47 μm thin-film silicon cell is 21.5% [4] and maximum recorded efficiency for inorganic solar cells is 24.7% [5]. However, silicon-based PV structures are rigid and not suitable for the applications which require lightweight and flexible PV materials for curved structures. Therefore, the applications are limited to certain shapes. PV materials based on conjugated polymers, due to the ease of processing, low-cost fabrication, being lightweight and flexible, are evolving into a promising alternative to silicon-based solar cells [6, 7]. Semiconducting polymers with suitable bandgaps, absorption characteristics and physical properties can be used for the fabrication of organic PV materials.

For OPV structures, PV effect is based on the electron transfer from donor-type semiconducting conjugated polymers (such as poly (3-hexylthiophene), poly (3-octylthiophene) and polyphenylenevinylene) to acceptor-type conjugated polymers or acceptor molecules (such as 6,6-phenyl-C_{61}-butric acid methyl ester and poly (9,9-dioctylfluorene-co-bis-N,N-(4-butylphenyl)-bis-N,N-phenyl-1,4-phenylenediamine) [8]. These materials have donor–acceptor heterojunctions to achieve the separation of the electron–hole pairs. Semiconducting polymers have lower dielectric constant but higher extinction constant than that of inorganic PV materials. To absorb the maximum amount of incident light, a thickness of around 300 nm is optimal [9]. However, due to the low carrier mobility, the optimized thickness of most polymer cells is less than 100 nm [10] due to the low carrier mobility.

The dye-sensitized solar cells (DSSCs or DSC) are thin-film photovoltaic materials discovered in the late 1960s [11]. DSSCs have slightly different working principle than traditional silicon solar cells. Light is absorbed by a sensitizer, which is affixed to the surface of a wideband semiconductor. Charge separation takes place at the surface via photoinduced electron injection between dye, semiconductor and electrolyte [12, 13]. Therefore, light absorption and charge carrier transport processes are separated. For more information on DSSCs, readers are advised to look into the works on suitable transparent electrodes [14, 15]; electrolytes [16] and improving the efficiency [13, 17–21].

Each active material used to fabricate a solar cell can only convert a certain wavelength of the light to electricity. To achieve the better photon absorption efficiency, two or more active materials with different bandgaps are deposited on top of each other to build up a tandem solar cell (TSC). Two or more heterojunction solar cells create a TSC. For more information on TSCs, readers are advised to look into the works on tandem solar cells consisting of two junctions which may be inorganic [22–26], organic [25–27] or dye-sensitized [28] and more junctions (multijunction) with higher efficiencies [25, 29, 30].

In hybrid solar cells (HSCs), unique properties of inorganic semiconductor nanoparticles are combined with organic polymeric materials. Organic materials absorb light as a donor and transport hole, while inorganic materials act as an acceptor to transport electrons. The advantages of combining organic PV materials with inorganic PV materials are lower cost and high absorption coefficient. The overall cost of the solar material is reduced by using organic thin-film technology which is low cost, easy to manufacture and versatile, while inorganic nanoparticles add high absorption coefficient and bandgap tunability [31]. For more information on HSCs, readers are advised to look into the works including but not limited to TiO_2 [32], PbS [33, 34], ZnO [35, 36], CdS [37], CdSe [38, 39], CdTe [40] and $CuInS_2$ [41]. Among the aforementioned PV structures, the most suitable type of textile-based wearable PVs is polymer-based organic PV structures since they are flexible and lightweight. Detailed information on textile-based PV structures is discussed in Sect. 10.2.2.

10.1.2 Piezoelectric Energy Generation

Piezoelectric phenomenon was first discovered in 1880 by French physicists Jacques and Pierre Curie (Curie brothers) who observed that an electric charge was produced on the surface of quartz when the crystalline material was subjected to a mechanical strain, termed as direct piezoelectric effect [42]. It did not take long before the reverse effect was also experimentally measured, termed as converse piezoelectric effect [43]. Piezoelectric materials, a subset of ferroelectric materials, exhibit the formation of a local charge separation known as electrical dipoles due to their non-centrosymmetric crystal structure when they are mechanically deformed or subjected to an impact. Piezoelectric materials can be divided into two categories: naturally occurring and synthetic man-made piezoelectric materials. Some of the earliest works were carried out on naturally occurring piezoelectric materials which included crystallite inorganic piezoelectric materials such as quartz, SiO_2 [42], Rochelle salt ($NaKC_4H_4O_6.4H_2O$ [44], tourmaline [45] and biological piezoelectric materials such as wood [46, 47], silk [48], bone [49], RNA [50], collagen [51] and DNA [52]. The synthetic piezoelectric materials can be further subdivided into three categories: crystal-based piezoelectric materials such as langatate,

$La_3Ga_{5.5}Ta_{0.5}O_{14}$ [53]; ceramic-based piezoelectric materials such as lead titanate ($PbTiO_3$) [54], barium titanate ($BaTiO_3$) [55], lead zirconate titanate (Pb(Zr,Ti) O_3 - PZT) [56–58], potassium niobate ($KNbO_3$) [59], lithium niobate ($LiNbO_3$) [60] and lithium tantanate ($LiTaO_3$) [61]; and polymeric materials [62–64] such as poly(vinylidene fluoride) (PVDF), poly(vinylidene fluoride-co-trifluoroethylene) P(VDF-TrFE), polyimide, odd-numbered polyamides and cellular polypropylene, among others.

Now, for piezoelectric materials, due to their anisotropic properties, it is important to define the directions of applied mechanical/electrical excitation and the resultant electrical/mechanical response. The relationship between the applied stimulus and the resultant response is thus dependent not only on the direction in which the stimulus is being applied but also on the measurement direction as well. To identify the directions in a piezoelectric element, a three-axis coordinate system (termed as 1, 2, 3 or i, j, k) analogous to the classical x, y, z orthogonal axes is considered (Fig. 10.1). The constitutive relations for a piezoelectric material can thus be defined by the following equations:

$$S_i = s_{ij}^E + d_{ij}T_j \tag{10.3}$$

$$D_i = \varepsilon_{ik}^T E_k + d_{ij}T_j \tag{10.4}$$

where S is the strain tensor, s^E is the elastic compliance matrix evaluated at a constant electric field, T is the stress tensor, d is a tensor of piezoelectric strain coefficients, D is the electric displacement, ε^T is a tensor of permittivity values evaluated at a constant stress vector, E is the electric field vector and the subscripts i, j and k represent the three spatial dimensions [65]. The piezoelectric coefficients themselves are defined with double subscripts, where the first subscript indicates the direction of

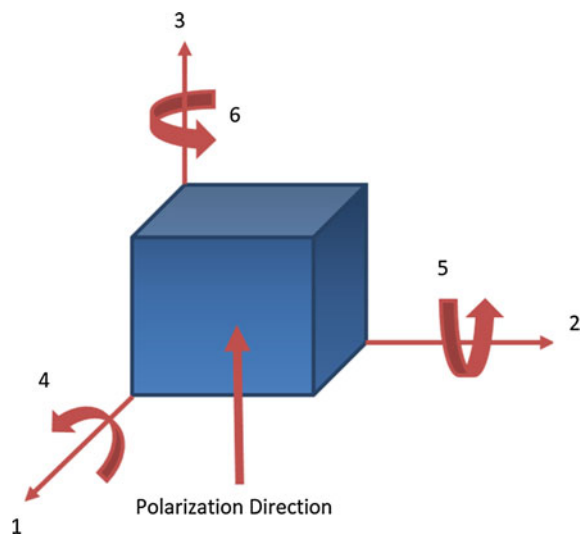

Fig. 10.1 Designation of axes in the piezoelectric materials wherein 1, 2, 3 are analogous to the classical x, y, z orthogonal axes. The direction of rotation around these axes is described by 3, 4 and 5, respectively

the applied voltage (electric field) and the second subscript indicates the direction of the mechanical stress/strain. In fact, the most important parameter for characterizing piezoelectric materials is its charge constant, d, which represent the generated polarization charge per unit mechanical stress (for direct piezoelectric effect), or inversely representing the mechanical strain experienced per unit electric field (for reverse piezoelectric effect). The piezoelectric material can be utilized in two operating modes: the stock configuration (operating in the 33 mode) and the bender configuration (operating in the 31 mode). For both cases, it is assumed that the poling direction is always in direction (3). In the 33 mode, both the voltage and stress act in direction (3), which means the material is strained in the poling direction (3) and the electric voltage is recovered in the direction (3). In the 31 mode, the material is poled in the direction (3) and the mechanical stress acts in the direction (1), which means the materials are strained in the perpendicular direction to the poling direction [66]. While the strain and coupling coefficients differ in stock and bender configuration modes, the stock configuration mode (d_{33}) generally shows higher values. Similarly, piezoelectric voltage constant (g) can be defined which is indicative of the converse piezoelectric effect of the materials. For energy harvesting application, the materials that can be deformed easily to induce larger strains and exhibit large coupling coefficients are desirable [67, 68].

Piezoelectric materials have been in use for various applications including but not limited to spark generators/igniters [69], buzzers [70], hydrophones [71], flexural mode projectors [72], microphones [4] and loudspeakers [73]. For textile-based applications, where repeated large amounts of strain are encountered due to body movement, ceramic materials cannot be utilized due to their brittle nature, low strain capabilities and of course the high toxicity of lead-based materials such as PZT. Piezoelectric polymers offer huge advantages over piezoelectric ceramics, including low density, high flexibility and lower cost. Unlike the piezoelectric ceramics, where the piezoelectric response arises from the non-centrosymmetric nature, piezoelectricity in polymers arises from the distribution of the polymer chains and its molecular orientation in the structure. Polymer-based piezoelectric materials are the most appropriate class for the production of piezoelectric textiles, while ceramic-based materials have larger piezoelectric strain coefficient values [74]. Therefore, this chapter will focus on polymeric piezoelectric materials and polymer-based piezoelectric textile structures.

10.1.3 Triboelectric Energy Generation

Triboelectric effect or the contact electrification process occurs at the interface where two surfaces of different materials come into contact with each other or generate friction with each other via rubbing. An electric charge transfer from one material to the other occurs when two diffirent materials contact to each other for a short time. The triboelectric effect has the ability to produce high voltage, and the effect is utilized in applications such as self-assembly of macroscopic crystals [75], photocopying and laser printing [76]. However, the effect was not considered to be suitable in the field of energy harvesting as the triboelectric charges produced on the surface of the material were known to be immobile and difficult to be conducted [77]. This hurdle was overcome by introducing back electrodes in the device which induced mobile charges, thereby providing the output current from the triboelectric effect.

In the literature, up to four modes of TEG operation have been established including vertical contact separation mode, in-plane contact-sliding mode, single-electrode mode and free-standing triboelectric layer mode [79]. In the process of vertical contact separation-mode TEG, two pieces of dielectric materials having hugely different tendencies to gain or lose electrons (see Fig. 10.2) make periodic contacts with each other, which generate static electricity (triboelectric charges) on the surface of the materials and create the electric potential difference between two electrodes which are connected on the back of these two materials. In contact-sliding mode, two dissimilar dielectric materials have electrodes on one side. The triboelectric charges occur in the area free from electrode, when the surfaces slide in parallel with each other.

In the single-electrode mode, there is only one electrode, which is stable and grounded, and also acts as the second dielectric material for triboelectric charge generation. The other dielectric material moves up and down to have a short contact with the electrode. In the free-standing triboelectric mode, pair of symmetrical electrodes is placed underneath a moving dielectric layer. The size of the electrodes and moving dielectric layer and also the gap between them are important parameters. An asymmetric charge distribution occurs when moving layer approaches or departures to/from the electrodes. Therefore, the electrons start flowing between two electrodes to balance the local potential distribution [79].

In order to improve the efficiency of the energy transfer, the triboelectric charge density can be enhanced by choosing the two charging materials far apart from each other in the triboelectric series, which was first published by Wilcke in 1757 [79]. Triboelectric series is a list of ranked materials based on their tendency to gain (negative) or lose charges (positive), so the further two materials chosen from the list, the greater is the charge transferred during the contact or friction process. Figure 10.2 shows the triboelectric series rankings for some conventional materials.

10.2 Textile-Based Energy Harvesting

Over the years, textiles have come a long way from acting just as a template for the integration of miniaturized sensors and harvesting elements to actually becoming the active sensing elements themselves and acting as the wearable energy harvesters. The criteria for wearable energy harvesting devices are that they must (1) be imperceptible to the user; (2) not load the user; (3) provide long-term life with reasonable power densities (dependent on the application); and (4) be cost-effective and inexpensive to produce. In fact, as discussed in the previous sections, for textile-based energy harvesting, polymer-based structures are more likely to meet the requirements of high flexibility and low weight. It must be emphasized here that the energy generation

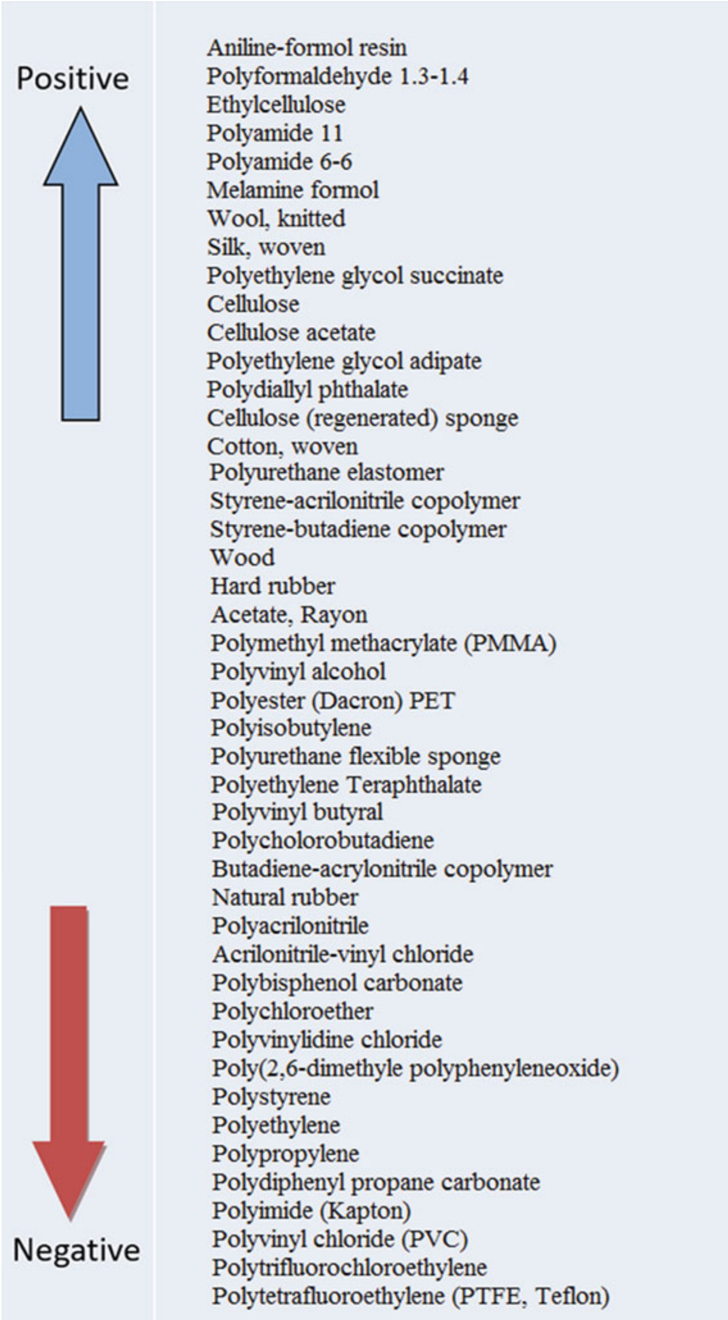

Fig. 10.2 Triboelectric characteristic for some common materials [78]

from organic PV and polymer-based PE materials can only be used for low-power electronic devices, whereas the triboelectric effect has been shown to power significantly higher-power consumption devices such as electroluminescent tubelike lamp. Taking into consideration the source of energy, it is imperative that whatever energy is harvested, it can be considered as a success since there is consumption of sunlight (for PV) or mechanical stress caused by human movements (for PE and triboelectric), which otherwise would have been lost/wasted.

10.2.1 Energy Harvesting Photovoltaic Textiles and Their Production Methods

There have been two significant routes for the development of textile-based PV production: firstly by inserting flexible OPV film materials on/in textile structures and the other being OPV fibre/yarn production. There are two ways to insert OPVs in textiles: by sewing flexible OPV films on the textiles by using conductive yarns or by inserting OPV film in special transparent pockets. While the OPV fibre production has mostly attracted materials and textile engineers, designers and technologists have typically followed the physical insertion route. From the perspective of textiles, fibres and yarns can be considered as the starting raw materials for textile structures, and thus, significant attempts have been made to produce solar cells in fibre form. The idea of producing a flexible photovoltaic fibre via a continuous process was first announced and patented by Konarka Technologies Inc. [80]. Wherein, an electrically conductive fibre core passes through a TiO_2 suspension to be coated with the interconnected nanoparticles which is then dried. The structure is then passed through a dye solution and dried again. The fibrelike structure is then passed through a polymeric electrolyte to be coated with the transparent electrode. Production of a flexible fibre-type poly-Si solar cell was reported in 2006 [81]. Using glass fibre as the core, p-type poly-Si and n-type poly-Si were deposited onto the core by using the plasma-enhanced chemical vapour deposition (PECVD) method. They also produced photovoltaic film structure by atmospheric thermal chemical vapour deposition (CVD). Top and bottom electrodes were deposited by thermal evaporation technique. It was reported that films produced by atmospheric thermal CVD showed high deposition rates of more than 100 nm/s, good crystallinity, high hole mobility and an efficiency of 1.35%.

Similarly, a power conversion efficiency of 0.5% was achieved from an OPV fibre, designed by O'Connor et al. [82] (see Fig. 10.3). They used polyimide-coated silica fibres as a substrate and built the layers by modified vacuum thermal evaporation system to rotate the fibre substrate. It was reported that the produced OPV fibre showed V_{oc} and I_{sc} of 0.39 V and 2.85 mA cm^{-2}, respectively, at an illumination intensity of 104 mWcm^{-2}. It was further claimed that the efficiency of the OPV fibrelike structure was nearly independent of illumination angle [82]. Liu et al. [83] produced an organic photovoltaic fibre by using an optical fibre as a core. In their work, the optical fibre was first dip-coated with ITO and further with PEDOT:PSS (~150 nm thickness).

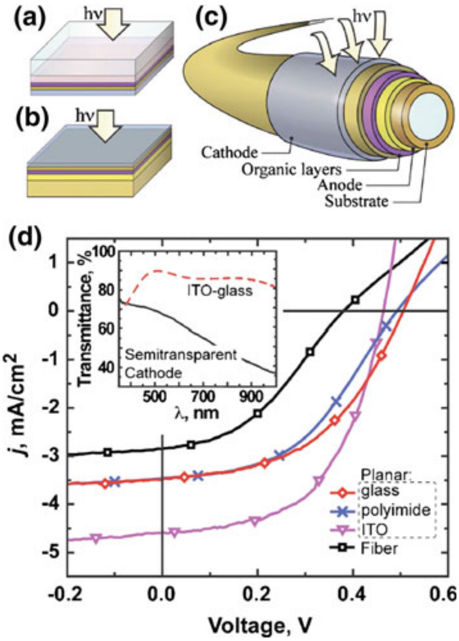

Fig. 10.3 Illustration of the three types of PV cells fabricated and analysed: **a** an archetypal organic solar cell deposited onto ITO-coated glass, **b** a top-illuminated planar device on glass or flexible polyimide substrate and **c** a flexible polyimide-coated silica fibre substrate device, with the layers deposited concentrically around the fibre. **d** The current density–voltage (j-V) relationship for the fibre and planar devices. The transmittance of the semi-transparent cathode is compared to ITO–glass substrate. "Adopted from *O'Connor et al. (2008) Appl Phys Lett 92:193306* with permission from AIP"

Fibres were then dip-coated with P3HT:PCBM (1:0.8) with a thickness of 300 nm and dried at 100 °C for 15 min. Finally, 0.3–0.4 nm of LiF and 100 nm of Al were evaporated onto one side of the fibre. They reported that produced OPV fibres could exhibit an efficiency of 0.1–0.65% [83]. Similarly, two OPV fibres having different active layers were designed and produced by using 0.59-mm-thick and 50-mm-long PP monofilaments as a core by Bedeloglu et al. in 2010 [84]. PP fibres were coated with PEDOT:PSS and annealed at 50 °C for 3 h. The annealed fibres were then coated with the active layer which was either P3HT:PCBM (1:0.8) or MDMO-PPV:PCBM (1:4) and annealed at 50 °C for 15 min. Finally, the transparent electrode consisting of 0.7 nm LiF and 10 nm Al was deposited on the fibre. The voltage characteristics of the fibres were measured, and it was reported that P3HT:PCBM-based fibres showed Voc of 360 mV and I_{sc} of 0.11 mA cm^{-2}, while MDMO-PPV:PCBM-based fibres showed V_{oc} of 300 mV and I_{sc} of 0.27 mA cm^{-2} [84]. Similar to the works on the design of OPV fibres, there are published reports of design of DSSC-based fibres [85, 86]. Flexibility is the most important advantage of OPV and DSSC photovoltaic structures over inorganic solar materials. Also, the power conversion efficiency of conventional inorganic solar cells decreases by nearly 20% when the temperature of the cell reaches to 60 °C under full sunlight, while the efficiency of DSSC-based materials is not affected at the same temperature [87]. However, unstable electrolyte solution may expand at high temperatures, which may cause sealing problems for DSSC. To overcome the drawbacks of liquid electrolyte, researchers are working on replacing DSSCs with solid-state or quasi-solid-state DSSCs [88]. Photovoltaic materials are not suitable for energy harvesting in the areas where the sunlight is scarce. Therefore, other energy harvesting smart materials, such as piezoelectric and triboelectric, would be a better choice for areas devoid of direct sunlight. Production methods of such piezoelectric-based textile structures and their energy conversion characteristics will be discussed in the next section.

10.2.2 Energy Harvesting Piezoelectric Textiles and Their Production Methods

A number of synthetic polymers such as poly(vinylidene fluoride) ((CH_2-CF_2)n), co-polymers of PVDF such as poly(vinylidene fluoride-co-trifluoroethylene) P(VDF-TrFE), polyimide, odd-numbered polyamides, cellular polypropylene have been studied for their piezoelectric (PE) properties [89–92]. Among all these polymers, polyvinylidene fluoride (PVDF) is the most widely studied polymer for its piezoelectric behaviour. PVDF itself is a semi-crystalline polymer, which is generally synthesized from 1,1-difluoroethylene (VF_2) via the free radical polymerization route wherein repeated molecular units of (CH_2-CF_2) form the long polymer chain of PVDF. In the polymer chain, while the hydrogen atoms are positively charged, the fluorine atoms are negatively charged [93]. Therefore, each monomer contains a dielectric dipole moment and constantly spaced monomers cause the polymer to act as a crystal. This semi-crystalline polymer may exist in at least five polymorphs: α-phase (form II), β-phase (form I), γ-phase (form III), δ-phase (form IV) and ε-phase (form V) [94–96]. At least three of these PVDF polymorphs are non-centrosymmetric and can display polar configuration which is related to piezoelectric properties. Furthermore, the application of mechanical, electrical and/or thermal conditions results in the interconversion of the molecular conformation from one form to another.

Form I is the most important polymorph of PVDF since it is predominantly responsible for the piezoelectric and pyroelectric properties of the polymer. It has an all transconfiguration (TTTT') and shows a strong dipole moment normal to the chain direction, and all chains are oriented parallel to b-axis [95]. It is formed by the mechanical deformation of the melt-crystallized α-phase PVDF material. It is a non-centrosymmetric with the conformation of head to head (CF_2CF_2) and tail to tail (CH_2CH_2), therefore making it polar and exhibiting piezoelectric properties. Crystalline form II is the most common phase and can easily be achieved via melt processing. The conformation of α-phase is a slightly distorted trans–gauche–trans–

gauche (TGTG’) with a unit cell that is centrosymmetric due to the anti-parallel packing of the two chains contained in the cell. Dipole moments are randomly aligned in the crystalline phase of the polymer, therefore resulting in a non-polar form [95, 97, 98]. Form III (γ-phase) can be formed via solution crystallization by using N,N-dimethylformamide (DMF), dimethylamine (DMA) or dimethyl sulfoxide (DMSO) [99] and by melt crystallization with high temperature and high pressure. It can also be transformed to β-phase by drawing. The configuration is an intramolecular mix of both α-phase and β-phase that is (T3GT3G’) [95]. Therefore, the piezoelectric effect of form III is lower than form I but higher than form II. Form IV (γ-phase) is produced by the transformation of non-polar α-phase by subjecting to a high electric field and so producing an inversion of dipole moments, so they become non-centrosymmetric. It can also be transformed to β-phase by subjecting to high electric field [95].

As mentioned earlier, the most important polymorph of PVDF is β-phase for providing enhanced PE properties. Due to the thermoplastic nature of the polymer, it can easily be melt-processed and molten PVDF will exhibit non-polar α-phase unless it is processed under the right combination of mechanical, thermal and electrical conditions [100]. If the polymer is subjected to the optimized conditions, randomly oriented dipole moments will align to form polar β-phase. However, it is important to consider that the piezoelectric effect of PVDF is only stable up to its Curie temperature which is about 80–90 °C. The most frequently used piezoelectric fibre production methods are discussed further in the next sections.

10.2.2.1 Electrospinning of Piezoelectric Textile Structures

Electrospinning is an electrostatic fibre formation technique which enables fibre production with a diameter ranging from few nanometres to several micrometres via the application of an electrical field [101, 102]. There are two established electrospinning techniques: solution electrospinning where the polymer is dissolved in an appropriate solvent or a mixture of solvents and melt electrospinning where a molten-stage thermoplastic polymer is used to form fibres. The main components of an electrospinning system are a syringe pump (feeding unit), a spinneret (with a metallic tip), a high-voltage power supply and a grounded collector (Fig. 10.4). There are a number of parameters that affect the fibre formation including solution viscosity, feeding speed, diameter of the hole(s) on the spinneret, applied high voltage, collector (size, shape, material, etc.) and the distance between the spinneret and the collector.

A certain polarity is injected into the polymer solution or the molten polymer via the high-voltage power supply, and the produced fibres are collected by a conductive collector having the opposite polarity. In the literature, works on electrospinning are mostly concentrated on solution electrospinning since almost all thermoplastic polymers require elevated temperatures to melt. For solution electrospinning, the polymer is dissolved in an appropriate solvent at a suitable temperature. The solution is then introduced into the capillary tube, which has a spinneret with a metallic tip. Due to the high electric field applied via the voltage power supply, an electric charge

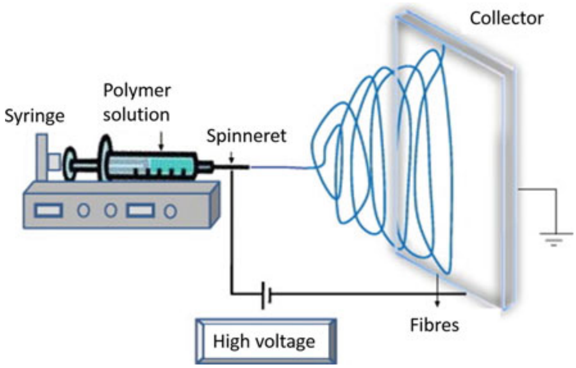

Fig. 10.4 Schematic of a typical electrospinning equipment "Modified from *Bhardwaj N and Kundu SC (2010) Biotechnol Adv 28:325–347* with permission from Elsevier"

is induced on the solution surface, while the solution leaves the spinneret. When the repulsive electrical force reaches a critical value and starts to overcome the surface tension of the polymer solution, first a conical droplet and then a charged jet are formed, which is termed as the Taylor cone. An unstable and a rapid whipping of the jet occurs between metallic tip and grounded collector where the solvent evaporates and leaves the polymer behind, resulting in the fibre formation [103, 104].

Electrospinning offers a few advantages over conventional fibre production technique of melt spinning such as possible production of nanoscale-diameter fibres (thereby enhanced surface area for end-use applications) and significantly less polymer consumption. The produced submicron fibres can offer extremely high surface area, pore interconnectivity and malleability to conform to a wide variety of shapes and sizes. In terms of electrospinning of piezoelectric nanomaterials, the biggest advantage the method provides is that the high electric fields used in the production of these nanofibres induce the ferroelectric properties to the materials in situ, thereby making the external poling step redundant. Using modified electrospinning processes and its derivatives, continuous single nanofibre and conventional dense nanofibre networks can be produced using near-field electrospinning (NFES) and far-field electrospinning processes (FFES), respectively. Typically, for FFES, the inner diameter of the needle is generally a few hundred micrometres (μm), the applied voltage is in the range of several tens of kilovolts (kV), and the needle-to-collector distance is more than ten centimetres. In NFES processing, the distance between the needle and the collector is much shorter as compared to FFES, and as the two conductive parts get closer, applied voltage is also reduced [103]. Typically, the electric fields required for the NFES are at least one order lower than the FFES, leading to a reduction in the perturbations and bending instabilities, thereby increasing the control over the resulting polymer jet and produced nanofibres.

Electrospun fibres have been utilized for various applications including filtration [105–107], tissue engineering [108–111] and energy harvesting [103, 112–115]. For energy harvesting applications, electrospun polymeric (PVDF, PVDF-TrFE), ceramic (PZT, $BaTiO_3$) and polymer/ceramic-based nanofibre/nanowire generators have been developed to harvest the nanoscale and microscale energy from the environment [102, 116–120].

Chang et al. [112] produced PVDF nanogenerators by dissolving 20 wt% PVDF in DMSO/acetone solution and further processing it by electrospinning. The distance between the needle and the substrate was only 1 mm, while the applied voltage was about 1 kV, resulting in the electric field of over 10^6 V/m. It was claimed that the high electric fields generated contributed to the alignment of dipoles in PVDF, together with the mechanical stretching caused during the jet formation. It was also reported that the as-produced PVDF-based nanogenerators showed piezoelectric behaviour and repeatable voltage output when mechanically stretched with the recorded peak voltage and current values from a single nanofibre of 5–30 mV and 0.5–3 nA, respectively [112]. It has also been noted in certain reports that the mechanical-to-electrical conversion of energy in randomly distributed electrospun PVDF nanofibres is significantly different from aligned nanofibres. While it was shown that the electrical potential is formed along the length of the nanofibre in NFES-synthesized structures, the electric potential in FFES-based structures is generated along the membrane thickness. Using various analysis tools such as polarized FTIR, piezoelectricity for P(VDF-TrFe) nanofibre mats was reported to originate from the C-F bond dipoles which were preferentially orientated in the direction normal to the mat surface leading to the production of electrical potential difference between the two opposite faces of the nanofibre under mechanical deformation. In a work carried out in 2011, PVDF nanofibres were electrospun on a flexible substrate with an aim to increase the energy harvesting by amplifying the current output. Five nanofibres were electrospun collaterally and tested under repeated mechanical strain. The nanogenerator was shown to generate a peak voltage and peak current of 0.2 mV and 35 nA, respectively [121]. Fuh et al. [122] demonstrated highly flexible PVDF nanofibre arrays on Cu foil electrodes of $\sim$200 μm thickness using four different substrates including paper. Due to the high flexibility of in situ-poled PVDF nanofibres and excellent conformability to convert the fluttering motion into electricity, the authors claimed that produced nanofibre arrays could be integrated into fabric structures [122]. Fang et al. [123] produced randomly oriented electrospun PVDF nanofibre membranes via FFES method. They prepared the polymer solution by dissolving 16% PVDF in DMF. The applied high voltage and the distance between the needle tip and the collector were 15 kV and 15 cm, respectively. PVDF membrane (with a diameter of 183±37 nm) was fabricated without a postpoling process and used as active layers for the conversion of mechanical energy to electrical energy. The device consisted of PVDF nanofibre membrane sandwiched between two aluminium foil electrodes. It was reported that piezoelectric membrane was shown to produce 2.21 V and about 3 μA under rapid compressive cycles. The authors claimed that the device had long-term working stability, and it was able to drive low-power electronic components [123].

While there are no disagreements on the observed enhancement of the β-phase of PVDF during electrospinning, until now there has been no clear evidence on the phase conversion mechanism. The literature is rather ambiguous on whether the rapid solvent evaporation rate or the high stretching forces experienced by the nanofibres prepared from low polymer concentration solutions are responsible for the transformation of the α-phase to β-phase. Zheng et al. [124] have studied the polymorphism of electrospun nanofibres by dissolving various ratios of PVDF in DMF/acetone mixtures and fabricating piezoelectric PVDF membranes with fibre diameters ranging from 100 nm to several micrometres. It was claimed that α- or β- or γ-phases of PVDF could be fabricated by controlling electrospinning parameters [124]. Similarly, Ribeiro et al. [125] investigated the effect of electrospinning process parameters on polymorphism of PVDF, fibre morphology and fibre orientation. Membranes were from a polymer solution containing 20 wt% of PVDF dissolved in DMF/acetone. The distance between the needle and the collector was stable (15 cm), while the flow rate, needle diameter, applied voltage and rotating collector speed were varied to investigate the influence of the parameters. It was reported that parameters resulting in a higher stretching of the jet or straining of the fibrils contribute the formation of the electroactive β-phase [125]. In a similar study carried out by Lei et al., a comparative analysis was carried out to assess the molecular arrangement of PVDF fibres using electrospinning and forcespinning techniques in order to understand the role of mechanical and electrical forces encountered during these processes. Unlike electrospinning, forcespinning is a mechanical spinning process relying on the generation of centrifugal forces to eject the polymeric solution jet at high speeds leading to their stretching. In their study, a 16 wt% polymer solution of PVDF and N-methyl-2-pyrrolidone/acetone (50:50) was used for electrospinning as well as forcespinning and samples were characterized using FTIR and XRD analyses. Interestingly, it was reported that using forcespinning, the mechanical stretching produced during the production can provide PVDF fibres with a β-phase of up to 95%. The electrospun fibres too showed a similarly high β-phase fraction of up to 99%, leading to the conclusion that mechanical stretching is the predominant reason for the high β-phase observed for these systems. In the electrospinning process, both mechanical stretching and electrical poling occur simultaneously, which contributes towards the orientation of the dipoles in the preferential direction, leading to a slightly higher β-phase.

Electrospinning technique has been used not only for the deposition of polymeric nanofibres but also for the production of ceramic nanofibres. The electrospinning of ceramic-based nanogenerators requires a polymeric solution (polymer dissolved in an appropriate solvent) acting as a carrier for the ceramic nanoparticles. PZT is commonly used in micro- and macroscale piezoelectric energy harvesting devices due to its high electromechanical coupling coefficient (d_{33} of $\sim$500–600 pC/N) as compared to PVDF (d_{33} of $\sim$30 pC/N) and ZnO (d_{33} of $\sim$12 pC/N) and used in conjunction with poly(vinyl pyrrolidone) (PVP) [102]. Chen et al. [102] fabricated PZT-based piezoelectric nanogenerator by electrospinning PZT/PVP solution on interdigitated electrodes of platinum fine wire arrays to obtain ceramic nanofibres, with a diameter of $\sim$60 nm and a length of $\sim$500 μm. Electrospun PZT/PVP nanofibres were then annealed at 650 °C to remove PVP and crystallize the PZT in the perovskite structure followed by a polarization process at an electric field of 4 V/μm across the Pt-interdigitated electrodes carried out at above 140 °C for 24 h. It was reported that the nanogenerator produced 1.63 V output when the structure was subjected to a periodic stress on to the soft polymer and calculated power was announced as 0.03 μW at 6 MΩ load and 40 Hz excitation [102]. Similarly, Cui et al. [126]

prepared energy harvesters using aligned electrospun PZT fibres on a PDMS-coated magnetite (Fe_3O_4) substrate. The structure was further encapsulated with PDMS and contacted at each end with silver electrodes. The poled fibres produced a maximum of 3.2 V open-circuit voltage and 50 nA short-circuit current. Similar to the electrospinning of polymeric nanofibres, the electrospinning of ceramic-based piezoelectric nanowires offers multiple advantages including (1) enhanced piezoelectric effect due to flexoelectric effect, i.e. material exhibits spontaneous electrical polarization due to strain gradient; (2) superior mechanical properties due to higher crystallinity enabling larger strains and higher flexibility as compared to bulk ceramics; and (3) enhanced sensitivity enabling measurable output at low force inputs.

10.2.2.2 Melt Extrusion of Piezoelectric Filaments and Their Use in Textile Structures

Melt extrusion is a fibre production method used for thermoplastic polymers. The basic principle of this method is to heat the polymer beyond its melting temperature for it to liquidize; push through small holes (spinneret) under pressure and then finally stretch it to induce tensile strength and crystallinity. Filaments produced via melt extrusion can directly be used in textile structures together with electrically conductive and conventional yarns. In recent years, there have been a few attempts for the production of two-dimensional woven piezoelectric fabrics. Magniez et al. [127] studied the effect of drawing on polymorphism of melt-spun PVDF fibres. They reported that nearly 80% of β-phase formation is achieved by stretching the melt-crystallized PVDF fibres at 120 °C between 25 and 75% of their original lengths. They claimed that drawing resulted in a significant change in the molecular orientation, polymorphism and tensile properties of the fibres [127]. An increase in the molecular alignment and creation of dipole moments occurred during the stretching process which converted the predominant α-phase to a dominant β-phase. In order to design the flexible two-dimensional textile-based piezoelectric force sensors, the as-produced piezoelectric PVDF fibres were integrated into a plain construction-woven textile structure together with conductive and conventional yarns. Polyamide yarn was used to separate the conductive yarns from each other, while PVDF fibres were used as warp in the sensing area. The weft consisted of polyester yarns outside the sensing area and inside the sensing area; it consisted of silver-coated nylon yarns and a non-conductive nylon spacer yarn. The produced 2/2-twill-woven textile structure showed a maximum voltage output of up to 6 V with sensitivity values of 55mV/N when tested under an impact load of 70 N at 1 Hz frequency [127].

Nilsson et al. [128] produced core–sheath fibres having carbon black/high-density polyethylene in the core and PVDF as the sheath component. They studied the effect of poling parameters on piezoelectric properties of the bicomponent fibres by varying the poling temperature (60–120 °C) and fields (up to 100 MV/m). For corona-poled fibres, it was reported that permanent polarization of dipoles occurred in a rather short time duration of less than 2 s. The as-produced bicomponent piezoelectric yarn showed an output voltage of nearly 4 V when subjected to a sinusoidal axial strain

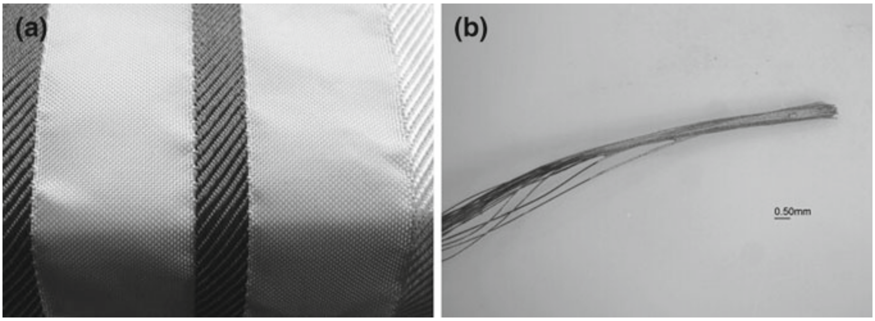

Fig. 10.5 **a** Woven textile structure containing PVDF bicomponent fibres and **b** inner electrode connection of bicomponent fibres "Adopted from *Nilsson et al. (2013) Sensors and Actuator A: Phys 15:477486* with permission from Elsevier"

of 0.07%, and the mean power was calculated to be nearly 15 nW from 25 mm length of fibre [128]. The fibres were further used in a twill construction-woven textile structure together with polyamide yarns as shown in Fig. 10.5a. In the warp direction, only polyamide yarns were used, while piezoelectric bicomponent fibres and polyamide yarns were used together in the weft direction. The piezoelectric part of the textile was 10-mm-wide bands wherein the bicomponent fibre was inserted in textile structure and then separated by a 30-mm-wide section where polyamide yarn was inserted. The core of the fibre acted as inner electrodes, and they are connected via compression moulding between two thin sheets of the material used in the core (Fig. 10.5b). A conductive silicon material was coated on textile structure to act as outer electrode. Heartbeat-sensing properties of the textile structure were tested by locating it around the chest of the test subject [128].

Soin et al. [129] have recently demonstrated a novel all-fibre piezoelectric textile structure based on weft-knitted three-dimensional (3D) spacer technology for energy harvesting applications. In this method, two textile structures are connected by a yarn which travels between them. Therefore, a third direction (Z) dimension occurs relative to the X and Y dimensions and the structure itself called as 3D spacer fabric. Piezoelectric PVDF monofilaments were weft-knitted in conjunction with metallic Ag-coated polyamide 66 (Ag/PA66) yarns and insulating polyester yarns to create a piezoelectric 3D spacer fabric. Ag/PA66 yarns act as electrodes to collect and extract the charge generated by piezoelectric PVDF filaments. Ag/PA66 yarn (143/34 dtex with a resistivity of $<1\,\mathrm{k\Omega\,m^{-1}}$) is plaited on the outside of each of the fabric faces; the insulating polyester yarn (84 dtex, false-twist texturized) is plaited inside the structure, and finally, the piezoelectric monofilament spacer (300 dtex) is tucked inside the two fabric faces (see Fig. 10.6) [129]. For detailed information on piezoelectric PVDF monofilament production via melt extrusion process, readers are advised to look into the relevant work on continuous piezoelectric PVDF fibre production [130]. The advantage of the process is that the piezoelectric fibres are poled during the fibre production process which requires considerably less time and

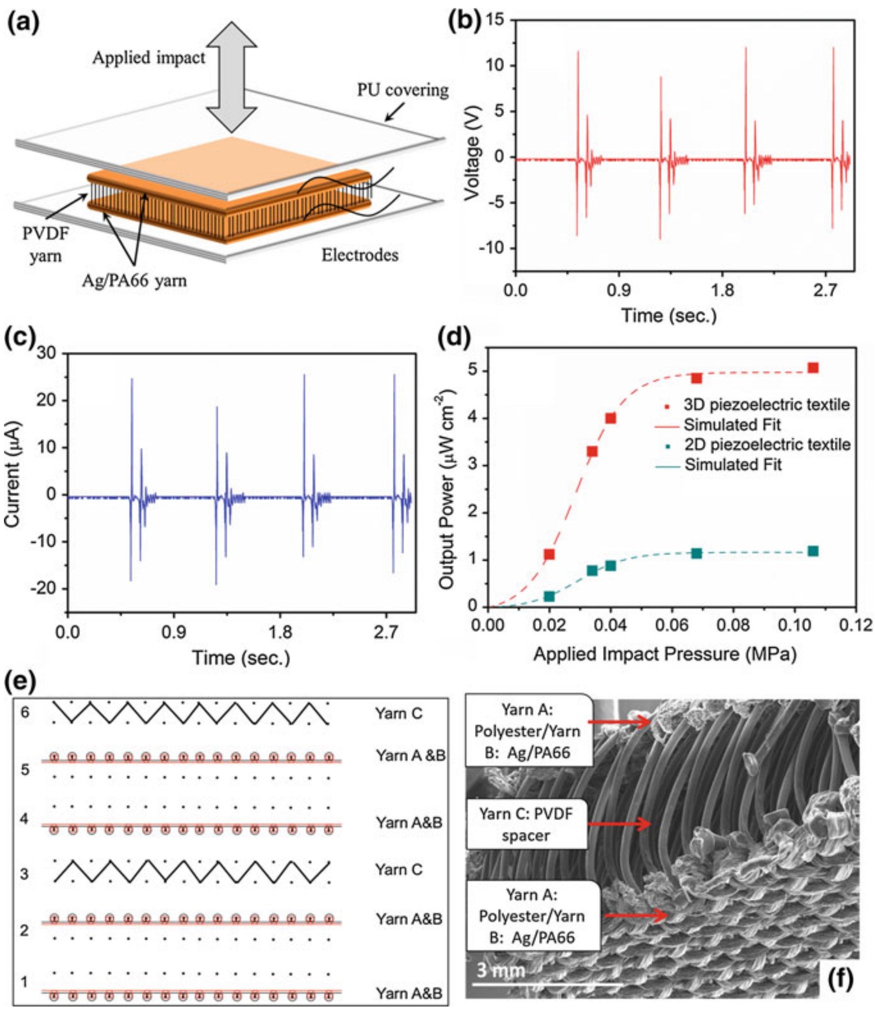

Fig. 10.6 **a** Schematic structure of the packaged 3D piezoelectric fabric power generator; typical **b** voltage and **c** current outputs of the 3D piezoelectric fabric (obtained at an impact pressure of 0.034 MPa across a 470 kΩ load); **d** variation of total output power as a function of applied impact pressure for 2D and 3D piezoelectric fabrics; **e** schematic of the fabric structure with the position of various yarns in the structure; **f** cross-sectional SEM image of the actual fabric clearly showing the position of piezoelectric and conductive yarns. Reproduced from *Soin et al. (2014) Energy Environ. Sci., 7: 1670–1679* with permission from the Royal Society of Chemistry

no postprocess is needed for further modifications and poling. Soin et al. [129] further tested the all-fibre 3D spacer piezoelectric generator (3D-PG) under a pressure of 0.106 MPa, which is comparable to the pressures generated during human walking. It was reported that the peak values of the open-circuit voltage and short-circuit current were found to be 14 V and 29.8 μA, respectively, from the 3D-PG fabric, with an effective area of 15 cm × 5.3 cm [129]. They observed an increase in the total power output from 0.08 to 0.4 mW over the measured impact range of 0.02 to 0.106 MPa. The team also produced a two-dimensional knitted fabric and sandwiched between two conductive fabrics for comparison purposes. The maximum power density of two-dimensional knitted fabric was nearly five times lower than that of 3D spacer fabric (1.18 and 5.07 μW/cm^2, respectively) when they were tested under the same conditions. The power density of 3D piezoelectric fabric was also higher than that of 2D structures reported in the literature [131]. Zeng et al. [131] reported an all-fibre piezoelectric 2D non-woven fabric consisting of $NaNbO_3$-PVDF nanofibre non-woven fabric as a piezo-active layer and two conductive knitted fabric, made from segmented polyurethane and silver-coated polyamide multifilament yarns.

$NaNbO_3$-PVDF nanofibre non-woven fabric was embedded between conductive knitted fabrics which act as top and bottom electrodes. The whole fabric structure was then tested at 1 Hz and a maximum pressure of 0.2 MPa. It was reported that 2D fabric structure produced a peak open-circuit voltage of 3.4 V, a peak current of 4.48 μA and a power output of 2.15 μW/cm^2 under cyclic compression tests [131]. To sum up this section, it can be claimed that 3D piezoelectric fabrics are better alternatives to conventional 2D fabric and electrospun structures for textile-based wearable energy generators. The excellent performance of the 3D spacer fabric-based generator was attributed to the following factors: (1) high β-phase of the PVDF fibres; (2) enhanced charge collection due to intimate contact between the PVDF fibres and conductive yarns leading to improved efficiency; and (3) transfer of the uniform compression pressure across the fabric surface. Furthermore, these energy harvesting textiles can be coupled up with the knitted and screen-printed carbon fibre-based supercapacitors for energy storage in wearable electronics (discussed in the following sections), which can potentially open up a completely new field of textile-based energy harvesting and storage.

10.2.2.3 Physical/electrochemical Deposition of Piezoelectric Materials on Textiles

Electrochemical deposition is a process by which a thin and highly adherent coating of metal, oxide or salt is deposited onto a conductive substrate via electrolysis of a solution containing the desired metal ion or its chemical complex. For piezoelectric materials, the most extensively studied material for electrochemical deposition on textile surfaces is zinc oxide (ZnO). ZnO nanorod and nanowire arrays, owing to their superior structural, optical and piezoelectric properties have been explored for a number of applications including piezoelectric devices, field-emission devices, dye-sensitized solar cells and light-emitting diodes [132, 133]. For textile-based energy harvesting applications, the requirements of high flexibility, lightweight and low cost have led to extensive research on the electrochemical deposition of ZnO on flexible conductive textile substrates. A significant amount of effort has been undertaken for controlling the structural and morphological properties of the one-dimensional ZnO nanostructures with high density and uniformity as their shape, size, distribution and crystallinity are closely related to their physical and piezoelectric properties. Likewise, the extension of 1D nanowire and nanoarray structures to 2D and 3D structures such as ZnO nanoflowers and ZnO nanourchins has exhibited potentially enhanced improvements on device performance [134].

For the electrochemical synthesis of ZnO nanostructures on a conductive substrate, the process is initiated *via* the deposition of ZnO seed layer on a clean substrate by dip coating, spin coating or sputter coating processes. For electrochemical deposition, the flexible working substrate is usually cleaned with ethanol and deionized water in an ultrasonic bath at room temperature first, followed by the deposition of ZnO seed. The process is sometimes repeated to enhance and ensure the attachment of ZnO seed layer particles to the substrate [135]. Generally, the seed solution is prepared by dissolving a 10 mM zinc acetate hydrate ($Zn(CH_3COO)_2.2H_2O$) in 50ml of ethanol and 1.5 wt% sodium dodecyl sulphate solution ($CH_3(CH_2)_{11}OSO_3Na$) surfactant. The samples are then annealed above 100 °C for a few hours to achieve good adhesion between the coated seed layer and the substrate. The electrochemical deposition of ZnO is carried out via the reduction of dissolved molecular oxygen via a two- or four-electron process (function of electrolyte and cathode properties) and zinc precursors, such as zinc chloride and zinc nitrate hexahydrate.

$$O_2 + 2H_2O + 2e^- \longrightarrow H_2O + 2OH^-$$
$$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$$

Ko et al. [135] deposited ZnO nanorod arrays on a commercially available conductive woven structure which consists of nickel-plated PET fibres. The conductive textile substrate was cleaned in ethanol for 10 min. and then in deionized water for another 10 min. at room temperature. The conductive textile structures were then dipped into seed solution, which was prepared as mentioned above, and taken out slowly and further annealed at 130 °C for 2 h in an oven. ZnO nanorod arrays were grown via a simple two-electrode system consisting of a working and counter electrode (Pt). The diameter and heights of ZnO nanorod arrays electrochemically deposited under an external cathodic voltage of −2 V for 1 h were measured to be 65–80 and 600–800 nm, respectively [135]. In another work reported by Gullapalli et al. [136], a mechanically flexible piezoelectric nanocomposite material was produced for strain-sensing applications. A stable paper matrix (70 mm in diameter, 0.47 mm thick) was used as a substrate and zinc oxide (ZnO) nanostructures embedded in the paper to form a 40 wt% ZnO nanocomposite material. A thin layer of gold was deposited on the nanocomposite structure, and the structure was then poled at 20 V for 30 s [136].

The I-V characteristic of the composite sensor as a function of strain was tested under both static and dynamic mechanical loading as shown in Fig. 10.7. They reported that voltage and current output of the composite structure changed as a result of applied strain under static loading in Fig. 10.7 and they claimed that the frequency of the dynamic response of the produced nanocomposite structure matched closely the excitation frequency such that the peak current outputs were ∼27, ∼260, ∼490 and ∼800 nA at the excitation frequencies of 0.1, 1, 2 and 4 Hz, respectively [136].

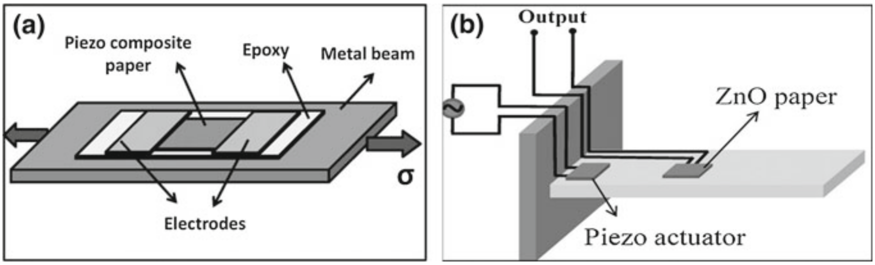

Fig. 10.7 Schematic depicting the experimental set-up for strain measurement **a** under static loading and **b** under dynamic loading. "Adopted from *Gullapalli et al. (2010) Small 6:1641–1646* with permission from Wiley"

Qin et al. [117] synthesized ZnO nanowires radially on the surface of Kevlar 129 fibres, which are known for its high strength, modulus, toughness and thermal stability, by using electrochemical/hydrothermal approach. The highly crystalline ZnO nanowires with a hexagonal cross section and a diameter in the range 50–200 nm with a typical length of $\sim$3.5 μm were produced [117]. Even when the ZnO-coated Kevlar fibre was made into a loop, no cracks or peel-offs were observed in the crystalline coatings, demonstrating the toughness of the material under mechanical deformation and bending, regularly encountered during human movement. An open-circuit voltage of 1 mV and short-circuit current of 5 pA were observed under the test conditions. The rather low current values were attributed to the lack of a dedicated bottom electrode below the sputtered ZnO layer leading to a high internal impedance resulting in poor charge extraction. It was later demonstrated that a number of such fibres could be overlapped in woven array; however, again without the dedicated bottom electrode, an open-circuit voltage of 3 mV and a short-circuit current of 17 pA only were obtained.

Khan et al. [137] study ZnO synthesis on textile structures and piezoelectric effects and energy harvesting characteristic of these structures. In one of their works, the research team synthesized ZnO nanoflowers, which were composed of needle-like nanorods, on conductive textile fabric substrate by using a simple low-temperature aqueous chemical growth method. The samples were then tested for their piezoelectric characteristic. They reported that the maximum output voltage was observed to be over 600 mV, while corresponding current was about $\sim$650 nA [137]. In another work of Khan et al., a commercial conductive woven textile consists of 55% silver and 45% nylon fibres with a final thickness of 0.3 mm and a resistivity of $<1\ \Omega sq^{-1}$ [137]. For the deposition, the conductive fabrics were first cleaned in isopropanol, acetone and deionized water in an ultrasonic bath and then dried with nitrogen air. The seed solution was prepared by dissolving zinc acetate in methanol and deposited on conductive textile structure at 4000 rpm for 30 s, followed by heating at 100 °C for several minutes to achieve a good adhesion of seed layer on the substrate. The growth of ZnO nanowires was initiated on the commercial conductive textile substrate at a temperature of 90 °C for 6 h. The growth density was determined as 240 ± 50 NWsμm^{-2}. For controlling the diameter of ZnO nanowires and enhancing the growth rate, a 25% ammonia solution was used. The diameter and the length of ZnO nanowires were measured to be 60±10 nm and 2500±100 nm, respectively. They reported an increase in generated output voltage from 0 to 4.8 mV when the applied force increases from 0 to 300 mN and then decreases back to 1.5 mV when the forces go back to 0 [137].

Energy harvesting from smart material-based textile structures is a multidisciplinary and rapidly developing research area. Piezoelectric- and photovoltaic-based energy harvesting structures need specific production techniques and special environments, such as high polarization voltages, glove box and clean rooms. However, triboelectric-based material production does not require special environment. Progress and recent developments of using triboelectric materials into textiles and wearable energy harvesting structures will be discussed in the next section.

10.2.3 Energy Harvesting Triboelectric Textiles and Their Production Methods

The use of triboelectric effect in wearable energy harvesting is a relatively new area of research. As mentioned earlier, the effect was not considered to be suitable for harvesting, as the triboelectric charges produced on the surface of the material were known to be immobile and difficult to be conducted [77]. This hurdle was overcome by introducing back electrodes in the device which induced mobile charges, thereby providing the output current from the triboelectric effect. Triboelectrification is a common phenomenon, and the triboelectric generator is based on the periodic processes of contact and separation between two materials with opposite polarized triboelectric charges which then drive the electrons back and forth in the external circuit between the electrodes, thereby realizing the conversion of mechanical energy into electrical energy.

Wearable triboelectric generators have been recently demonstrated by Cui et al. [138], in which the generator was composed of nylon and Dacron (polyester) fabrics which was used for harvesting body motion energy (Fig. 10.8). The generators were developed on cotton cloth as the backing layer on which ten copper foil strip electrodes (2 cm×28 cm×0.05 mm, separated by a 1-mm gap) are pasted to form a grating structure. These electrodes are then covered by five Nylon strips and five Dacron strips, alternately. Finally, the strip electrodes covered by Dacron cloth in parallel form the positive electrode of the generator, and the strip electrodes covered by Nylon cloth connected in parallel form the negative electrode of the generator [138]. Upon relative sliding between the two contact surfaces, Nylon tends to lose electrons, while Dacron will accept it. The electrons are injected from Nylon to Dacron which leads to Nylon carrying the positive charge and Dacron carrying the negative charge. It was demonstrated that through the frictional force generated between the forearm and body, the triboelectric generator can turn the mechanical energy efficiently into electrical energy and power-up and electroluminescent tubelike lamp easily with

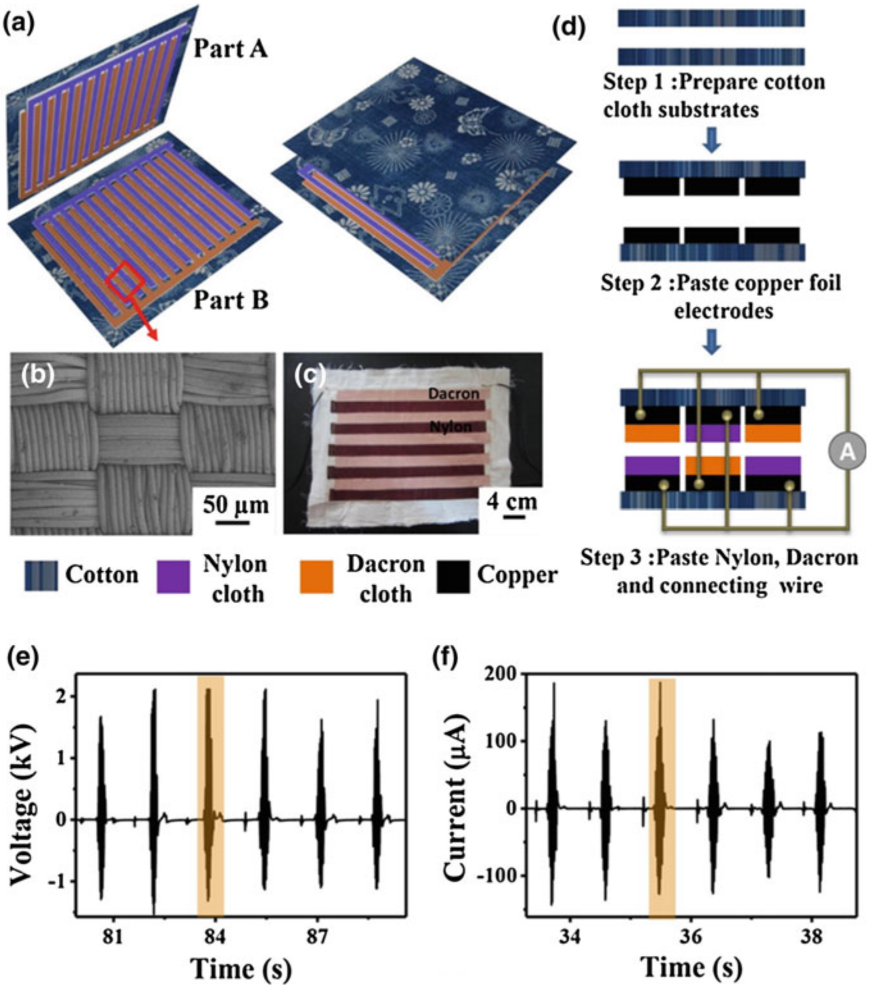

Fig. 10.8 **a** Schematic diagram of the cloth-based wearable triboelectric generator. **b** SEM image of the microstructure of Nylon cloths surface. **c** Photograph of half part of the fabricated wearable triboelectric generator. **d** Fabrication process of the wearable triboelectric generator. **e** Open-circuit voltage and **f** short-circuit current at an average sliding velocity of 1.7 m/s. "Adopted from *Cui et al. (2015) ACS Appl Mater Interfaces 7 (33): 18225–18230* with permission from ACS"

the maximum output current and voltage of 0.2 mA and 2 kV, respectively, with a charging rate of nearly 69 µC/s [138].

Ko et al. [139] produced a conductive textile structure and a polydimethylsiloxane (PDMS)-coated conductive textile structure to test the triboelectric charge generation. Conductive textile acted as a triboelectric material when rubbed with PDMS part of the other structure as well as an electrode. They then produced triple-stacked and multistacked devices by overlapping conductive textiles and PDMS-coated conductive textiles repeatedly. Triboelectric energy generation of the structure was tested under external forces of 3.54 kgf during footsteps test. They reported that the triple-stacked triboelectric generator showed 2.88 times higher voltage output and 2.45 times higher current density than that of the single layer [139].

Seung et al. [140] reported a wearable triboelectric nanogenerator (WTNG). They used an Ag-coated textile and PDMS nanopattern-based ZnO nanorod arrays on a silver-coated textile template as active triboelectric materials. They claimed that the structure was fully flexible and foldable with high-power-generating performance [140]. The nanopatterned PDMS-based WTNG and the non-nanopatterned flat PDMS-based WTNG were tested under a compressive force of 10 kgf. Observed output voltage and current were 120 V and 65 μA, respectively, from the former structure, while the latter showed a voltage output of 30 V and a current of 2 μA. They then produced a four-layer-stacked WTNG and tested under the same compressive force. The voltage output and current of the structure were measured to be 170 V and 120 μA, respectively [140]. Lee et al. [141] developed a textile-based TNG consisting of a textile-based substrate, aluminium (Al) nanoparticles and PDMS. The TNG was tested under a periodic mechanical stress applied by an adjustable bending machine. A power density of 33.6 mW/cm^2 was obtained from the textile-based TNG. The team attached the TNG on a commercial arm sleeve to take advantage of human arm movement to power a commercial LED bulb [141]. Kim et al. [142] fabricated a highly stretchable 2D fabric nanogenerator containing interlaced fibres which consist of Al wires and polydimethylsiloxane (PDMS) tubes with vertically aligned nanowires which provided a high-aspect-ratio nanotextured surface. Interlaced fibres were bonded to a waterproof fabric to have an all-weather TNG. The highly stretchable 2D fabric showed an output voltage and current of 40 V and 210 μA, respectively [142].

10.3 Textile-Based Energy Storage

Storage of harvested energy in flexible storage systems for wearable applications is a new area of research. Using conventional solid-state batteries and capacitors spoils the desired flexibility of the wearable device. To have a fully flexible lightweight energy-generating and storing wearable textile materials, textile-based flexible batteries and supercapacitors need to be coupled with energy-generating textiles. Therefore, the resulting textile structure will have the ability to generate as well as to store energy from the environment. A number of researchers are aware of the need for such flexible energy storage devices and have carried out a significant number of works on the subject. Hu et al. [143] demonstrated fully flexible lithium ion batteries. They used simple Xerox paper, which has significantly lower electrochemical impedance than the commercial membranes, as a separator with free-standing carbon nanotube (CNT) thin films. CNT films were prepared by dispersing arc discharge-synthesized CNTs in water with sodium dodecylbenzenesulfonate (SDBS) as a surfactant and used as cathode and anode current collectors. Prepared CNT inks were blade-casted on a stainless steel substrate and dried to obtain highly flexible CNT films. The resistance and the density of the films were measured to be ∼5 Ω/sq and a density of 0.2 mg/cm^2. $Li_4Ti_5O_{12}$ and $LiCoO_2$ were prepared by mixing 70 wt% of the active materials, 20 wt% carbon and 10 wt% PVDF binder in N-methyl-2-pyrrolidone and then blade-coated on CNT films. Once the composite films dried, they were gently shaken in water to separate the films which were then coated on both sides of Xerox paper and sealed off with 10-μm-thick PDMS. The battery showed an energy density of 108 mWh/g when cycling between 1.62.6 V [143].

Yu et al. [144] worked on flexible supercapacitors by producing solution-processed graphene/MnO_2-nanostructured textiles. Graphene solution was coated on to polyester textiles by a simple dip-drying method as a conformal coating. Nanostructured MnO_2 was then deposited on conductive textiles by electrochemical deposition process. It was reported that MnO_2–graphene pseudo capacitors offered specific capacitance of nearly 225 F/g at a scan rate of 10 mV/s and excellent stability with only a 5% variation in the capacitance measured over 5000 cycles [144]. Kwon et al. [145] designed a cable-type flexible battery. The research team electrodeposited Ni-Sn material on a 150-μm-diameter Cu wires to form a hollow helix anodes. Three of Ni-Sn-coated Cu wires were twisted together, and then, four of these twisted yarns wrapped together on a 1.5-mm-diameter rod. A modified PET and aluminium wire were used as the separator and cathode, respectively. These were then wound around the hollow helix anode and then coated with a $LiCoO_2$, acetylene black and PVDF binder in a 90:5:5 mass ratio. The whole structure is placed in a heat-shrinkable tube, and a liquid organic electrolyte was injected into the hollow space at the centre of the electrode assembly. They reported that a stable capacity of 1 mAh/cm was obtained with a potential plateau at 3.5 V under electrochemical test [145].

Textile-based triboelectric nanogenerators, piezoelectric structure and OPV materials produce microwatts to milliwatts of power density, and for a full integration, these energy harvesting textiles need to be combined with flexible supercapacitors and batteries for storage in wearable electronics. To this effect, a few examples have come forth in which flexible batteries have been introduced into the textile structure. Pu et al. [146] have demonstrated the integration of triboelectric nanogenerator and flexible lithium ion battery for wearable electronics. Commonly available soft polyester fabric was selected as the starting substrate and was consecutively coated with conductive Ni film by electroplating (Ni cloth) and insulating parylene film (parylene cloth). Belt-type Ni cloth and parylene cloth (5 mm wide) were used as the building block and woven into a 5 cm×5 cm TENG cloth. All the Ni cloth belts were connected together as one electrode of the TENG, while all the parylene cloth belts were connected as the other. It was observed that the TENG textile retains the mechanical flexibility, air breathability, water washability and thus comfort of the original polyester cloth. The output characteristics of the fabricated TENG textile were characterized by using contact separation mode wherein two pieces of the fabric were brought in contact with each other and then released. The releasing and pressing of two pieces of TENG cloths can be understood as the contact separation of the individual parylene cloth and a Ni cloth, since all the parylene cloth wires and Ni cloth wires are, respectively, connected together as two electrodes. Contact electrification, i.e. electron transfer from tribopositive Ni film to tribonegative parylene film, occurs once the two TENG cloths are brought into close contact. This charge separation creates an electric potential difference between the two electrodes given by the following equation:

$$U_{EPD} = \frac{-\sigma d}{\varepsilon_0}, \tag{10.5}$$

where σ is the triboelectric charge density, ε_0 is the vacuum permittivity and d is the distance between two electrodes. When the TENG is released, the open-circuit voltage (V_{oc}) increases as the EPD is increased, while Voc decreases when the TENG is pressed. When the TENG is shortened, the EPD will drive the flow of electrons between two electrodes through the external circuit, creating two current pulses (I_{sc}) with opposite directions when being released and pressed with the maximum V_{oc} and I_{sc} observed of 50 V and 4 μA, respectively. The TENG cloth demonstrated the capability of converting the mechanical energy of various human motions into electricity when being worn at different positions on the human body; the LIB belt showed decent electrochemical performances even being severely folded at 180° for 30 times. Furthermore, the LIB belt was charged by the TENG cloth for 3 cycles and powered a heartbeat meter strap capable of remote communication with a smart phone, verifying the viability of the whole wearable and self-charging power unit for future wearable smart electronics.

10.4 Outlook and Conclusions

The development of new materials, techniques and architectures for environmental-friendly energy harvesting techniques from renewable sources is an important challenge and indeed a very important target for a clean future. Piezoelectric, photovoltaic and triboelectric materials are well-known smart materials that can generate low-power, green electricity from renewable sources. Production of these materials in the form of nano/microfibre and yarn and various forms of fabric structures, especially for wearable applications, has attracted interest of researchers from different fields. The initial results in the field have shown that flexible, lightweight and non-toxic fibre-based energy harvesting and storage structures can provide an alternative to solid planar technologies. Further development of the area warrants a judicious selection of device architecture, techniques, fibrous structures and importantly development of ultralow-power management architectures. Almost all the prototypes demonstrated in the literature have been fabricated with techniques, such as microfabrication and electrospinning, which have multiple processing steps and are thus unsuitable for mass production techniques. The most challenging part is to adapt these laboratory-scale productions to scale up to mass production techniques. The most promising techniques for mass production seem to be piezoelectric fibre production via a continuous melt extrusion and poling process [130] and 3D piezoelectric spacer fabric structure [129]. On the other hand, there are some foreseeable technical challenges associated even with the 3D spacer fabrics, which include (1) optimization of positioning, spacing and the thickness of the spacer piezoelectric yarn and its arrangement in the 3D structure to enhance the piezoelectric response; (2) optimization of fabric density and thickness of the spacer fabric for different applications; (3) ensuring that the conducting yarns used in the opposite faces do not come into contact with each other during the knitting process or during the cutting procedure; (4) as the textiles are intended for use as wearable energy harvesting textiles, the important factors such as air permeability, wicking properties, stretchability and recovery need to be tested and controlled in order to provide a high level of comfort to the user; (5) the effects of wear and tear, washing and regular use also need to be verified to ensure reproducibility of the piezoelectric response and provide a certain lifetime value for the fabric. Furthermore, the whole structure of energy harvesting wearable structure should be biocompatible, biodegradable and environmentally friendly. All these techniques seem to be very promising for the wearable energy harvesting and storage systems, and it is very likely to find flexible and efficient self-powered electronic devices in the markets in the near future.

10.5 Summary

The harvesting of waste energy from the ambient and everyday human activities to provide "on-demand power" has been long considered as an attractive alternative to traditional rechargeable batteries for providing electrical power to low-energy consumption devices. The traditional smart materials and their thin-film architectures are efficient for static applications wherein they do not routinely encounter the stresses and strains which will arise for more intensive body-worn applications. The prerequisites for such body-worn energy harvesters include high mechanical strength, flexibility, lightweight and high efficiency. In this chapter, smart functional fibres and textile architectures incorporating energy harvesting methods of photovoltaic, piezoelectric and triboelectric effects are presented alongside recent examples for fibre-based energy storage applications as well as hybrid generation and storage systems. While major improvements are being made in the processes as well as the efficiency of such systems, significant challenges exist in enhancing the efficiency of them to their planar counterparts still lie ahead of us.

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Chapter 11
A Strategy for Material-Specific e-Textile Interaction Design

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Abstract The interaction design of electronic textile (or e-Textile) products is often characterised by conventions adopted from electronic devices rather than developing interactions that are specific to e-Textiles. We argue that textile materials feature a vast potential for the design of novel digital interactions. In particular, the shape-reformation capabilities of textiles may inform the design of expressive and aesthetically rewarding applications. In this chapter, we propose ways in which the textileness of e-Textiles can be better harnessed. We outline an e-Textile Interaction Design strategy that is based on defining the material specificity of e-Textiles as its ability to deform in ways that match the expectations we have of textile materials. It embraces an open-ended exploration of interactions related to textiles (e.g., stretching, folding, turning inside out) and their potential for electronic recognisability for deriving material-specific concepts and applications for e-Textiles.

11.1 Introduction

e-Textiles as a field of research emerged with the development of conductive yarns at the turn of the century [1], with a backdrop of prominent research areas as Wearable Computing and Tangible Interaction Design. It extended the aspirations of Wearable Computing [2] by presenting the possibility of making computers fit the body comfortably, and provided an unobtrusive medium for integrating digital controls into garments. e-Textile research today is a fast-growing multidisciplinary field that involves various specialisations such as electronic engineering, materials science, textile design, and interaction design that aspire to find innovative ways of merg-

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S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_11

ing textiles and computation. On the one hand, materials scientists have looked into textile structures at a molecular level to give them smart properties such as colour change (e.g., [3]) or stain resistance (e.g., [4]). On the other hand, engineers and designers have found ways of manipulating electronic components and circuits to be compatible with textiles, such as wrapping silk fibres with copper for making conductive threads [5], or developing "sewable" electronics (e.g., Lilypad Arduino [6]) for easy construction of e-Textiles. With the availability of new technologies and materials, there have been an increasing number of applications and innovations populating the domain of e-Textiles.

It is the textileness, or the tangible and material qualities of textiles, that sets apart e-Textiles from other computational media. We find that textileness of e-Textiles is addressed in much detail for the construction or making of e-Textile sensors and substrates. For example, qualities of textiles such as softness, flexibility, durability, and comfort guide the technical developments and innovations in new smart materials (e.g., [7, 8]). However, a similar rigour of incorporating textile qualities in the design of interactions with e-Textile artefacts is still found to be lacking and largely dominated by conventions adopted from digital devices (e.g., having trackpads or push buttons on textiles) [9]. Although such products have helped to move the field forward, we argue that an emphasis on experiences and tangible interactions that is specific to the material of textiles can assist in realising the full potential of e-Textiles.

We thus contribute to the field of e-Textiles by outlining a strategy that can be undertaken to support a material-specific investigation of e-Textile Interaction Design. The aspiration is to develop a unique interaction design language for e-Textiles that embraces the deformability and tactile manipulability of textiles and extends beyond the past conventions of digital interfacing.

11.2 The Need for Material-Specific e-Textile Interaction Design

With the emergence of digital technologies, the mechanical necessities did not anymore constrain how the appearance of a device would be connected with its inner workings. The separation between the outer controls from its inner workings is most significant in computer interfaces where actions and functions are increasingly abstracted. Input devices, such as keyboards or touch screens, allow users to interact with digital information by tapping, clicking, moving a pointer, scrolling, swiping, or making multifinger gestures on a touchpad. Today, with computation entering our everyday objects, we face the challenge of relating the physicality of digital interfaces to its underlying functions.

Tangible Interaction Design Research emerged at the end of the twentieth century and sought to address the "physical-world modalities of interaction" [10]. It embraced the material, embodied, and multimodal qualities of human–computer interaction in contrast to the cognitively heavy interface design of verbal, visual, and auditory representations [11].

The Interaction Design of e-Textiles faces a similar challenge of deriving meaningful interactions and digital interpretations to benefit from the novelty of using textiles as a tangible medium for electronic interfacing. e-Textile research methods are thus closely related to the approaches from Tangible Interaction Design, as both research fields are fundamentally concerned with exploring the relationship between physical artefacts, people, and spaces for relevant digital interpretations.

Functional overlays: The increasing miniaturisation of computational components has allowed interface designers to abandon the traditional screen keyboard set-up and focus on extending the scope and control of digital information with physical objects and everyday environments, through a confluence of bits and atoms [12]. In the field of Tangible Interaction Design (TID) [13], this approach of studying everyday objects as bearers of digital functions or as handlers for digital information investigates existing forms, contexts, and spatial relations between the physical and the digital for creating meaningful couplings.

This approach is also visible in e-Textile design, but is characterised by an additive strategy of layering new functions over an existing textile object to enhance its capabilities. For example, in the Ralph Lauren jacket with iPod controls, the buttons for controlling the music are added to the sleeve of the jacket [14]. Although involving sophisticated technical implementation, they simply transfer interactions from digital devices in the form of "pressing the play button" onto the textile surface. There is no doubt that the direct adaptions of digital interaction paradigms onto textiles are appropriate in certain domains. However, a significant challenge and innovation potential lies in the investigation and development of an interaction design aesthetic that is closely derived from the medium of textiles.

Emphasis on engaging interactions: A field that is closely associated with e-Textile Interaction Design is Wearable Computing. Typical examples of wearable computing applications include health monitoring in medical or sports industry (e.g., a sports bra with an integrated heart rate monitor [15]). These products act as passive information-gathering systems but do not involve active manipulation of textile materials for interfacing. We see this as a significant omission, as the tangibility provides immense potential for developing new kinds of "rich user interfaces" [16], which utilise the topologies of textiles and movements to express different interactional and expressive qualities.

A consideration for rich user actions has supported the research on new ways of interacting with digital objects, such as taking photographs with a digital camera [17] or setting an alarm clock while expressing one's mood [11]. By assessing the tangible interactions and the ways in which people organise their embodied interaction [18], designers of computing systems can support more freedom and expression in interaction. Digital systems may also provide an opportunity to develop skills, familiarity, and engagement to use the capabilities of the body to good use, and control multiple parameters of physically rich and complex systems [19].

In the context of e-Textile design, however, a focus on rich interactions that are specific to the medium of e-Textiles remains underexplored and relies mainly on giving double meanings through layered actions and functions. For example, with tangled interactions [20], the expressivity of an existing surface is sought to be expanded by adding multiple layers of interactions. Such as, in the interactive pillow [20], the familiar action of hugging or squeezing a cushion also becomes a way of digitally communicating with a loved one. Although this approach to designing e-Textiles creates interesting layering of meanings in interaction, it still relies on the familiarity of textile objects rather than challenging the interaction potential of textiles as shapeable materials.

A call for material-specificity: With the material turn in HCI, the physicality and material composition of computation has been foregrounded in Tangible Interaction Design [21]. In the material-centric approach, computation is seen as a material that can be changed and shaped like traditional materials such as clay or wood. While some researchers have linked the materiality of computation with craft practices [22], others have called for better methods and theoretical frames for addressing this phenomenon in design (e.g., [23, 24]). The different approaches to the materiality of interfaces deal with the mouldability of not only the digital content, but also the physical components and artifacts."Computational composites" [25] are seen as new composite materials, of which the computer is a constituent. Vallgårda and Sokoler [26] describe the designing of computational objects as similar to the traditional practice of formgiving, where hands-on exploration of material possibilities drive the discovery process. For example, the collection of textile sensors made by Perner-Wilson and Satomi [27] analyses the potential of conductive yarns and textile construction techniques to develop innovative textile shapes that mimic the functions of common electronic sensors (such as pressure or tilt sensors). These textile sensors are amongst a growing number of works that explore different textile production techniques to embed electronic components within textiles (e.g., [28]). Interactive textile substrates that embody enhanced material properties have been developed in the form of surfaces that can be cut and shaped in a similar manner as regular textiles, for example, heatable or burnable knitted fabrics [29]. We learn from these projects that work with the materiality of textiles for embedding interactivity as part of the e-Textile substrates, but our work focuses on using the materiality approach for shaping interactive e-Textile forms and applications.

We argue that developing engaging interactions while staying grounded in the materiality of textiles is beneficial for creating an intuitive and novel interaction language that is specific to e-Textiles. We propose to interpret textiles in terms of their interaction potential rather than referring directly to existing artefacts as a way to move beyond functional overlays and support the development of new forms and applications for e-Textile Interaction Design. Interactions can be considered extractable from their sources and used as ingredients for building new objects that afford these interactions [30]. Taking this idea forward, while staying grounded to the materiality of textiles, we describe a strategy that is developed around extracting our everyday encounters with textiles (such as stretching, knotting, crumpling, and hanging) as a rich resource for material-specific e-Textile Interaction Design.

11.3 Enabling Textile Interactions as a Strategy for Material-Specific e-Textiles Interaction Design

Textiles populate our everyday environments in the form of objects, surfaces, and textures. We are closely accustomed to the way textiles behave, and we use this material familiarity to modify and use textiles in different ways on a daily basis. For example, we fold our clothes to make them compact for storage, throw open a tablecloth over a table to get the maximum spread, and stretch the covers over the mattress to remove wrinkles. We have an intrinsic understanding of the material properties of different textiles; for example, knitted fabrics are stretchy, woollens are warm, and satin is slippery.

Hinged on our tactile knowledge of textiles, these everyday manipulations of textiles constitute a rich repository of interactions related to textiles (e.g., stretching, folding, piercing) that are unlike how we typically use electronic objects. Specific textile interactions correspond to certain generalisable deformations and relate closely to the material properties of textiles; for example, folding creates a piling or layering effect, or pulling a drawstring bunches the textile.

We propose using textile interactions as resource and indicators of material-specificity in e-Textiles design process as a strategy for ensuring the resulting e-Textile artefacts still retain their textile qualities despite being experimental in their form and appearance.

The strategy is thus based on defining the material-specificity of e-Textiles as its ability to reformulate or deform in ways that match the expectations we have of textile materials. Consecutively, textileness of an e-Textile interface can be a measure of the extent of textile-like manipulations enabled by it.

In the next section, we formulate the key challenges in adopting this strategy in the design process and present how we address them in our e-Textiles work.

11.4 Addressing the Challenges for Material-Specificity in e-Textile Interaction Design

In order to develop a material-specific e-Textile design practice around textile interactions, we firstly understand the interaction potential of textiles. Secondly, we identify the ways of making the textile interactions electronically recognisable in a textile-friendly manner. And thirdly, we explore the ways of associating these material-specific e-Textile forms to meaningful digital interpretations. With an aim of discussing these challenges in an illustrative manner and to give a hands-on view of our tactics for addressing them, we selected four examples from our e-Textile research work to help outline the material-specific strategy that we propose.

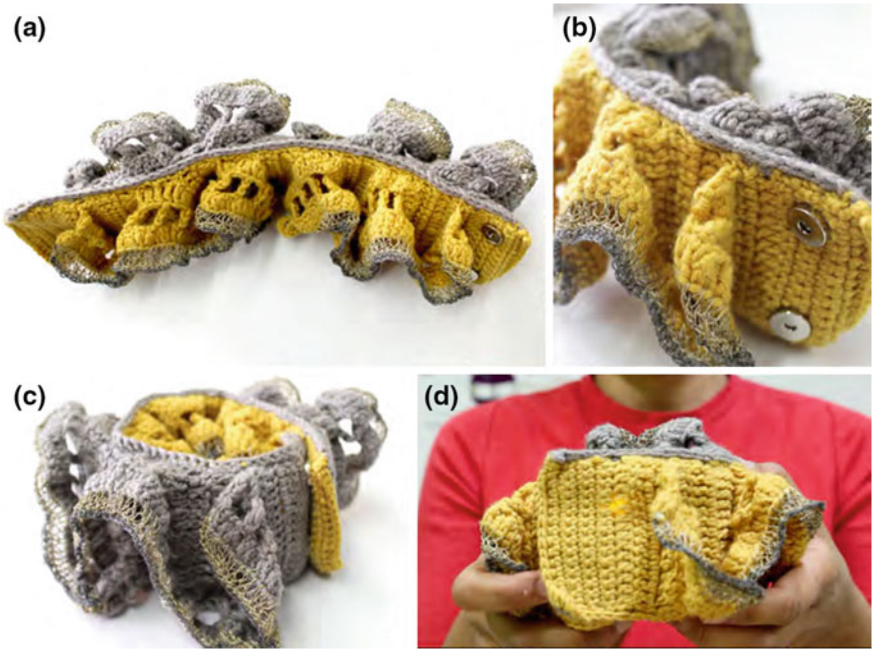

Fig. 11.1 The Flip-Around Light Dimmer. **a** The crocheted device is open (switched off). **b** Magnetic buttons on the end can be joined to make a closed loop. **c** The device in the loop form: switched on. **d** Flipping it around brings the two alternating sides in and out. Video available at http://narrativize.net/turn-around-textile-interface/

11.4.1 Design Cases: Some Examples from Material-Specific e-Textile Explorations

We begin by introducing the four e-Textile research examples where we placed textile interactions as the key driver for designing e-Textile interfaces. We will refer back to these examples in the later sections and use them to highlight the particular aspects of material-specific e-Textiles design process.

11.4.1.1 The Flip-Around Light Dimmer

The Flip-Around Light Dimmer (Fig. 11.1) is a crocheted device that can be flipped inside out. The strap-shaped device has two textured sides distinguishable by their colours (yellow and grey). The ends of the device have magnetic buttons, which can be joined to switch on the device. Once in a loop form, it supports the action of flipping around, bringing the two sides alternatively from inside to outside. With each flip, a corresponding value is sent to a connected device or a computer that controls the brightness of a lamp in the room. Using textile interactions for shaping

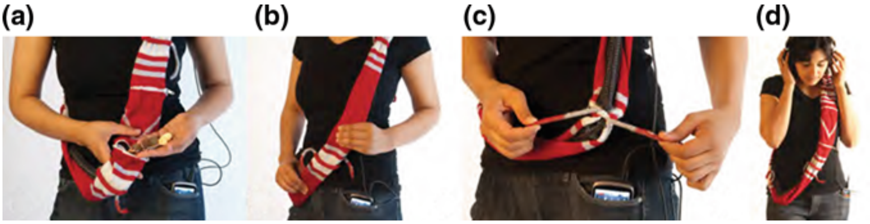

Fig. 11.2 The Music Sleeve: **a** An opening that allows coins to be dropped into the sleeve. **b** The sleeve is worn across one's shoulders, rotating the sleeve moves the coins within. **c** The movement of the coins can be obstructed by tying the string. **d** The music player on the phone is wirelessly controlled. Video available at http://narrativize.net/66/

textile interfaces is often an iterative process where hands-on explorations of making and testing guide the design process. We use this project to talk about how thinking through textile interactions for electronic sensing drives the form iterations.

11.4.1.2 The Music Sleeve

The Music Sleeve (Fig. 11.2) is a wearable controller for playing music on a mobile device [31]. The knitted sleeve, which otherwise acts as a scarf, can be worn on one's shoulders and made to function as a music controller by putting a handful of coins in it. The coins, being metallic, activate sensors by joining conductive areas while moving inside the knitted tube. The sleeve is worn and rotated around one's body to move the coins inside, and the drawstrings are used to trap the coins in certain areas to trigger different functions on the connected music player. The Music Sleeve is constructed by combining a custom knitted fabric and normal jersey fabric. This was a decision made during the prototyping process and helped to accommodate the constraints of the available textile construction tools without comprising the quality of textile interactions. Through this project, we discuss how the opportunities and constraints of the textile construction tools used for making e-Textiles can influence not only the overall form but also the circuit design and layout.

11.4.1.3 The Soft Radio

The Soft Radio (Fig. 11.3) is a crocheted spherical device that fits in the palm of a hand. It is soft to hold and has the texture of regular crocheted textile. The radio has a loop on the top that can be twisted to change between two modes: volume and channel seeking. The values corresponding to the present mode (i.e. volume or FM band frequency) are changed by wrapping the knitted chord around the crocheted sphere. The direction of the wrapping determines whether the values are decreased or increased. Additionally, the loop on the top can be manipulated to activate the hold setting to avoid unintentional activations. Identifying the interaction states and

Fig. 11.3 The Soft Radio: a crocheted radio that uses textile interactions of wrapping and twisting for operating the radio. Video available at http://narrativize.net/softradio//

qualities (such as binary or directional) of textile interactions helps in mapping functions and developing coherent interface concepts. We use this project to illustrate the role of finding relationships between textile interactions and digital functions for developing an interface logic.

11.4.1.4 e-Textile Interaction Elements

e-Textile interaction elements (or TIEs) (Fig. 11.4) are artefacts that were designed to support an open-ended exploration of textile interactions. They can be considered as parts or units of e-Textile interfaces that can be assembled, scaled, or modified to make coherent e-Textile devices. We used these TIEs in a preliminary user study to collect the initial observations and interpretations about material-specific e-Textile design. The three TIEs used in the study were designed each with a different textile-related interaction in mind (i.e. turning inside out, rolling up, and stuffing). However, conductive threads or a working circuit was not implemented on these TIEs to encourage the participants to come up with their own interpretations for electronic behaviours. The study consisted of three interviews with two participants in each session. Through a series of questions and tasks that focused on identifying different features of the TIEs that could be relevant for digital interfacing, we used them explorations to facilitate a discussion around the potential of using interactional textile qualities

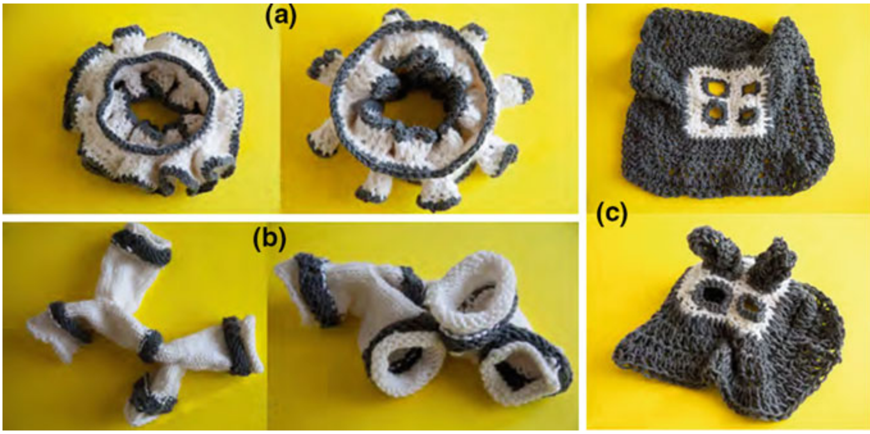

Fig. 11.4 e-Textile interaction elements used in the study: **a** A doughnut-shaped TIE that could be turned inside out. **b** A branching set of knitted sleeves that could be rolled up. **c** A flat TIE with openings in the centre such that the corners could be stuffed through them

for developing use contexts for e-Textiles. By sharing the insights from this project, we consider opportunities for associating material-specific e-Textile forms to digital interpretations.

11.4.2 Mapping the Interaction Potential of Textiles

We started by observing how we handle and manipulate textiles in our everyday lives for exploring the interaction potential of textiles that is grounded in its materiality. Emphasising the deformable qualities of textiles as distinct from other materials that are associated with technical objects such as metal, plastic, or glass, we extracted interactions that particularly highlight the textile-like qualities (e.g., turning inside out, stretching, and piercing). We name these as textile interactions (Fig. 11.5). Other interactions, such as simply touching or pressing, that we did not consider distinctive enough or to be particular to textiles were excluded.

Extracting and collecting this wide range of textile interactions that consisted of different actions required a variety of movements, energy, precision, and time helped to map the interaction potential of textiles and could be used as a resource in design. Although these interactions are enabled by the material qualities and formal affordances of the specific underlying objects, the interactions may be considered as principles of manipulating textiles that can be abstracted from their particular instances. It was then possible to reinterpret them through less well-known and more exploratory shapes to design e-Textiles. For example, each of the three e-Textile devices presented in the previous section were developed from varied textile interactions that were extracted from different sources. The Flip-Around Dimmer

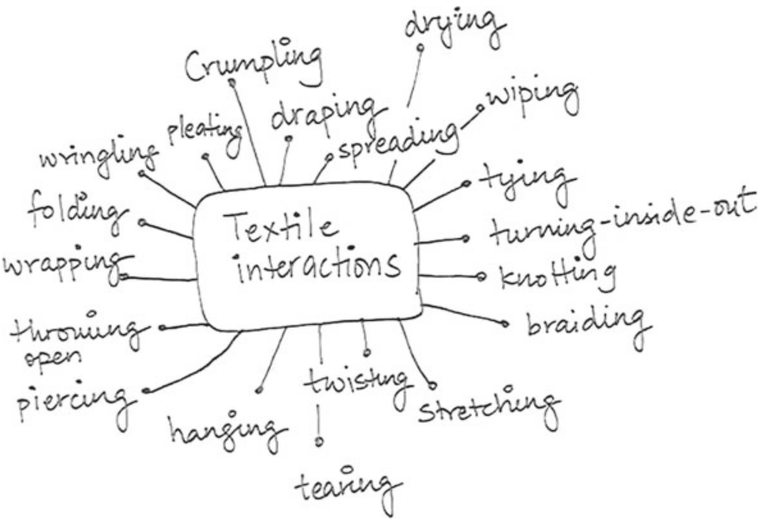

Fig. 11.5 Textile interactions: our collection of extracted textile interactions

started from the textile interaction of turning inside out. The Music Sleeve used the quality of soft textiles that lets one access and manipulate objects lying behind a textile surface. And the Soft Radio started from the interactions of wrapping and twisting.

11.4.3 Translating Textile Interactions into Sensors

In order to work with textile interactions for making exploratory shapes, it was crucial to consider how they could be made electronically recognisable—such that these textile interactions could function as electronic sensors or activators. Constructing electronic contacts and components from textile materials, such as threads and fabric, was observed to preserve what we identified as distinctive textile interaction properties. We therefore preferred conductive textile materials for making the interaction-based sensors and reduced the use of regular electronic components to the absolute necessary. We found that adopting principles from electronics such as conductive textile parts that touch to complete a circuit helped to negotiate the overall textile forms, while the textile tools and techniques guided the details in shaping.

Using textile contacts to make interaction sensors: The principle of electronic switches is to have at least two separate conductive points that come in contact to complete the circuit, for example by pressing a button, moving a lever, or turning a switch. In e-Textiles, one way to achieve this is to design textile forms that allow certain parts to come in contact with one another through specific interactions that

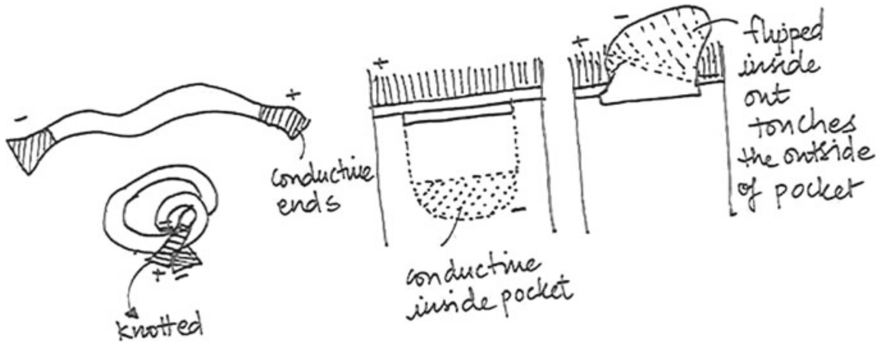

Fig. 11.6 Using textile contacts to make interaction sensors: *sketch* showing a knot sensor and pocket-shaped flip sensor

otherwise would stay apart. For example, straps with conductive ends that complete the circuit when knotted together, or a conductive inside of a pocket that comes in contact with the conductive edges when pulled out (Fig. 11.6).

Shaping the conductive areas to come in contact with specific textile interactions closely influenced the form iterations and circuit layout of the e-Textile artefacts. For example, in the design of the Flip-Around Dimmer (Sect. 11.4.1.1), the interaction of flipping in and out was tested and developed through several form iterations. Figures 11.7, 11.8, 11.9, 11.10, and 11.11 show the different stages through which the form evolved while continually considering the textile interaction as a facilitator of electronic sensing.

The form iterations did not always follow a linear progression but changed from one idea to another incorporating and discarding elements, or even making significant lateral jumps. For example, a change in the direction of form development can be seen in the iterations from Figs. 11.10 and 11.11. Sometimes, small-scale prototypes can also be made for testing the textile interactions and deformations. As an example,

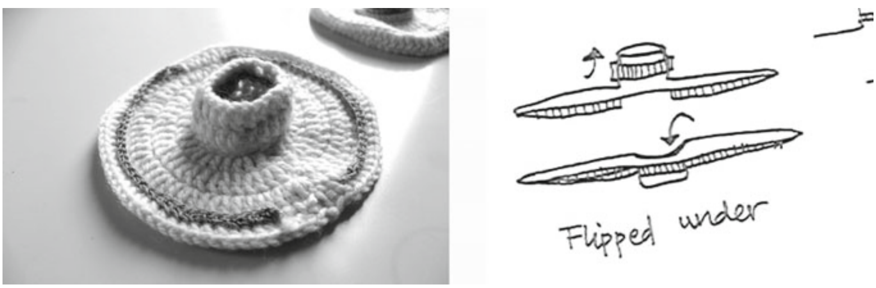

Fig. 11.7 Form iteration 1: a crocheted hollow tube at the *centre* of a circular base. The tube can be flipped under or over to make contact with the corresponding two sides of the base

Fig. 11.8 Form iteration 2: duplicating and layering the first form to diversify the interactions. *Left* The tubes are flipped separately on opposite sides. *Middle* The tubes are flipped together to the *bottom* of the circular surface. *Right* Trying out deformations: when the tubes were flipped to the same side, one or both of the circular bases could be squeezed together. This observation led to an idea of adding a textured pressure sensor that could be hidden between the layers and squeezed along with the action of flipping

Fig. 11.9 Form iteration 3: a tentacle-like form was introduced that could act as a pressure senor between the two circular layers. It added an interesting visual and tactile quality to the interactions. However, the two actions of flipping and squeezing were felt to be not so coherent. We decided to shift our focus back to the flipping action

Fig. 11.10 Exploring deformations: we observed that the new tentacle-like form afforded a flipping action where all or part of its tentacle-like forms could be turned inwards into the central opening and turned around. It also provided a rich tactile experience

the final form for the Soft Radio was derived by making quick and small mock-ups of using the action of wrapping as a starting point (Fig. 11.12).

Tangible exploration of the textile artefacts created during prototyping guided the iterative process and was essential for understanding the deformable qualities to make textile contacts by aptly placing conductive areas.

Considering the constraints and opportunities of textile construction tools and techniques: Being mindful of the textile production techniques and tools was an essential factor for implementing the textile sensors and shaping finer details. It

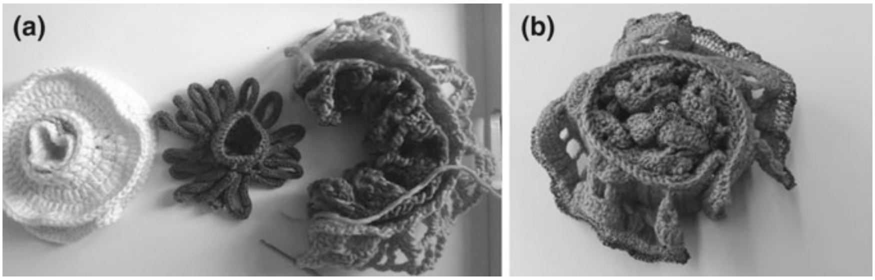

Fig. 11.11 **a** An overview of the stages in the form iterations. The tentacle form was then evolved into a two-sided elevated structure that contained yarns on *top* of the frills. **b** The final form of the Flip-Around Dimmer. The form could be opened or closed with magnetic buttons so that the flipping action would only work when the ends are joined. When open, the device would remain switched off

Fig. 11.12 Examples of the form iterations for enabling textile contacts with wrapping: **a** A central sphere with vertical flaps forming overlapping layers. A furry chord could be wrapped so that it goes between the flaps. **b** A sphere with conductive parts along its equator and a "tail" that could be wrapped around it. The chord would touch the conductive parts in different orders depending on the direction of the wrapping. **c** The resulting form of the Soft Radio

was important to perceive the technical possibilities and constraints related to textile production techniques in connection with electronics. Factors such as insulation, reliability of connections, or electrical resistances influenced the appearance and tactility of the e-Textile artefacts. Different textile production techniques, such as knitting, embroidering, and weaving, present different configurations of fibres, yarns, and substrates to compose the fabric. Considering these constraints in the prototyping process resulted in unique shapes that use conductive areas in an innovative manner to recognise interactions.

This was particularly apparent in the making of the Music Sleeve (Sect. 11.4.1.2). We used sewing and knitting to construct the Music Sleeve. The knitting machine allowed us to knit customised fabric with unique properties in terms of conductivity, stretchability, pattern, colour, and dimension. However, it was not possible to implement the sensors as we had initially imagined using only a knitting machine. Knitting always takes place in the horizontal direction, one row at a time. With the domestic hand knitting machines, it is cumbersome to include vertical lines of yarn while it is straightforward to add different yarns in the horizontal rows.

Since we needed conductive yarn to travel in both horizontal and vertical directions, we decided to split up the tube into two long parts (Fig. 11.13). The first part

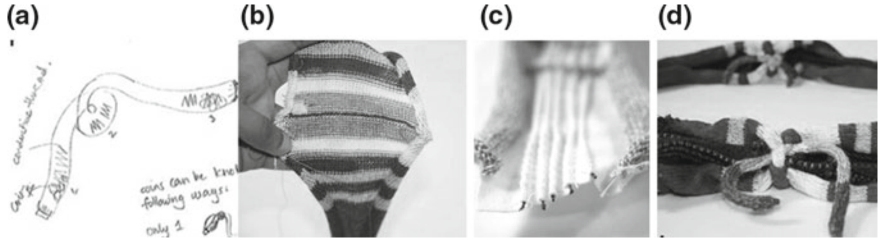

Fig. 11.13 Constructing the Music Sleeve: **a** Initial concept sketch of how the coins would travel and be knotted inside a tube. **b** The horizontal conductive rows on the knitted part of the sleeve. **c** Vertical data lines sewed into narrow chordings on the second part. **d** Both parts attached together to form a tube with four integrated drawstrings

with horizontal rows was knitted. The second part with vertical conductive yarn was made by sewing conductive yarns on to a jersey fabric that matched the elasticity of the first knitted part. To insulate the data lines on the jersey fabric, we sewed them into narrow chordings that created an initially unanticipated corrugated pattern and gave the sleeve a unique aesthetic quality. Moving from double- to single-bed knitting to accommodate the change of pattern, then made it possible to use two yarns in such a way that the conductive yarn was knitted always on the back of the fabric keeping it insulated from the outside.

11.4.4 Associating Material-Specific e-Textile Forms to Meaningful Digital Interpretations

Exploring forms for e-Textiles that are grounded in textile interactions often led to hybrid shapes and features that were not directly associated with textiles or electronics. This gave space for designing and evolving experimental forms by making and testing. At the same time, working with novel and unfamiliar interactional forms presented a challenge for redefining our expectations and assigning new meanings.

The appropriation of textile interaction sensors was facilitated by systematically identifying the interactional qualities of the e-Textile prototypes at hand and comparing them to digital behaviours.

Identifying interaction states and qualities: The textile interactions cause particular kinds of deformations, which are visible and tangible in the material. Textile interactions such as wrapping, rolling, or twisting have a directional quality, while stuffing or crumpling changes the distribution of the volume around an e-Textile artefact. The effect of some interactions remains longer, such as knotting or stuffing, while others, such as crumpling or stretching, might yield an ephemeral effect. We refer to the distinguishable deformations exhibited by textile artefacts when manipulated as their interaction states and could correspond to the digital states of an e-Textile artefact.

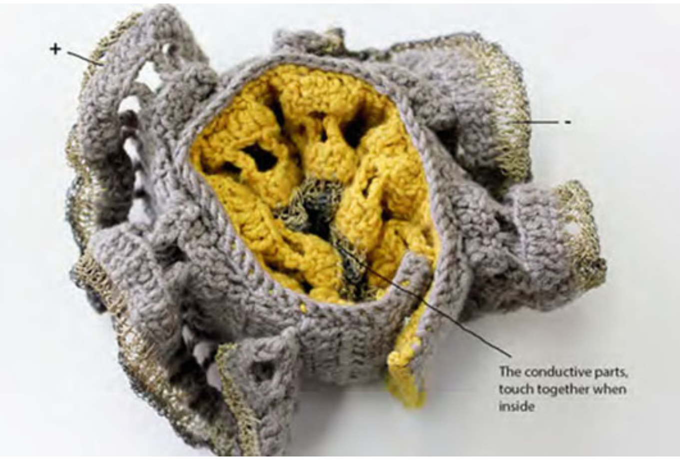

Fig. 11.14 Flip sensor: the frills stay apart on the outside and touch together on the inside

Fig. 11.15 Shape sensor: three conductive rows on the knitted tube act as analog sensors detecting the shape of the stretched tube

Working with textile sensors made from conductive yarns does not have the precision of regular digital switches. Nevertheless, their noisy behaviour can be minimised by programming a microcontroller to interpret the signals as digital or analog inputs. For example, the act of flipping around used in the light dimmer prototype is transformed into a digital input by recognising a flip when the conductive parts of the textured frills touch to complete a circuit (Fig. 11.14). An analog input can be emulated by reading and grouping the voltage changes dynamically. For example, in Fig. 11.15, a series of stretch sensors are used to dynamically determine the overall shape of the textile object.

Identifying the interaction states, thinking about interactional qualities in addition to the electronic sensing possibilities formed the basis for finding material-specific digital interpretations in our explorations.

When working with a specific application such as navigating through music files, or communication with loved ones, these interaction states give an analogical framework to find the most suited e-Textile interface elements. The exploratory hands-on investigations of interpreting textile interactions can be carried out by the designers as part of the concept development process and implemented for specific design incentives. In the case of working in an open-ended setting where applications have not yet been decided, exploring the interaction states could provide a starting point for imagining future scenarios for e-Textiles. We illustrate both these cases for recontextualising textile interaction forms through the design examples of the Soft Radio and the user study with textile interaction elements (Sect. 11.4.1).

Reinterpreting interaction states for mapping electronic functions: The form of the Soft Radio was closely derived from the interaction of wrapping and twisting; however, the mapping of functions for the textile interface was developed during the prototyping process. For this, the interaction qualities for the action of wrapping were identified; for example, wrapping embodies a directional quality (clockwise or anticlockwise), or that wrapping around something soft can make the whole distorted or squeezed depending on the force applied.

We chose to work with wrapping as a direction sensor, as it was found to be most reliable for the circuit we could make. It reminded of familiar directional digital controls, such as volume knobs, scrolling through menus, navigating through a playlist, or balancing and panning options for speakers or lights. The design of how the machine digitally interpreted the signals depended on the resources and skills available to prototype the device. In this case, we chose to work with scrolling and changing volume using wrapping and developed the interface logic with this as a starting point. The radio was a suitable match for the interactions as channel seeking/tracking exhibited a similar directional quality as afforded by the action of wrapping. We also proposed it to be a more suitable than other kinds of directional controls such as scrolling through music tracks in a music player, which would be more difficult to navigate without a screen.

In order to make a clear interface logic and to avoid too many controls for different functions, we used wrapping of the same chord as actions for both navigation and volume control. A twist sensor, which consisted of a textile loop and acted as digital switch, was added on the top of the device to work in combination with the wrapping sensor. Since twisting the loop made only a temporary textile contact, we chose to make it a toggle switch that would activate every time the loop was twisted. This allowed us to switch from "volume" to "channel seeking" modes in the radio. In this way, the interactions of wrapping and twisting led to the overall interface story of a radio. Other functions of a pocket radio such as a mute button and a hold function (against accidental activations) were then applied using the same interface logic (Fig. 11.16).

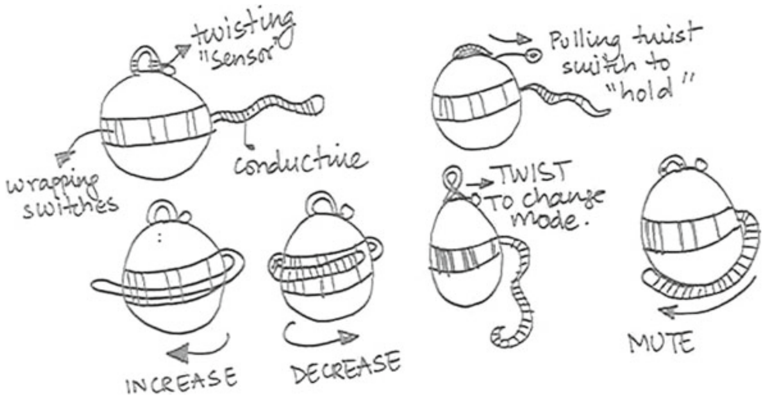

Fig. 11.16 Function mapping to the textile interactions on the Soft Radio: wrapping directions determines increase or decrease in volume or channel seeking, twisting the loop on *top* changes mode between volume and FM frequency tracking, wrapping the chord to the *bottom* mutes the radio, and pulling the loop down locks the current settings of the radio

The function mapping was thus a dialogue between the states of the textile interactions, the digital qualities that they relate to, the feasibility of electronic implementation, and how well the different parts fit together in the same interface logic.

Maximising interpretations, investigating e-Textile interaction elements (TIEs) with others: In our user studies with TIEs, we introduced the idea of textile interactions for e-Textiles to participants who were not previously part of the design process. We organised the exploration sessions into four stages: first, the idea of textile interactions was introduced and the aim to develop novel e-Textiles was explained. Second, the participants were asked to close their eyes and describe the TIEs handed to them one by one. The reason for this was that we wanted the participants to focus on the material and topological features of the objects so that they would remain open-minded about associating the textile qualities with functions or applications. Third, we asked the participants to explore the interaction states for each TIE. The participants were encouraged to think of the TIEs as parts of imaginary interfaces and tangibly explore ways of manipulating them. We further encouraged them to envision possible configurations, actions, or sequences of gestures that could be used to identify the corresponding states of the TIEs distinctly. Finally, we asked the participants to rethink the interactions in terms of what they could signify for doing a specific task, or as an expression. The participants were free to imagine any context of use and to explore playfully.

The findings are summarised in Figs. 11.17, 11.18, and 11.19. The exploration with participants resulted in numerous discoveries of unanticipated uses for the TIEs. For example, a participant noticed that gathering the textile on one part of a TIE simultaneously stretched out the other side (Fig. 11.19). This made her suggests that the interaction of shifting the volume of the material around the surface of a TIE could

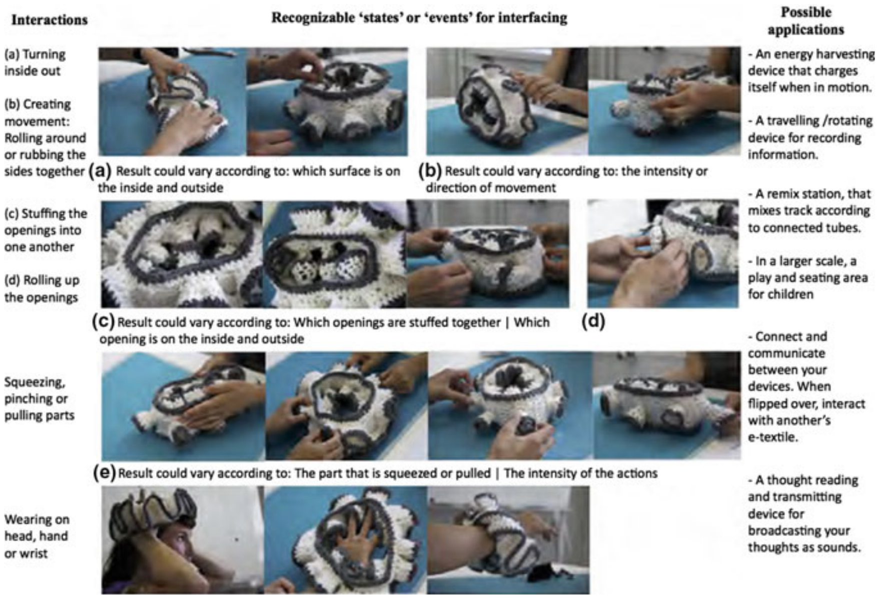

Fig. 11.17 A compilation of main interactions, states, and applications suggested by the participants in the workshop for the doughnut-shaped TIE

Fig. 11.18 A compilation of main interactions, states, and applications suggested by the participants in the workshop for the TIE with branching sleeves

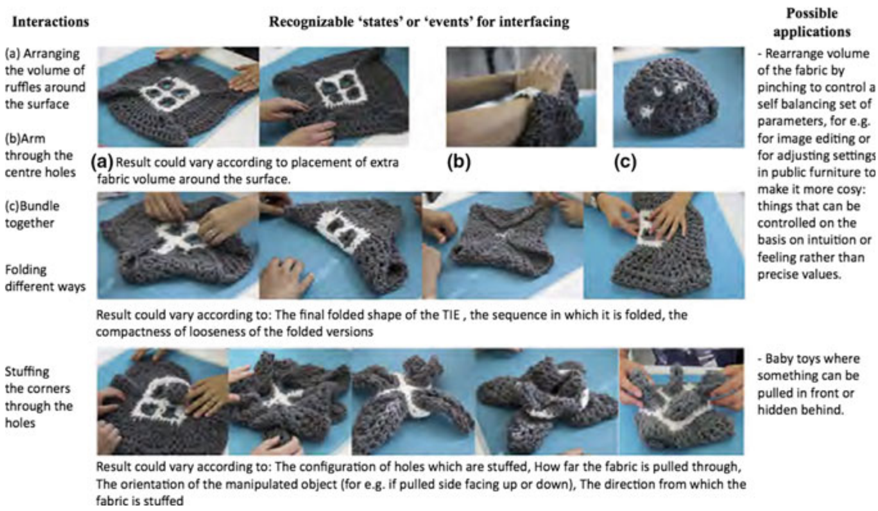

Fig. 11.19 A compilation of main interactions, states, and applications suggested by the participants in the workshop for the flat TIE with openings in the centre

be utilised for controlling settings in a more fuzzy way such as adjusting the cosiness of furniture where users might have different ideas of what cosy means. In some cases, the participants suggested ideas for devices that were based directly on the form of the TIE. For example, organic creature-like qualities of the doughnut-shaped TIE evoked ideas for different kinds of devices, such as a headpiece for reading and broadcasting thoughts, and an animated machine that rotated or pulsated around a space to gather information (Fig. 11.17). Other ideas for applications suggested by interacting with the TIEs were filtering, sharing data between devices, a music remixing station, children's story book which dimmed the room lights when read, and a cleaning device.

In this way, the TIEs that were made through explorations of textile interactions and textile contacts were used for enabling discussions, provoking interpretations, and exploring different application areas for e-Textiles. The TIEs provided the participants with tangible and interactive ways of entering the material-specific e-Textile Interaction Design approach.

11.4.5 Summary: Tactics for Retaining Material Specificity of Textile Interactions in the e-Textile Design Process

In the above subsections, we demonstrated some of the key challenges and how they were addressed in our design process for employing the strategy of using textile interactions as a marker for material specificity. The investigations can be summarised as follows:

1. **Extract** (collecting textile interactions): observing and extracting the most textile-specific interactions from everyday objects.

2. **Reformulate** (translating into textile sensors): giving new forms to the textile interactions for making them electronically recognisable by using textile contacts as a principle for electronic sensing while considering the possibilities and constraints of textile production techniques.

3. **Recontextualise** (seeking meaning and value through experiencing): to identify the interaction states in accordance with the general formal affordances presented by the textile sensors and considering the inherent interactional qualities for finding digital interpretations that are specific to the material interactions.

These tactics are not sequential but represent the underlying investigations that are integral to the material-specific e-Textile Interaction Design process.

11.5 Discussion and Concluding Remarks

e-Textiles enable computation to occur within the textile substrates [32], making textiles a novel medium for electronic interfacing. The decade-old field of e-Textile research has had to overcome many challenges regarding integration, durability, as well as practical and technological knowledge development before the first commercially available e-Textile products could appear. Nowadays, while technology is rapidly developing, there is an increasing need to focus on experiences and tangible interactions specific to the medium of e-Textiles to be able to design engaging and desirable e-Textile products.

Interaction design in e-Textiles is still an afterthought and largely follows the approaches from related fields such as Tangible Interaction Design, or Ubiquitous and Wearable Computing. We propose to examine the material specificity of e-Textiles as a way to investigate and develop the underexplored interaction design potential. Drawing from approaches in the field of Tangible Interaction Design that build on the quality and materiality of interactions, we define the material specificity of e-Textiles as its ability to reformulate or deform in ways that are similar to textile materials.

We put forward a material-specific strategy for e-Textile Interaction Design that utilises textile interactions as a distinctive resource and driver for the concept design and prototyping. Furthermore, drawing from our works in e-Textile design, we outlined a set of tactics that addresses the main challenges in using textile interactions as central to the design process. These were summarised as "extract", "reformulate", and "recontextualise" textile interactions through hands-on explorations at different stages of the design process.

Contrasting properties of textile and electronics: The two constituent domains of e-Textiles—textiles and electronics—are very different from one another in form, material, and behaviour. Textiles, in general, are thought to be soft, flexible, porous, and susceptible to different environments, whereas electronics are usually hard, precise, and protected. We observed that working with these contrasting properties of electronics and textiles contributed to achieving material specificity in the prototyping process.

While the development of miniature electronic sensors or flexible circuit boards is on one end of the spectrum of how the negotiations between the two domains shape the resulting e-Textiles, the series of textile sensors made by Perner-Wilson and Satomi [27] lie on the other. The first assists the integration of electronic components on textile substrates by adding one on top of the other. The latter transforms electronics to be remade using textile materials. This transformation has resulted in forms that are novel to both textiles and electronics, but specific for e-Textiles. We could argue that the material specificity of e-Textiles lies in the negotiations between these two domains on how they transform themselves to meet the requirements of the other. Therefore, working with the contrasting properties of textiles and electronics to explore new forms for e-Textile sensors and actuators while minimising the use of ready-made electronic components contributes to the material-specific strategy we propose for e-Textile Interaction Design.

Taking an open-ended approach: An open-ended approach was taken for defining and working with the material qualities of e-Textiles, and the applications or functions were partly or wholly derived through the process of prototyping and interpreting the textile sensors. Taking this approach enabled us to stay grounded in the direct and embodied interactional relationship that is formed when handling a piece of textile artefact while supporting varied interpretations for recontextualisation of the textile sensors. Hällnäs and Reström [33] discuss a need for change in approach from "designing for use" to "the presence" of computational objects and highlight the goal for design as making computational objects that enable people to give them different meanings or roles in their varied lives. Similarly, approaches such as of Critical Design [34], Ludic Engagement [35], and Reflective Design [36] emphasise on creating space for critical reflection, curiosity, and engagement with technical objects to build an active, aware, and enjoyable dialogue with them. They highlight the role of playing with the notion of ambiguity as a strategy for provoking curiosity, multiple interpretations, and engagement with computational objects.

Following this argument, the form explorations for material-specific e-Textiles that often resulted in unconventional textile forms could be used for provoking varied interpretations. Particularly, foregrounding the strangeness of the e-Textile forms could evoke curiosity and playful reflection for making new meanings that arise from the materiality of interactions rather than from preconceived notions. This aspect could be useful in workshop settings like in the case of the TIEs study, where e-Textile elements made from textile interactions were used to enable discussions and for identifying unique interaction-oriented use contexts for e-Textiles.

However, it can be challenging to go beyond describing the physical features and interaction states of the artefacts, to deriving an original application or digital meaning. While designers might be trained to make these associations and think creatively with the constraints of form, further methodological research is needed for facilitating user interpretations in settings that involve varied participants to gain truly insightful results. Focusing purely on the physical features, we did not explicitly consider any sociocultural connotations in the making of the textile artefacts in our work with e-Textile interactions. This may become relevant depending on the research context and could be addressed in the recontextualisation part of the design process.

Going beyond: In this chapter, we elaborated on e-Textile design that focuses on ways of making textile manipulations electronically recognisable by incorporating conductive areas that can be activated through different textile interactions. But the same consideration of using textile interactions as sensors can be applied when dealing with integration of any new component or responsive fabric materials with regular textiles. Getting a deeper understanding of textile behaviour in relation to the technological constraints and the nature of textile production techniques assists in modifying them to work together. Thus, the tactic of reformulating textile interactions can be generalised as one that takes particular technological constraints in relation to textiles into account for working with textile interactions.

Similarly, the constraints and opportunities of textile construction techniques can be used as a basis for exploring new forms of textile interactions. While it is possible to choose a production technique that is best suited for an e-Textile design (such as in the example of the Music Sleeve), an open-ended experimentation with textile tools and techniques can also be a path for discovering novel forms and expressions for e-Textile interfaces. Figure 11.20 shows three examples of textile interaction elements made from experimenting with an embroidery machine.

In recent years, with computation disappearing inside materials and everyday objects, there has been a growing need to reconsider the approach of designing products and systems. e-Textiles is a still developing field of research and product development. As the technology gets more advanced and new responsive materials get integrated, it is desirable that e-Textile research supports a discourse around the new roles and appearances taken by our technical objects.

The proposed material-specific e-Textile Interaction Design strategy aims at articulating e-Textiles independent of the conventions of standard electronics when it comes to formal and interactive aspects. In doing so, it makes space for exploration, curiosity, and interpretations for rethinking the role of e-Textiles in our everyday lives. The design of computational objects and devices has so forth predominantly been developed around how the digital environment is structured and consequently how interfaces can help in understanding and navigating through these preconstructed information systems. With the boundaries between physical and digital objects increasingly blurring, the material-specific e-Textile Interaction Design looks to not only shape new forms of digital interactions but also reorganise the fundamentals of how the digital is constructed.

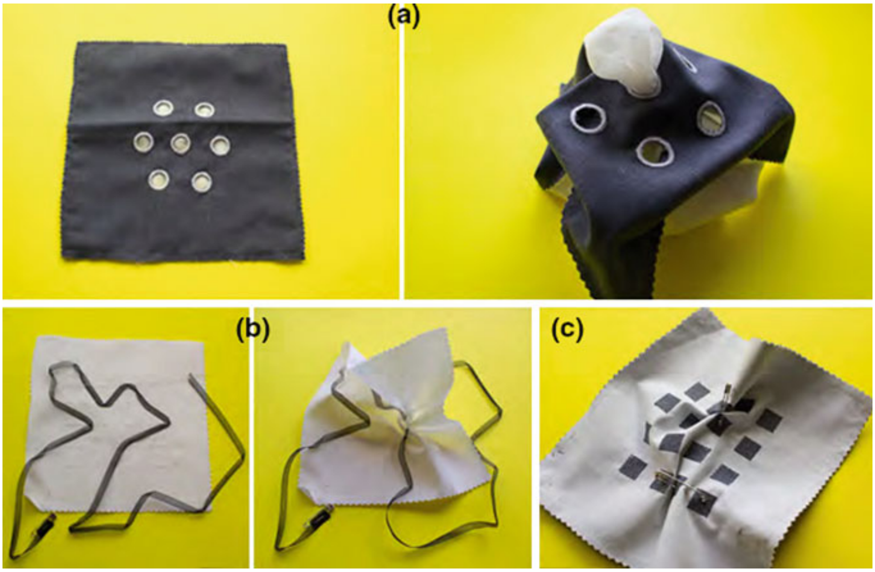

Fig. 11.20 Examples of textile interaction elements made from experimenting with an embroidery machine: **a** A flat textile artefact that can be deformed by pulling the inner fabric layer outwards. **b** A flat textile artefact that can be crumpled by pulling at the string. **c** An e-Textile that works with the textile interaction of piercing, enabling different conductive layers to be connected together with a metal pin

Summary

- **e-Textile Interaction Design**: In this chapter, we emphasise the need for developing an area of investigation within the field of e-Textiles that takes a material-specific approach to interaction design.
- **Enabling textile interactions as a strategy for material specificity**: We propose a strategy that is based on defining the material specificity of e-Textiles as its ability to deform in ways that match the expectations we have from regular textile materials.
- **The main challenges in prototyping for material-specific e-Textile Interaction Design** are described as follows:
  - Envisioning how textile interactions can be made electronically recognisable as a process of shaping e-Textile artefacts.
  - Incorporating the constraints and opportunities of textile construction tools and techniques in designing e-Textile interfaces and circuits.
  - Interpreting the interactional qualities of the textile sensors for deriving digital meanings.

- Investigating the contrasting properties of textiles and electronics as a resource for development.
- Supporting multiple interpretations and meaning making through interactions.

- **The key tactics** for undertaking the proposed strategy is summarised as follows: (1) Extract: collecting textile-specific interactions; (2) reformulate: translating textile interactions into textile sensors; and (3) recontextualise: exploring digital functions through evaluating physical and interactive characteristics of textile sensors.

Acknowledgements This work is part of ArcInTex ETN research, which is an EU-funded Marie Sklodowska Curie European Training Network Project (more info at http://www.arcintexetn.eu).

A part of the empirical research included in the chapter was undertaken at the Embodied Design Research Group of the Department of Design in Aalto University, Finland.

We thank Berit Greinke (Design Research Lab, UdK Berlin) for corrections that greatly improved the manuscript.

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Chapter 12
Designing for Smart Clothes and Wearables—User Experience Design Perspective

Jonna Häkkilä

Abstract Due to the recent years' advances in prototyping techniques, flexible electronics, and component miniaturization, research has emerged to explore novel concepts and functionalities for wearable computing. So far, the attention has been mostly toward technical rather than user experience studies, seeking to illustrate novel and proof-of-concept-level functional prototypes. In this chapter, wearable computing is approached from the user experience (UX) design point of view. The principles of UX design are discussed with respect to the area of designing smart clothes and accessories, and three examples of concept designs, focusing on young athletes, a solar powered coat design, and a smart handbag design, are presented.

12.1 Introduction

The past decade has witnessed giant steps in the area of computing technologies, and waves of digitalization and everyday mobile technology use have spread over urban societies. We currently carry around computing gadgets, such as mobile phones and tablets, and new form factors are emerging to the mass market. In particular, in the health and wellness domain, various physical activity trackers have already been adopted by large user groups, e.g., in the form of bracelets and armbands. The world is substantially moving toward wearable computing. Although the technologies in today's wearable products are mostly still in the form of gadgets or standalone objects, the designs are getting lighter, more aesthetic and more closely integrated to the clothing and human body. Also in research, wearable computing is emerging from being a technology-dominated field toward the fields of user experience design, industrial design, and textile design.

In this chapter, user experience (UX) design aspects are considered in respect to wearable computing design, especially smart clothes. With smart clothes, we mean objects of *wearable computing, which integrate technology and intelligence in a way that the form factor design follows the one of a clothing design*. Smart clothes provide

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S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_12

new possibilities for the design of tangible user interfaces, aesthetics, and rich user experiences. In addition, smart clothes offer potential for developing concepts that link with, e.g., sustainability, energy efficiency, and recycled material, providing an interesting playground to design for underexplored angles of wearable computing. In the following sections, we take an overview to UX research and human–computer interaction (HCI) research on topics of interest for smart clothes and wearable computing. We then present three design cases on our smart clothes design research.

12.2 User Experience Design and Research for Wearable Computing

12.2.1 User Experience and Ubiquitous Computing

User experience research is linked with the wider field of user centric design (UCD), which puts the target users in the center of the design process by involving them throughout the design process. Typically, a UCD process starts from end-user research through interviews and observations in the field and is followed by a concept design phase where users are involved, e.g., through participatory design sessions. Toward the end of the design process, an evaluation of design prototypes is made with user tests, and the designs are iterated according to their results. User experience research is a relatively young field, which has developed to its own track from a basis of usability research, taking a broader view in evaluating and designing interactive products. Although a single definition for UX concepts and theory is challenging to find [1], it is generally agreed that UX goes beyond the instrumental values and utilitarian aspects [2]. Hassenzahl defines user experience (UX) as *'a momentary, primarily evaluative feeling (good–bad) while interacting with a product or service'* [3].

Whereas traditional usability research has focused on investigating interaction performance, error rates, and ergonomics and has used measurable and quantifiable factors in evaluation processes, UX research emphasizes the importance of subjective, emotional, and aesthetic aspects related to the interaction with products and services. User experience is defined as consisting of both utilitarian and hedonic aspects [4]. The utilitarian side typically dominates in the overall motivation for application design; however, in constructing the user interface, hedonic aspects are important to consider in order to create pleasurable and engaging experiences. Hedonic aspects can also relate to different values that are represented through the design, and which the target user can relate with. In contrast to conventional graphical user interfaces, when smart clothing and wearables are considered, tangible factors such as material selections and physical form become an important part of the user experience design. They can affect both utilitarian and hedonic sides of the user experience design, e.g., through usability and comfort.

Wearable computing is part of the larger domain of ubiquitous computing. In ubiquitous computing, the computers and sensor systems are considered to be integrated to our everyday environments, blurring the borderline between physical and digital worlds. The field has largely be driven by Mark Weiser's vision [5], which presents how computers will disappear in the periphery of human attention, leaving the environments calm and serene. Smart clothes easily integrate with this vision, as they can truly hide the technology within the garments we wear every day.

Ubiquitous computing is deeply rooted in its computer science and engineering background, and UX research aspects have so far played a nominal role. To illustrate this, for instance Dünser et al. report that for the mixed reality research papers in 1993–2007, only in 10% included any kind of user evaluation [6]. In a literature review assessing UbiComp-related research papers pre-2014, Väänänen-Vainio-Mattila et al. report that only a minor part of them included UX evaluation aspects, and even then, mostly applying a narrow selection of methods [7]. UX is still mostly considered from the utilitarian perspective, e.g., usability, and the hedonic qualities are often summarized under simplified categories, for instance with descriptions such as 'playful' or 'fun.' However, UX research has the potential for a much richer vocabulary, and closer exploration can offer more concrete feedback and ideas for designers.

12.2.2 Aesthetics and Materiality in Interaction Research

When designing tangible user interfaces, material qualities are an integral part of the holistic experience. Material qualities of physical objects have been thoroughly considered in areas such as art, industrial design, and mechanics, but research on the material's role in interactive systems has been somewhat sporadic, leaving much to explore. Tangible user interfaces (TUIs) can make use of the human senses in a richer and more multidimensional way than conventional digital user interfaces (UIs) [8]. Thus, it is valuable to explore the different qualities that are perceived and associated with different physical materials.

So far, the focus in the research on materiality qualities in HCI has mostly concentrated on proof-of-concept-level installations, where a certain material has been evaluated as part of the concept. For instance, interactive systems using water in the user interface have been studied. With water, user study participants have described that the cool water creates a pleasant sensation against the skin [9, 10], and spilling water has been reported to offer a more powerful UI feedback than simulated virtual feedback [11]. Aesthetics can also relate to the fragility and lifespan of the user interface, as with ephemeral UIs [12].

Systematic studies on materiality in HCI are so far scarce, with a few exceptions. On the methodological side, Jung and Stolterman have introduced the material probes method [13]. The method proposes a step-by-step procedure to gain information on different tangible materials in order to gain hands-on knowledge about user perceptions, and to help, e.g., industrial designers when designing interactive systems, [13]. Häkkilä et al. present a study comparing user experiences when interacting with different natural materials [14]. The user experience findings on using natural material reflect the curiosity, aesthetics, and playful nature of the interaction, and they provoke many associations and memories.

12.2.3 Wearables UX

Wearable form factors for computing are becoming increasingly important. Wearable computing, as discussed here, includes clothing-type form factors, but also accessories such as handbags and jewelry, as well as smart watches and head-mounted displays (HMDs) [15]. In addition to clothing and accessories, also user interfaces on the skin offer interesting possibilities, of which Liu et al. provide a good overview [15]. When considering UX with wearables, we can see two main trends on which the design has focused—designing for utilitarian needs, or designing with aesthetics as a goal. Utility is heavily emphasized with so called functional clothing and when designing for accessibility and special user groups. Aesthetics is in a major role when jewelry-type form factors are considered or, e.g., when the target user group is trend or fashion conscious.

One of the areas where beauty is an inherent design goal is digital jewelry. Aesthetic design has to be a conscious goal or at least an important and integral part of the end results. Gadgets are progressing toward increasingly small form factors, such as rings. For instance, Ashbrook et al. have introduced Nenya interactive ring concept with aesthetic design [16]. Recently, end-user products have gained the maturity level to truly integrate biosensors to an aesthetic ring design. Oura ring, launched in 2015, supports physical activity and sleep rhythm monitoring with a jewelry-type design form factor [17]. Different bracelet-type gadgets have become popular especially among health and wellness monitoring, and FitBit and Polar Loop can be found on the wrist of many users. Pakanen et al. have investigated different tangible UI features and input mechanisms to a bracelet-type wearable, and propose different design solutions, which address visual and haptic aesthetics [18]. BuddyBeads is an interactive bracelet concept for social and emotional group connectivity between teenage girls [19]. Fortman et al. have charted design preferences for digital jewelry with an online survey and report that form factor, functionality, display, and interaction design were perceived as the most important factors in the design [20]. With a similar study on wearable wellness devices, Rantakari et al. report that functionality and form factor were seen as the most important design factors, compared, e.g., to context-awareness and sharing features [21].

Fashion-related wearable computing has gained attention during past few years, but it has been pointed out that research in this area is still taking its baby steps [22]. The need for fashion orientated software and hardware design will rise, but it is yet to be seen how the devices will vary in their expressions [23]. Currently, most of the concepts and research are heavily exploratory in nature. Juhlin et al. have presented an explorative study on different material qualities in the context of fashion, fabric, and shape-change [23]. Examples of fashion show-type wearables include a robotic Spider Dress [24] and the Twitter Dress [25]. Here, the former is based on sensors and actuators, whereas the latter displays twitter feeds embedded to the dress surface. Colley et al. have presented several concepts for a handbag with an integrated public display, and investigated, e.g., adapting the outlook of the handbag to match the user's clothes [26]. The user study showed positive responses on the smart handbag concept, but, not surprisingly, highlighted that privacy aspects are important, as the display content is very visible and public.

Eyeglasses-type wearable computing has gained lots of attention since the project Google Glass [27]. Interest on Google Glass project has been demonstrated, e.g., in the invited keynotes given by Thad Starner [28] and Mark Billinghurst [29], both pioneering researchers in the area. Prior art on head-mounted displays (HMDs) has focused mostly on utilitarian use cases. Early work has considered areas such as architecture and construction sites [30, 31], helping fear of flying [32], or with Parkinson's disease [33]. Recently, the use of HMDs has been demonstrated as part of experiential UIs, for gaining experiences such as surprise and thrill. The Oculus Rift HMD has been demonstrated, e.g., for experiencing a simulation of flying as a bird in the sky [34], or how it is to ski on a physical skiing slope but with a view to virtual reality [35]. Also different directions to the aesthetics and visual style of eyeglasses-type wearables have been explored [36].

Research around smart watch form factor has started to bloom due the launch of several commercially available smart watches that function as an extension or replacement for smart phones. So far, the focus of the research has been on investigating suitable input mechanisms to interact with the smart watch, proposing different techniques from mechanical tilting and clicking [37], eye tracking [38] to deformation of the skin under the watch [39]. It their study, Schirra and Bentley have reported that users stated that the appearance of the smart watch had impacted on their purchasing decision. They desired a model that had a subdued design and could pass as a normal watch [40].

Clothes-type wearable computing has addressed both the utilitarian and hedonic sides of user experience design. Hedonic experiences are demonstrated, e.g., with fashion-related wearables, as mentioned before. Multisensory feedback has been harnessed for communication purposes, and an example of emotional communication is the Hug Shirt, which is used to send hugs over a distance [41]. Utilitarian aspects are addressed especially with wellness-related smart clothes concepts, such as in detecting joint movements [42], or movements of an unborn baby with sensors integrated to maternity clothes [43]. Also safety-related domains and target users such as firefighters [44] provide a high-utilitarian emphasis for wearables design.

12.2.4 Positioning Statement

In the following, three examples of designing smart clothes or wearables are presented. These examples represent different ways on how user experience research has been integrated to the concepting and design process. The examples have been conducted in the research team led by the author during 2015. Although all these examples can be regarded as falling into the area of UX design and user centric design, the presented research cases represent somewhat different design processes and methods. Thus, they can provide tools and inspiration for other researchers and practitioners working in the area of smart clothes and wearables design.

The cases introduced in the following include three different types of form factor concepts for wearable computing. Case I presents a design concept where sensor technology is attached to wearable sports gear as removable stickers; Case II addresses a concept and design that integrates the technology as part of the clothing (a jacket) itself; and Case III demonstrates a smart accessory design. It is to be noted that this chapter focuses on the process and methods used, not on presenting the content-related findings of the user studies.

12.3 Case I—Ice-Hockey Youth

12.3.1 Context and Motivation

The first concept introduced in this chapter relates to health and wellness technologies. Tomorrow's health-related systems and services will increasingly take advantage of a myriad of different sensor systems, which can track our physical activity and everyday life. Today, sensor technologies have achieved a sufficient level of technical feasibility, miniaturization, and cost efficiency as to be able to be easily integrated into various types of everyday objects. This enables an omnipresent tracking of our activities, which consequently provides an overview of our lifestyle. The role of technology in monitoring our everyday activities, physical exercise, and overall lifestyle is promising, but requires yet more research and development work both for the technical aspects as well as for design.

Integrating wellness technologies into clothing and other wearable gear is an intuitive step following on from the carrying of sensors as separate gadgets, e.g., step counters and mobile phones. In particular, with sports, integrating sensors and tracking technologies in clothes allow them to be taken effortlessly with the user when doing exercise, and avoiding additional loose items that can hinder the performance or get tangled with other objects.

Whereas wearable form factors offer good possibilities for data collection, they are typically limited in their interaction interface. Many wellness gadgets already function together with a smart phone app, which provides the user interface to access the information. Since mobile phones have become a generic tool for their communication and user interface (UI) functionalities, they have been widely adopted also when developing new technology or service concepts. This approach, i.e., a combination of wearable tracking technologies and a mobile app providing the user interface, was found to be suitable also in this case.

12.3.2 The Concept

The wearables concept is targeted to young ice-hockey players, and it introduces attachable tags that collect the player's activity data during training sessions. The work has been described in more detail in [45]. The player is equipped with several tags that can be attached to ice-hockey gear to collect data on movements and collisions during the activity. The data is then transmitted to a smart phone, where it is processed and viewed after the ice-hockey training or game, see Fig. 12.1. In the concept design, the target was to utilize printed electronics for manufacturing the tags, enabling low-cost mass production for the end product.

The collected data and individual user's mobile app were part of a larger service concept. In the concept design, the data from the training session would be collected from each player, enabling the coach to see the overall picture of the team, as well as comparisons between team members. Also, each player would get a visualization of their own performance in respect to the whole team, handled in an anonymous way. Moreover, the concept design included the idea of enabling the addition of other 3rd party service providers, e.g., a personal trainer or a doctor, modularly to the application, and to share data with or receive recommendations from them.

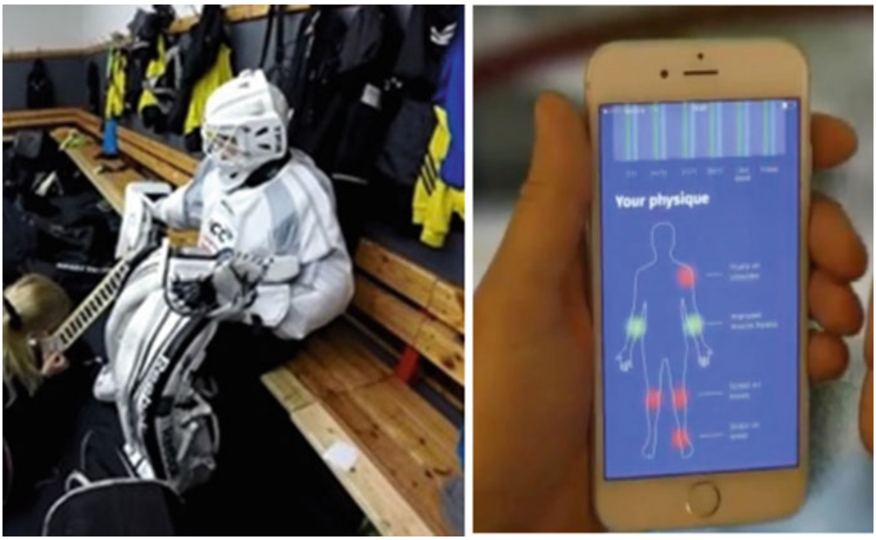

Fig. 12.1 Concept of using wearable tags and mobile app to collect data from ice-hockey training

Fig. 12.2 Examples of brainstorming tasks in concepting workshops—creating a big picture of stakeholders and brainstorming with a mobile app prototype as a stimulus

12.3.3 Design Process

The overall design process of the holistic concept consisted of the following main steps:

- Concepting workshops,
- Concept design, with first mobile app mock-ups,
- Creating a video presenting the key use cases,
- Wearable prototype and mobile app demos (simulated), and
- Concept evaluation in the field.

The concepting workshops held consisted of a multidisciplinary group of participants from industry and academia, brainstorming around concepts related to digital health services. During these workshops, different methods derived from the service design were applied to facilitate the discussion and ideation process. Examples of co-creation methods used in the concepting workshops are illustrated in Fig. 12.2. As an outcome, the workshops resulted in creation of a persona, a stakeholder map, a day-in-the-life story, and service chain descriptions of different health and wellness-related services that could potentially be joined with the key concept. The developed persona, Niklas, was a 13-year-old ice-hockey player, and the application and service concepts were developed with him as a target user.

A wearables concept, including an industrial design for attachable sensors and an interactive prototype of a mobile app, was developed through several sketching and prototyping phases. Figure 12.3 (left) illustrates early hand drawn sketches, which were further developed and printed to product-looking sensor stickers (Fig. 12.3, right). These could be attached to the ice-hockey gear and clothes. The final concept is illustrated in Fig. 12.1.

In order to evaluate the concepts, an evaluation workshop was organized with a team of 13-year-old ice-hockey players. The test and feedback session with the young athletes was made in the field, i.e., at an ice skating rink, during a standard training session. The evaluation session lasted approximately 2.5 hours. In the beginning of

Fig. 12.3 Designing wearable tags: sketches and printed mock-ups

the training session, researchers explained the concept to the players, and attached, or helped to attach, the simulated sensor stickers to their training gear. The boys wore the stickers through the whole training time on ice, after which the mobile phone application concept was discussed together with the wearables concept and form factor.

12.3.4 Discussion on User Experience Perspective

Case I has presented a wearables concept where the technology is attached to the wearable gear as removable stickers, taking ice hockey as a domain for the design case. The aim for this concept was that a modular design would allow greater freedom for the user (or a coach) to decide optimal and interesting body areas to be monitored, and tailor personal tracking solutions.

In this concept, we paid attention to both utilitarian and hedonic aspects in the user experience design. The aim was to create a concept with utilitarian value and a useful use case, and the service itself promoted healthy lifestyle, personal training, and sports. Hedonic aspects were considered especially through the polished designs of the prototypes, and the tags were designed to be professional and aesthetic looking, as well as easy to use.

The use of persona creation as a method in the design process has gained controversial discussion [46], but despite this, it still remains a commonly used method. In our case, the persona functioned both as a communication tool as well as an aid for designers. In particular, when making visual designs, sketching and illustrating descriptions of the concept, a selected, defined target user persona was important to have in order to create a unified vision and presentation of the concept. The role of the persona was important also when communicating the concept within the interdisciplinary project. As is usual with this type of project, several workshops with people with various different backgrounds and roles were included in the process, and a persona provided a consistent and illustrative tool when referring to the concept design.

12.4 Case II—Solar Cell Coat

12.4.1 Context and Motivation

The second case presented in this chapter considers clothing-type wearable computing and introduces a coat-like garment. Clothes integrated computing components represent one of the typical approaches to wearable computing. They have also become more easy to construct and prototype with available toolkits, e.g., Arduino microcontrollers, and gained more public attention through Google Project Jacquard [47]. The concept presented in the following sections features a flexible solar cell integrated to a coat and is motivated by trends for sustainable design and energy harvesting. The aim of the concept design was to produce a design vision, which communicates to a large audience a sustainable approach for wearable computing design. The concept and prototype was targeted to a design exhibition, which set high standards for its overall appearance. Thus, a polished design clearly articulating the design vision was more important than the technical functionality of the prototype.

12.4.2 The Concept

The concept *Solar Shirt* is a coat-like design garment, presented in Fig. 12.4. The garment includes solar cells as an integral part of the design—hence the concept name, *Solar Shirt.* The Solar Shirt uses felt as the main material, and the clothing design approach applies arctic design—matching the design style to that of the arctic nature and environment. The use of natural materials (over manmade fibers) gives warmth and softness to the design and aligns with the ecology focused values of the concept.

The concept illustrates the possibilities of using energy harvesting as part of the design and envisions how wearable computers could be designed in a manner such that they actually produce the energy they use, rather than consuming energy from external sources. The solar cells are manufactured with printed electronics technology and come in flexible and thin format. In addition, the coat includes a similarly flexible electrochromic display. The functionality of the concept is designed

Fig. 12.4 Solar Shirt wearable computing design concept—final prototype

around environmental sensors. The coat includes sensors that detect the ambient noise level, and the pattern shown on the coat's display changes when a threshold noise value is exceeded. The final prototype of the design concept is presented in Fig. 12.4. The Solar Shirt was presented as part of the Kaiku exhibition at Ventura Lambrate, during Milan Design Week 2016.

12.4.3 Design Process

In this case, the concept design began with a design brief, which defined the target of creating an outdoor coat-type wearable computing concept employing solar cells as part of the design. In this first phase, several different concept designs were created at a sketching level, and the work was conducted in groups of 4–5 design students. The starting point of the work was to explore the design possibilities from the clothing and

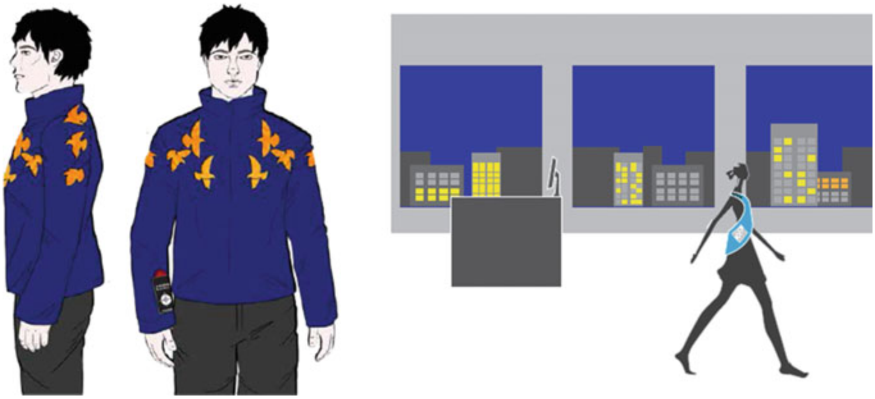

Fig. 12.5 Sketches on different concepts illustrating outdoors coat-type garments with solar cells

industrial design concept point of view, and, differing from the other two design cases presented in this chapter, end users were not involved in the design process. The first concepts designs were illustrated through sketches and use scenarios were drawn. Figure 12.5 illustrates this phase in the design process. Figure 12.5—left illustrates an early sketch of the concept with alternative design of coat-integrated solar cell modules. This visual design was soon abandoned when refining the style of the concept, and also because of the unavailability of the required technology.

Figure 12.5—right presents an early draft of the concept that was selected for further development. The picture presents a use scenario, where the garment is worn in a city environment, and the integrated sensors collect environmental data from the user's surroundings. The form factor of the garment is beginning to take shape, i.e., an asymmetric design that goes over one shoulder across the user's chest. This concept was then developed further into a physical prototype (see Fig. 12.6). Figure 12.6 presents two early constructions, where the shape of the garment and the material selections are tested on a human size mannequin. The prototype was developed in phases by iterating the design, the cut lines, and materials used. The final prototype was constructed using a clothing design process and equipment, and the finalized prototype is presented in Fig. 12.4.

12.4.4 User Experience Perspective

In this wearables concept, the utilitarian aspects were included mostly in the design aim—the target was to concept an outdoors coat-type wearable computing garment, which utilizes solar cells. The utility factors came from the use of energy harvesting technology, the functionality of the concept, and from the wearing comfort that would affect to the usability of the garment. Hedonic design aspects came from the

Fig. 12.6 Shaping the early wearables prototype with a mannequin: early shaping of the form factor (*left*) and an already mature prototype of the concept (*right*)

aesthetics of the design and through the material selections, which were chosen to associate with luxury, sustainability, and comfort.

With this design case, the design process prioritized clothing design over engineering and technology implementation. Thus, the prototype was designed according to the principals and practices of clothing design. Altogether, the *Solar Shirt* concept focused on creating a polished final design piece and in communicating the design vision, creating an example on how energy harvesting garments could look in the future.

12.5 Case III—Smart Handbag

12.5.1 Context and Motivation

The third concept presented in this chapter addresses the design of a wearable public display, which are still rare in the area of wearable computing, although some examples do exist. For instance, using wearable public displays to visualize social media feeds is done in [25, 48]. Mauriello et al. have integrated displays into runners' shirts at sporting events [49], and Puikkonen et al. [50] tested a Tic-Tac-Toe T-shirt which integrated the game on the front side of a t-shirt by using single-colored LEDs. In our research, we were interested in exploring the user perceptions of a public display integrated to a personal item, which the user carries around in their everyday life context.

The design cases also investigate an underexplored form factor in the area of wearable computing—the handbag. Handbags are interesting objects as they combine the functionality of carrying important items, with a fashion and appearance conscious form factor. They are at the same time very visible, but still personal and intimate objects.

12.5.2 The Concept

The research on interactive handbag employing a public display included three different concepts: using the display, (A) to match the handbag to the user's outfit and context, (B) as a see-through interface to the handbag content, and (C) as an information display. The concepts are described in more detail in [26].

Concept A, i.e., matching the handbag to the color of the wearer's shoes or jacket, focuses on aesthetics and fashion design. It considers handbag as a part of a larger outfit, and the context-awareness and adaptive display content are used for hedonic purposes. This approach also enables a chameleon effect, which further explores the idea of matching the handbag to other surfaces on which it is placed on or against to. An illustration of the polished concept design is presented in Fig. 12.7.

In design concept B, the handbag surface was composed of a display creating a see-through illusion to the contents of the bag. In the study presented in [26], different visualization techniques from full color images to X-ray style were explored. In addition, the concept included the ability to interact with the items in the bag through the bag's surface display and to show the brand of a perfume bottle contained within.

The smart handbag concept C employed the handbag's surface as a public information display. The smart handbag provides possibilities for its wearer to interact

Fig. 12.7 Design concept of a smart handbag adapting its colors to the user's outfit

socially, in public, in a more ad hoc way than is possible with traditional printed designs. For example, the user may select a personal motto or statement to be displayed on their handbag.

12.5.3 Design and Research Process

The research process for the smart handbag concept included iterative prototype design, the development of several concepts, testing them in a user study, and finally creating a 3D modeled, polished industrial design of a selected concept (concept A, illustrated in Fig. 12.7). The user study was conducted with two early prototypes, which were constructed as interactive, responsive artifacts by using off-the-shelf technology.

The prototype design consisted of several parts. Two off-the-shelf handbags were modified by cutting and sewing to fit a tablet in and to attach a mock-up camera lens on one side of the bag, see Fig. 12.8. Graphics design for the displayed items was made, and several different visualization techniques were used. The concept was evaluated in a user study with the wizard-of-Oz method, and for that, a mobile phone application was implemented to enable a hidden human operator could control the content that was shown on the handbag.

In the user study, it was important to collect feedback not only of the concepts themselves, but also about how it was perceived in use. As the prototype relied on wizard-of-Oz techniques and was not mature enough to be tested completely in-the-wild or in a long-term study, it was decided that the study would include tasks that would expose the user to public situations. During the approximately 1-hour study session, the user was asked to walk through a university campus cafeteria with the interactive handbag. This task, although short, provoked many comments and reactions from study participants and increased the validity of the feedback.

Fig. 12.8 The interactive handbag prototypes used in the user study. The study task to match the handbag pattern and *color* to the clothes is conducted

12.5.4 User Experience Perspective

The research conducted to concept an interactive handbag resulted in several concepts, which emphasize different user experience design aspects. Matching the handbag's outlook to the clothes or environment clearly appeals to the hedonic side of UX, as it seeks to offer an aesthetic and personalized design solution. Using the attached display as a see-through surface to the handbag content or as an information display focused on utilitarian needs as design drivers. With these concepts, the functionality needs careful UI design that takes into account privacy aspects. Thus, addressing the aesthetics and hedonic values is a less risk-prone and easier design approach.

12.6 Discussion and Conclusions

This chapter has addressed the user experience design perspective on wearable computing and has introduced three different wearable computing design concepts from the user experience design point of view. Wearable computing design, when the term design is understood in a similar way as in smart phones and other mobile technologies, is still taking its early steps. The push for wearable computing has so far been coming from the technology side, demonstrating engineering and computing solutions. However, when the technology matures and the concepts begin to aim for commercial markets rather than being research demos, the pressure to create appealing industrial and user experience design grows.

As technologies become more mature and prototyping tools easier to use and more widely adopted, the ability to produce high-fidelity prototypes grows. With more mature prototypes, the chances to employ wearable technologies in real life increase, and evaluating concepts in-the-wild with users becomes easier. When the basic technology works reliably, one can pay more attention to other aspects of the prototype. This means that the design aspects become more prominent in the research. It becomes more relevant to investigate the user perceptions in a holistic manner and to find solutions on how to introduce the technology to larger audiences. With ever smaller components, the ability to integrate technologies invisibly to garments and accessories grows and design restrictions become less of a concern. With declining energy consumption, battery charging demands become less, and the use of wearable computing more flexible.

The presented example concepts illustrate three different approaches to wearable computing—solutions where the technology is attached and integrated to the wearable garments or gear (Case I and II, respectively), and designing a wearable accessory (Case III). As the technical implementation and manufacturing are becoming easier, there will be great growth potential for products and business in this area. In the future, the role of designers and technologists working in the wearable technology and smart textiles area can make a difference in the everyday lives of wide audiences. Although the topic is currently at the beginning of its era in terms of commercial applications, it will become mainstream tomorrow.

The examples presented in this chapter place different emphasis on the design processes as well as in user experience design. When the use cases were tested and different features of the concept were evaluated, we utilized wizard-of-Oz techniques in order to achieve an illusion of a seemingly better technical maturity level for the prototypes. This was done with Cases I and III, where the design process included the concept evaluation with target users. In Case II, with *Solar Shirt* concept, the aim was to communicate a design vision that integrated solar cells as part of the visual design of a wearable item to a wide audience. Here, special attention was paid to get the visual design, material selections, and overall appearance to ensure the final garment appeared polished. This affected the user experience design, which was driven toward luxurious and aesthetic factors.

It is hoped that the examples presented in this chapter provide inspiration for the user experience design work in the domain of smart clothing and wearables. The presented case studies can be used as examples of design processes where each has a different emphasis and reflects different aspects of user experience design.

12.7 Summary

User experience (UX) design considers both utilitarian and hedonic aspects of the design. Functionality and selected use cases largely define the priority and balance of utilitarian and hedonic UX design. Utilitarian aspects are addressed especially through usability and accessibility aspects. Polished designs and material selections affect largely to the hedonic side of the user experience with the prototypes.

This chapter has presented three examples of designing smart clothes and wearables. The examples address different form factors and domains of use, namely ice-hockey gear with sensors attached (Concept 1), a coat-integrating solar cells for energy harvesting (Concept 2), and a smart handbag with an integrated display (Concept 3). These concepts have been designed and evaluated with different methodological approaches and emphasis in the design process. The user experience design goals have an effect on what steps are emphasized in the design process and how polished the final prototypes are. To gain more reliable assessment of the user experience design, the concepts and prototypes should be evaluated with users in the real life use context. With smart clothes and wearables, for instance the wearability and social acceptability can be better assessed in-the-wild. The design process examples presented in this chapter seek to provide hands-on background information and inspiration for researchers and practitioners working on user experience design of smart clothes and wearables.

Acknowledgements The work presented in this chapter has involved several students, designers, and researchers working under the author's supervision. For the Case I, ice-hockey gear, I want to thank Mira Alhonsuo, Lasse Virtanen, and Juho Rantakari. For Case II, the solar cell coat design, I want to acknowledge students in my interaction design course in winter 2016, Paula Roinesalo for her design of the final prototype and Anu Kylmänen for the supervision from the clothing design perspective. For the interactive handbag concept, I wish to acknowledge Lasse Virtanen for the concept visualization; Ashley Colley for the technical implementation; and Minna Pakanen, Saara Koskinen, Kirsi Mikkonen, and Tuomas Lappalainen for the user study. This research has been supported by a grant from Tekes—the Finnish Funding Agency for Innovation as part of 'The Naked Approach—Nordic perspective to gadget-free hyperconnected environments' programme.

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Chapter 13
Designing (Inter)Active Costumes for Professional Stages

Michaela Honauer

Abstract This chapter deals with smart costumes that are made for the usage on professional stages, e.g., theatre, ballet or performances of pop stars. Such costumes can be *active* or *interactive* depending on whether they are reactive to their wearers or the environment, or not. The requirements of *(inter)active costumes* are different in comparison with conventional costume design because the individual computational features have to be developed and integrated properly. Creating, staging and maintaining them challenge in particular the established structures of traditional production houses in theatre. This chapter analyses the crafting process of *(inter)active costumes* for the performances of singers or musicians and for professional theatre or ballet. Furthermore, it seeks to outline the requirements that are needed to succeed.

13.1 Introduction: Professional Performances and Tech Costumes

The increasing potential of smart clothes in different areas of everyday's life is uncontroversial. This book shows how electronic textiles are being integrated in fields such as fitness, health care or fashion. Many visions and examples address the support or enhancement of daily routines with smart clothing for everybody [1, 2]. But what about e-textile applications for professionals such as actors or dancers that are used to wear costumes as a specific type of working garment? In this chapter, I focus on smart textiles that are created for the use on professional stages such as theatre, ballet and performances of pop stars. The goal is to outline the characteristics of this special type of costumes that have integrated electronic or computational components.

The production, staging and maintenance of conventional stage costumes for professionals follow a determined process and adhere to the given departmental structures in theatre or ballet houses [3, 4]. Costume designers usually develop the idea, and tailors then craft the clothes. In this phase, the wearer is only involved

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© Springer International Publishing AG 2017
S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_13

for fitting. A few days before staging the play or the show, there is usually the first dress rehearsal. For the performance, a dresser helps the wearer with dressing and undressing. The dresser can also take care of preparing, cleaning and storing the costume. All the persons and departments who are responsible for a costume usually have a poor knowledge of electronics and hence are not able to create or maintain smart textiles for the stage. But who integrates the computational components into *(inter)active costumes*, and how can the development and maintenance of tech features be incorporated into the given infrastructure of professional institutions? In this chapter, I further investigate the creation process of *(inter)active costumes*. I look at the design and technical development phase, shortly examine the staging process and analyse the characteristics for maintaining this new type of costume when a show runs.

A costume traditionally helps an actor to visually outline the performed role, and usually, it has no tech features embedded. Such costumes could have many different appearances depending on the show's overall view, the director's style, the costume designer's taste or simply the size of the budget. All costumes have to meet some specific criteria for getting staged. Likewise, the integration of tech features into professional stage costumes is an individual endeavour and underlies similar but also additional criteria. But what are the specifications of smart stage costumes and how to design them? This chapter further deals with the requirements of electronic costumes and seeks to outline what is needed for creating them. For this, I include field studies we, the HCI research group at Bauhaus-Universitaet Weimar, have conducted and I talk to experts that are experienced in designing and developing such costumes.

13.1.1 A Definition of 'Costumes'

In general, costumes are meant to clad a person and generate a certain impression about the shown character from a spectator's point of view [5]. Further, one can distinguish between costumes in the narrower and broader sense. A costume in the narrower sense just means the clothing and in the broader sense wigs, masks, jewellery, accessories, shoes, hats and make-up are also part of a costume [3, 5]. My research focuses especially on the clothing, thus on costumes in the narrower sense, but I also have a strong interest in the overall impression an *(inter)active costume* causes when it appears on the stage. Hence, I do not exclude the characteristics of costumes in the broader sense if they are part of a technical composition.

Costumes that are worn on professional stages differ from those that are employed for other events, e.g., carnival or live action role-play. Professional costumes hold a minor role because they are used to support the wearer in playing a certain character and to underline the overall outcome of a performance [5]. In contrast, a carnival costume catches the major focus of a spectator because presenting the outfit is more important than representing a character. According to previous publications of my research group, I assume this is likewise relevant for *(inter)active costumes* [6]. Besides, costumes as professional applications are individual artefacts. They are not produced for the mass market or for end-users, but they have an artistic sense and they are meant to be made for creative expression [7, 8].

13.1.2 'Active' Versus 'Interactive'

There are many different terms to describe that tech features are combined with fabrics (e-textiles, electronic textiles, smart textiles, smart clothing) or attached to the body (wearables, wearable computing). Electronic costumes are special because they are a kind of working garment worn by actors, dancers or singers [6]. I call them *(inter)active costumes* and distinguish between *active* and *interactive costumes* depending on the amount of control. *(Inter)active* costumes can be both e-textiles or wearables depending on whether the electronic components are seamlessly integrated into the fabrics or purely attached to the wearers' body.

Active refers to stage garments that have technology integrated but cannot react to a user's or environmental input. You can only switch on or off the function(s) of the costume, like an LED display with pre-produced and played-back content. If the technical components are addressable, one can only change the playback content, but they are not reactive to the wearer's or environmental input.

Interactive costumes go beyond that because they enable its users or the environment to establish a reciprocal relationship with the electronic clothes. They are reactive to the wearer's or environmental input, which means that they are intelligent to a certain degree. The interaction is defined through the interplay of sensors and actuators as it is typical for all interactive applications.

13.2 Background: Related Works

The world of wearable technologies and electronic textiles in the performance arts and celebrity shows has grown enormously in recent years, but computational textile applications in theatre or ballet are still rarely seen [9]. This section gives a brief overview of research and performance projects in that area. I summarize related works that investigated in interactive theatre, dance or performance arts and that studied the creation process or other characteristics related to this topic. Additionally, I list some real-life samples of (inter)active costumes in pop music and ballet. In doing so, I make no claim to be exhaustive but rather want to give an impression of the variety of (inter)active costumes. A more detailed and comprehensive overview of wearables and electronic textiles as well in performance arts as in other application fields can be found in the literature [1, 2, 8, 10].

13.2.1 (Inter)Active Costumes and Performance Arts

The list of publications discussing examples of wearables or electronic textiles in performance arts is multifaceted. The use of computational clothing is a key artistic feature for many performance groups and performance artist. A wide range of them employs the technologies for digital music performances [11–14]. It is characteristic for those types of interactive music performances that the wearables are applied to generate the sound which has a strong influence on the choreography, whereas the implemented technologies are very diverse. Other examples utilize electronic garments for visual-based performances [7, 15, 16]. The integrated technologies function as a kind of screen [7, 16], or they project light beams into their environment [15]. This type of visible computational garments has an expressive character, and lasers or LEDs seem to be the most popular tech solutions.

I found no publication dealing directly with (inter)active costumes in the broader or narrower sense (compare Sect. 13.1.1) in theatre or dance performances, although many examples apply wearable technologies for enhancing the performance through sensed bodily data [17–22]. The technologies used for this range from wearable microphones and cameras, over movement and orientation sensors, to self-manufactured sensors (e.g., a breath sensor [18]). However, the technical features are attached to the performers' bodies and the show is to be supported by those digital mediums. Except two papers [21, 22], none of the publications explicitly discuss if the wearable computing is part of the costuming or not, and how this may influence the costume design process. Two other projects describe the use of LEDs [17] and electroluminescent wires [23] that are integrated into the clothing which indicates that the authors see those as electronic components associated with the costume.

In the literature, one can find references to wearables used in the performances already in the second half of the last century [8, 10]. For instance, in 1956, a Japanese artist named Atsuko Tanaka performed in her *Electric Dress* which consisted of wires and painted incandescent light bulbs [8]. Around twenty years later, the German artist Rebecca Horn showed the *The Feathered Prison Fan* to the public [10]. It is constructed out of fans and large feathers, and it can hide a person. These examples prove that the idea of technical refined costumes is not an invention of the twenty-first century. Furthermore, the misuse of contemporary technology led artists then as now to create (inter)active costumes. But today, it has become easier to embed technical features into clothing because computational components are tinier, one can buy them almost ready-made for any purpose, the power supply can be solved smarter, and wireless technologies allow communication to the environment without cumbersome cables.

In the last twenty years, more and more pop stars or other celebrities appeared in (inter)active costumes on the stage [8]. The majority of these stage outfits is illuminated by and composed of lasers or LEDs. One example that attracted a lot of media attention was Bono's/U2 *Laser Jacket* with 240 integrated lasers, designed by Moritz Waldemeyer in 2009 (see Fig. 13.1). In the same year, the engineer-cum-designer, as Waldemeyer calls himself, created Rihanna's *Laser Shoulder Pads* with

Fig. 13.1 Bono performing in his *Laser Jacket* during the U2 360 tour, 2010. Photograph by Brantley Gutierrez (c). Image courtesy of Universal Music

more than 50 integrated lasers. In 2010, he collaborated with the French fashion designer Alexandre Vauthier for making the *LED Dress* Rihanna wore during her UK tour. In the years after, Waldemeyer produced more LED-illuminated stage wear, e.g., the *LED Jackets* for Take That, Will.I.Am/Black Eyed Peas and Ok Go.

Another pop star who surprises the public regularly with her fancy stage costumes is Lady Gaga. In 2010, she wore the *Living Dress* that changes its appearance (retractable and fluttering skirt, opening wings on the back, morphing hat) during her shows (see Fig. 13.2). It has been created by fashion designer Vin Burnham and animatronics designer Adam Wright. In 2013, Lady Gaga presented the *Bubble-Blowing Dress* that has been designed by Studio XO at a festival. This piece is a body architecture, as one of the creators calls it [24] and houses some 3D-printed bubble machines. Also in 2013, Studio XO was involved in the production of Lady Gaga's *Flying Dress* an interactive costume in which the artist really flew. The creation of this high-tech dress was the teamwork of fashion designers, engineers and pilots.

The works of fashion-tech designer Anouk Wipprecht are similarly interesting. In 2011, she cocreated an illuminated stage outfit with stylist Bea Akerlund for Fergie, the singer of the Black Eyed Peas. Together with other experts, they designed everything from the shoes enclosed with emitting materials over a Swarovski-twinkling belt to an LED-covered top. In 2014, Wipprecht made interactive costumes for the performance group Cirque Du Soleil in collaboration with Italian architect Niccolo Casas and 3D-printing experts. These performance outfits consisted of 3D-printed shoulder pieces with remote-controlled high-power LEDs that had a strobe effect. In the same year, the fashion-tech designer herself presented the *Faraday Dress* during a music performance together with the band ArcAttack at the Maker Faire festival [25]. The dress functions as a Faraday cage while tesla coils shoot arcs onto the wearer.

Fig. 13.2 Lady Gaga performing in her *Living Dress* during The Monster Ball tour, 2010. Image courtesy of Samantha Jones, published at Flickr, CC BY 2.0

Fig. 13.3 *Snowfall Tutu*, The Nutcracker, Brooklyn Ballet, 2014. Image courtesy of Billie Grace Ward, published at Flickr, CC BY 4.0

Creating this piece was not only a fashion design challenge since millions of volts surrounded the wearer.

Another (inter)active costumes project presented here is a work done for the Brooklyn Ballet by the hacker collective NYC Resistor. The contribution consists of six LED tutus (see Fig. 13.3), hair clips, and a so-called Pexel shirt (see Fig. 13.4). The tutus for the ballerinas are to simulate a snowfall effect while being sensitive to their wearers' movements. For this, the team has integrated accelerometers at the

Fig. 13.4 *Pexel Shirt*, The Nutcracker, Brooklyn Ballet, 2014. Image courtesy of Billie Grace Ward, published at Flickr, CC BY 4.0

back of the corsets and connected it to two dozens of neopixels in between the fabric layers of each costume. The Pexel shirt that has LEDs on the chest and alongside the arms has been custom-made for the dancer. It contains four accelerometers in sum and lights up when the dancer flexes his muscles or moves his wrists. The hair accessories built with LEDs are not reactive to their wearers.

13.2.2 Further Considerations

Several research examples that are investigated in interactive theatre can be found in the literature. The majority of them explores interactive environmental technologies such as motion tracking [17, 18, 21, 26, 27] or reactive projections [17, 20, 21, 28]. Likewise, interactive projections are very popular and often used in dance performances [20, 21, 23, 29, 30], sometimes combined with motion sensing technologies, too [23, 29]. Some examples make use of offstage operations [17, 18, 30], so that the audience cannot see the performer or technical operator, but it can perceive the onstage reaction, e.g., sound changes or influenced screen projections. Other performances even involve the audience to interact with the stage events and influence the outcome of the play or dance show [26, 28, 29].

An approach of practice-based research presents design principles for creating and staging interactive technologies for dance performances concerning the perceptibility by the audience, the enhancement of a performance, the aesthetics, the dramaturgy and the production process [20]. Here, costuming is a minor focus but since (inter)active costumes can also be characterized as reactive technologies it has relevance. Previous publications of the same research group consider costuming when analysing several dance production processes [21].

The creation process of (inter)active costumes has been examined in a case study where the authors combined the traditional costume design process with an interaction design methodology [22]. The resulting procedure proposes, in comparison with the traditional costume design process as described in Sect. 13.3.2, to finish the first prototype already in the pre-rehearsal period, test and improve it during the rehearsal phase, and be ready with the (inter)active costume when the dress rehearsal takes place. This restructures the usual production phase. Furthermore, it demands a closer collaboration between designers and engineers, and it involves the users at an early stage in order to include their feedback into the design cycle. Another longitudinal research investigates interactive technologies and dance [20, 21, 31]. As already mentioned, some of their inspected dance tech projects also made use of wearable technologies. Here, the authors point out that the costume's production requires more time than usual costume design [21]. They also suggest finishing the costumes early enough for testing purposes and state that dancers need costume rehearsals earlier than one week before the opening night. The investigations of my research group have revealed similar ideas [6, 9].

Some previous studies survey factors of wearability [32, 33]. Although these works have been removed from the context of use, they provide interesting insights into the research on (inter)active costumes. They propose guidelines for designing wearables comprising criteria such as size, shape, weight, location, interaction comfort and aesthetics [32]. While others concentrate their research on psychophysical factors of wearability such as pressure, texture, thermal balance, moisture transport and freedom of movement [33]. These criteria may all be relevant when focusing on the wearer's perspective, how they adapt to (inter)active costumes, how comfortable they feel when wearing them or how they handle the functions of technological costumes.

Other works in the field of theatre and ballet concern working tools for costume designers and choreographers, or dance teachers. One of them analyses the use of images by costume designers for collecting ideas and communicating them to other departmental responsibilities [34]. Their research results propose guidelines for a costume designer's digital workbench. Other practices examine the use of interactive applications for giving elaborated feedback to dancers about the accuracy of their poses and positions [35, 36]. Thereby, the used technologies follow different approaches. One proposal makes use of an e-textile garment for learning ballet techniques [35], another applies motion tracking for comparing a dancer's movements to pre-recorded images in order to give feedback similar to a studio mirror [36].

13.3 Understanding the Creation Process

Designing (inter)active costumes adds new and unusual tasks to the creation process. Technical features need to be considered already during the ideation and concept design. In the crafting period, electronic knowledge is required for implementing them, and when the show runs, (inter)active costumes have to be maintained. This section asks who is part of the team that creates an (inter)active costume and how responsibilities are split up. The first part gives insights into the applied research methods. The second part shows that the creation process of (inter)active costumes strongly depends on the project's conditions whereas the traditional creation process follows a strict and well structured procedure.

13.3.1 Methodology

To develop a deeper understanding of how smart costumes are created in professional contexts, I follow different approaches in my research. First, I collaborated with a local theatre house where I assisted in developing electronic components for costumes in two productions. Through this experience, our research group (HCI group, Bauhaus-Universitaet Weimar) gained insights into the creation and staging of costumes in a real-life theatre setting [9]. Second, the same research group developed and staged interactive costume prototypes within an interdisciplinary university setting [6, 9]. That enabled us to run through the whole process, from ideation over design and technical development to rehearsing and staging. Third, for my ongoing research I conduct and qualitatively analyse expert interviews with people around the world that have developed interactive costumes for professional stage performances in the music business and in ballet. Based on our previous studies, I conduct focused conversations on their experiences in developing (inter)active costumes or extract related information from existing interviews conducted by others.

13.3.1.1 Ethnographically Oriented Action Research

Getting a realistic impression of how professionals create and stage costumes is one of my main interests. Thus, I joined two productions as participant-observer [37] at a small theatre house that is open-minded to stage interactive costumes. The theatre's departments are traditionally structured, and creative responsibilities such as costume or stage design are clearly separated from technical areas such as lightning technics or sound engineering, though certain crafting expertise (e.g., tailoring) is affiliated to them. This type of inquiry is to be understood as action research because the contribution was carried out in a collaboration with a community partner [38]. It enabled our research group to investigate the infrastructure of professional theatres and define further needs for creating and staging (inter)active costumes [9].

I worked as intern in the video department of the theatre house during the first production. Coincidentally, I got the chance to develop electronic components for a costume after a conversation with the costume designer and the director. The costume was a ready-made version of a panda bear whose eyes should glow red in certain situations on stage (see Fig. 13.6). Thus, I participated in the creation, rehearsing and staging phase, and I was able to record everything in a working diary for qualitative analysis afterwards.

For the second production, I was invited as external designer to assist in realizing an interactive costume. The costume, a custom-made fat-man suit, should smoke out of different orifices (see Fig. 13.6). It was my task to develop a technical solution for the costume while mediating the interests of the creative department and the technical area.

13.3.1.2 Research In and Through Design

The best way to understand the process—from finding the right idea over developing appropriate designs, and integrate smart technology into costumes, to finally bring a production on stage—is to practice it. We, the HCI group at Bauhaus-Universitaet Weimar, chose an university setting for creating and staging a theatre piece that contains interactive costumes [6, 9]. This gave us the possibility to orchestrate the content, the used materials and technologies as well as the time frame for the entire production. Our research concerned the design process itself and, at the same time, the designed objects helped generating insights. Hence, this self-directed procedure can be identified as a research-in-and-through design process [39].

During this project, the creation of interactive costumes was the main focus. It has been developed over one semester with an interdisciplinary and international student teams consisting of people studying applied computer science, product design or media art and design. In addition, we collaborated with an external drama educator/theatre pedagogue practitioner who led an introductory workshop and directed the final phase where we brought everything onto the stage. The project kicked off with a visit in a local theatre with the goal to get a deeper understanding what costumes are. We continued in the ideation phase with a body-storming session and elaborated material researches. After having developed the interactive costumes hand in hand by designers and engineers, this project ended with a user evaluation. Semi-professional actors tested everything while rehearsing and staging it. In doing so, we indirectly observed them via video recordings and conducted semi-structured interviews afterwards.

13.3.1.3 Expert Interviews

Continuing the research, I conduct semi-structured interviews with experts in the field. The interview partners are selected according to their projects and experiences in designing and crafting interactive costumes for professional stages. They are fashion or interaction designers, engineers, computer scientists, costumiers or people who have experienced both the creative side and the technical side of such a process. Their project experiences range from costume design for pop stars and fashion shows, to ballet and theatre-like performances. In the majority of cases, I contact them via email, explain shortly the subject matter of my research (investigation on the creation of interactive costumes) and ask them for a video call. The duration of each interview is between 20 and 90 min depending of the availability of the interview partner. With permission of the interviewee, I video-record every conversation in order to be able to do a qualitative analysis of the transcripts later on. Their profession and role during the creation process in mind, I ask them questions such as follows:

- how their textile artefact works in detail,
- what kind of fabrics, materials and electronic components have been used,
- what was first in the ideation and development phase - fashion or technology,
- with whom they have collaborated and what the tasks have been like,
- how long the different phases (ideation, design, technical development) lasted,
- what difficulties did appear and how did they finally solved it,
- what was different in comparison with a traditional costume design,
- who was responsible for the maintenance before, during, and after a performance,
- who introduced the costume and its functions to its wearer, and how,
- how much rehearsal time was needed, or
- how many times/how long has the costume been on stage.

In addition, I analyse interviews of high relevance that have been conducted by trade journals, online tech platforms or other practitioners in that field. Although they do not include exactly my set of questions, those interviews often address similar key aspects and obviously document-related experiences. This approach completes the knowledge our research group could generate through practice-based research-in-and-through design and ethnographically oriented-action research. I am able to compare our own practical experiences with those of the different applications the professionals have achieved around the world.

At the time of publication of this article, I base my analyses on five interviews covering the creation of more than ten (inter)active costumes.[1] I conducted two initial interviews with engineers that are aware of design issues. One has experiences in the creation of wearables and (inter)active fashion for celebrities for more than ten years. He reported about different creation processes, ranging from realizations for fashion designers, over the making of stage outfits for pop stars, to remittance works for private clients. The other was and still is a leading technician who develops and improves different (inter)active ballet costumes in close collaboration with the creative responsibilities. Furthermore, I have analysed three other expert interviews found online [25, 40, 41] until this publication. They also concerned the creation of stage outfits for pop stars or performance groups.

13.3.2 Challenging Traditional Structures

My research tries to outline how (inter)active costumes can be built for and applied to professional stages such as established theatre or ballet houses. For this, I take other

[1]The creation process of these (inter)active costumes was not always discussed or explained in detail for every single phase (ideation, development, staging, maintenance) but at least for interesting points regarding the challenges and innovations when creating (inter)active costumes.

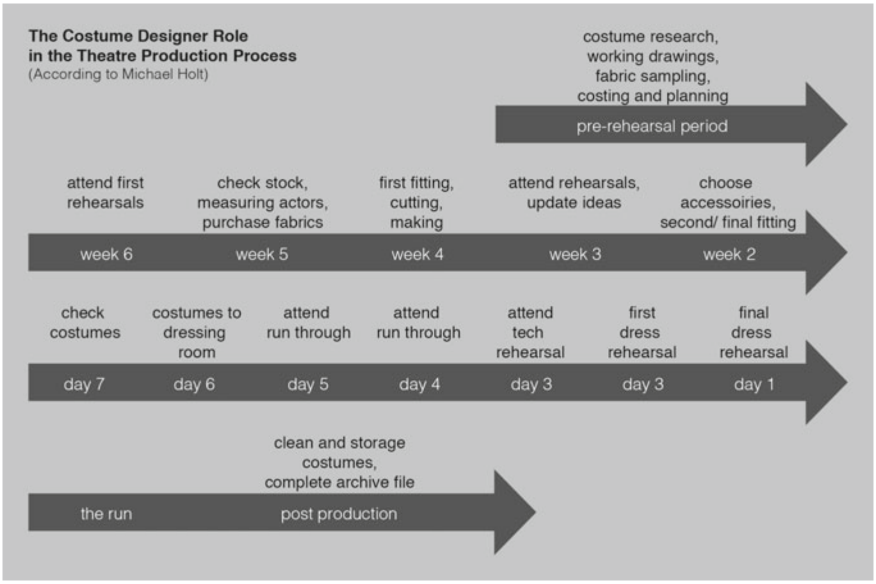

Fig. 13.5 The traditional production process in theatre from a costume designer's point of view. Illustration adapted from Michael Holt (compare [3]). Graphics by Michaela Honauer. Image courtesy of HCI Group (c), Bauhaus-Universitaet Weimar

professional stages, like performances of pop stars, into account because lots of examples that make use of (inter)active costumes during a show (compare Sect. 13.2.1) do already exist there. I investigate how those have been created and compare it to the traditional costume design process in theatre.[2] In this subsection, I describe the results explored through my research group in an ethnographically oriented action research and a research-in-and-through design process in comparison with the preliminary findings of the initial expert interviews (see Sect. 13.3.1).

13.3.2.1 Costume Design Process in Theatre

The traditional costume design process in theatre follows a predefined structure as shown in Fig. 13.5 (compare [3, 4]). It is characterized by a pre-rehearsal period, the rehearsal period, the run period and the post-production period. Pre-rehearsal, run and post-production have a more or less defined time frame depending on the house's practices or the duration of a season and the pausing. The rehearsal period is almost the same at all theatre houses. They are strictly organized for all departments over six weeks.

[2]Here I assume that the creation process of costumes for ballet is similar to the process in theatre.

Fig. 13.6 The two costumes where we added reactive technology for a local theatre house. *Left* Theaterhaus Jena *The Panda Show*, a panda mask with *red*-glowing eyes, initially activated by the actor through a push-button, finally staged with a simple on–off button. *Right* Theaterhaus Jena *King Ubu*, a fat-man suit that can smoke out of its armpits and rear, finally staged without the smoking feature. Photographs by Michaela Honauer. Image courtesy of HCI Group (c), Bauhaus-Universitaet Weimar

I experienced the same for the collaboration with a theatre house where they called it production period. It took exactly six weeks and was well organized from the first day until the opening night. Fixed deadlines and creative/stage/production/technical management meetings were predetermined but in between the departments[3] were relatively free to organize their daily business and focus in particular on specific priorities as long as they reached the given goals.

In the two real-life examples at this theatre house, the concepts of the (inter)active costumes were both based on the costume designer's initial visions (see Fig. 13.6). She had ideas in mind but she was not able to realize them on her own because she lacked the technical knowledge and was too busy creating all the other costumes. So it became my task to work on it. Unfortunately, the costumes were already designed and the challenge was to integrate the technical components afterwards. After discussing the ideas for the implementation with the creative staff (costume designer, tailor) and technical staff (light technician, electrician), I built low-fidelity prototypes for checking if the concepts had the desired effect and then I finalized the costume prototypes. Until a few days before the show was played the first time, I mostly had separate meetings with the tech or creative staff. That hindered the creation of the (inter)active costumes enormously because it took too much time and I was always mediating between the interests of both parties. With regard to the traditional process

[3]The departments are administration, direction, production management, stage management, scenic design and construction, lightning, sound and costume design [3].

(Fig. 13.5), a costume designer usually has the first intense contact to the tech team during the tech rehearsal three days before the performance runs. This led to the fact that one of the two (inter)active costumes did not work properly during the trial run of the performance two days before opening night. In case of the panda mask, we were able to find a solution shortly, and for the fat-man suit, we did not because it was technically much more complex. Another issue was the missing rehearsal time with this new kind of costume. The actors were in general sceptical and did not get familiar quickly enough with the tech features. In addition, one actor had safety concerns. For these reasons, the director finally decided not to use the smoking feature although he initially supported the idea of staging (inter)active costumes.

13.3.2.2 Process of Individual Costume Designs

The Process of the University Setting

The self-directed student project my research group has conducted within a university setting evolved quite differently in comparison with the design process I have experienced at the theatre. Already in one of the first meetings, we mixed up interdisciplinary teams consisting of two or three students each with at least one technology and one design student in. The reason behind this decision was to force the development process to be done hand in hand by tech and design know-how from the very start. It was a fruitful collaboration we established inside each team. The interactive costumes project resulted in the creation of three costumes for Jules Verne's *Twenty Thousand Leagues under the Sea* (see Fig. 13.7). The ideation process took about four weeks. Design and tech students developed their costume ideas together with equal emphasis in the creative and electronic area.

Fig. 13.7 **a** *The Octopus Sea Creature* can move two tentacles at its front through motorized skeletons and has a glowing brain for expressing its moods. **b** *Captain Nemo* has a living robe which can glow in the dark and vibrates if someone comes closer to the integrated distance sensor. **c** *The Diving Suit* has a fin-like pattern that glows *blue* or *white* according to sea or land mode and wears an oxygen tank which can be controlled via a display on the suits glove. **d** All costumes in the dark. Photographs by Marko Schmidt/Jena. Image courtesy of HCI Group (c), Bauhaus-Universitaet Weimar

Continuing this, the crafting process of the interactive costumes project also turned out to be a balanced tech-design development since the designs of the costumes were unfinished until the electronic features have been merged into it. In other words, the engineers influenced the costume designs, and the designers influenced the technical development. Additionally, both sides learnt from each other, and hence, design students were able to understand the technical details, and engineers developed an understanding for design. The development phase took about ten weeks.

Finally, when the rehearsals started, all team members were in charge of maintaining the interactive costumes and explaining the features to the actors and the director. Of course, and this is in the very nature of each profession, the people of the technical study programme took care of the electronic components and the design students were busy with the aesthetics of the outcome. Although some features did not (yet) work at that time, the actors were at least able to imagine them. They were very open-minded and curious to experience the interactive features. We realized that they indeed needed more time to get familiar with their costumes than they usually would do. But after a rehearsal session that was dedicated for getting trained with the interactive features, they got it and could continue rehearsing the piece. Additionally, the actors gave us interesting feedback. But they also detected weak points in our concept designs since they had quite a different perspective on the costumes as users and wearers. We realized staging the costumes within a two-day workshop. The first day was needed for preparations, and on the second day, we had intensive rehearsals for many hours. A 5-min internal improvisation was intended as performance result of this project.

The Processes Described by Experts

The expert interviews I have conducted and analysed so far revealed that no creation process was like the other ones. The creation of every single costume I have looked at proceeded differently depends on the individual conditions, the involved persons and the desired outcomes of each project. The general idea for an (inter)active costume came in most cases from the wearer him/herself, from the stylist or from the stage or creative director. They had an abstract concept in mind, and thereupon, it was worked out more precisely towards a real concept design by a fashion designer or an engineer who has also sophisticated know-how or extensive experiences on the design side. In one case, the wearer was also the designer of the costume and additionally she came along with an elaborated technical knowledge for developing the interactive costume.

For all examples, it is not really clear how long the phases of ideation, design and development have been as they often merged into one another. Some projects had to be finished in only a few weeks, while some took half a year, and others turned out to be further developments of earlier prototypes. But the time given possibly influences the design and/or the tech concept. For instance, if a team has only two weeks until the costume is to be staged, then the realization will be quick and dirty, and probably, it is not as stable and elaborated than it would have been if they had more time.

All interviewees described a close teamwork of design and technological responsibilities. Depending on the composition of the team, the collaboration between engineer and either stylist, or stage director, creative director, choreographer, fashion designer or tailor was characterized by frequent consultations for a better mutual understanding and resulted in an iterative procedure. The engineering teams were smaller (one or two persons) or bigger (three or more persons), and accordingly technical work was split up into subtasks depending on the budget and the complexity. One interview partner explained that the engineering part could be outsourced as well. Then, the technicians have less influence on the concept design and purely try to realize the desired tech effects.

The question of what came first, technology or design, has been answered quite differently. In a few cases, the design was the first big step, especially when a fashion designer was involved. Nevertheless, the creation process was in the majority of the examples a back and forth between design and technological development. Only for one costume, the form followed function because the technology was dangerous to life and the physical integrity of the wearer had highest priority.

The last important phase I am interested in is staging and maintaining the (inter)active costumes. In almost all cases, the introduction to the wearers was shortly before opening night. The reason for this seems to be the high professionalism of the performers. I assume that a tight time schedule may also have relevance for this. Only in one case, there was a step-by-step fitting over a longer period. But usually, performers are trained to quickly adopt an outfit for their show and some even have a technical attitude, as one interviewee has described it. Similar as it is for the traditional theatre process, the interview partner who worked on ballet costumes said that tech rehearsals have been two days and dress rehearsals took place one day before opening night.

Depending on the project goal, the (inter)active costumes have been used either one time for an event or multiple times for a whole tour or a season. In one case, the costume has been used for about two years and the team had three versions of the (inter)active jacket. That enabled them to repair one or two, and to have always a backup version for the stage. During a performance, the costumes are usually used for a short period of time on the stage, e.g., for a few songs. But maintaining them is a crucial point for every engineer. Most (inter)active costumes had to be repaired constantly when the show ran since they were a kind of customized prototypes and not already an upgraded version of a previous project.

13.3.2.3 Summary

The previous paragraphs have pointed out that the creation processes of (inter)active costumes are as different as the costumes. Our research group followed a structured time schedule for the student project but it differed from the traditional costume design process complied within established theatre houses. In contrast, the expert interviews revealed that the creation of (inter)active costumes in real-life settings, such as the preparation of pop star performances, is always a customized process.

It depends on several factors, such as how concrete the costume idea is, if a fashion designer is involved, whether the computational part is outsourced, how big the team is and how much time is left for the development. Only for a ballet application, I found that the last steps of the procedure (time of tech and dress rehearsals) were similar to the one at theatre. But in comparison with my own experiences at a theatre where we had not enough time, where I mediated between creative and technical responsibilities and where the actors were not open-minded, the ballet costumes had much more time for the development period (about five months). Furthermore, in the ballet example the collaboration between creatives and technologists was characterized by a mutual understanding and the dancers enjoyed exploring this innovative type of costume. Nevertheless, the engineer wished to have more and earlier tech dress rehearsals in order to potentially avoid the high maintenance effort during the show.

All experts reported a fruitful interdisciplinary collaboration between the opposite responsibilities. This may be caused by the fact that the engineers had a distinct intuition for design, and the designers often had basic tech knowledge, or at least, they were open for a step-by-step creation which enabled the team to embed the electronic components properly into the clothes. This was similar in the study we have conducted in the form of a self-directed creation process with students. On the contrary, in our theatre study I was the mediating person who compromised the fixed structures of the different departments since the base for mutual understanding is not yet fully grown in traditional theatre. Concluding the gained insights, the creation of (inter)active costumes challenges the existing infrastructure at theatre [9]. A deeper collaboration between creative and technical departments is necessary at an earlier point. The traditional costume designers have to open up for electronic knowledge, and technicians need to engage stronger in design matters. Prospectively, thinking more and more interdisciplinary is as essential as the design–tech teamwork—one affects the other.

Likewise, the time given for creating an (inter)active costume differed in the studied examples. Time is an issue and has an impact on the design and technical concept. Furthermore, every creation of an (inter)active costume was customized. Traditionally, the costume designer has (only) six weeks for creating all costumes needed for a play. However, the discovered creation time of the (inter)active costume examples considered in this chapter referred in most cases to the production of only *one* (inter)active costume or in addition some more copies of it. I believe that the six weeks given through the traditional theatre structure is not adequate to create (inter)active costumes for a play, neither for creating more than one nor for creating one next to other conventional costumes. This can be substantiated by the studies conducted at a theatre house where staging (inter)active costumes failed because of insufficient time for the development, for the interdisciplinary collaboration and for rehearsing.

A last thing to point out here concerns the rehearsals with (inter)active costumes. The studies we have conducted within a university setting and within a real-life setting at a theatre indicated that actors need much more rehearsal time with (inter)active costumes than they would need with usual ones. Whereas the expert interviews emphasized that professional performer do not need more rehearsal time because as professionals they are used to wear any type of garment. They are able to quickly adopt them for their role as long as the interviewed experts provided them with detailed explanations about the (inter)active features, what happens and how. I have several assumptions why the results of our studies differ from this. One reason might be the fact that we worked with semi-professional actors in a laboratory setting at the university. Although they were open-minded and curious to explore our costumes' prototypes, they all had acting experience only next to their regular tasks as pupils, students or within another profession. The professional actors in the theatre setting seemed not to be open to work with (inter)active costumes. They found reasons why they constrained them in acting and concentrating on their role. On the contrary, the costume examples evaluated through the expert interviews were in the majority of cases the idea of the performers themselves or their creative advisors (stylist or creative director) who are people that take care of the performer's image. Hence, those performers were per se more liberal to show up on stage wearing (inter)active costumes. I believe intuitiveness of the (inter)active costumes is not a reason for this phenomenon because the experts negated it when asking how intuitive their creations have been.

13.4 Requirements for Crafting (Inter)Active Costumes

Based on the experiences I gained through the studies of my research group in the laboratory and in the field and based on the insights I achieved through the expert interviews (compare Sect. 13.3), the key aspects needed for creating and successfully staging (inter)active costumes on professional stages can be derived. These requirements might be essential for designers, engineers, stylists, creative directors, stage managers, actors, dancers or other staff members in the field of theatre or ballet.

13.4.1 General Costume Specifications

The described studies revealed that the creation of (inter)active costumes challenges traditional theatre structures (compare Sect. 13.3.2) because the scheduled production cycle mandatory for the design of costumes holds some constraints that inhibit an appropriate development, testing and rehearsing. Hence, crafting (inter)active costumes is a special case and actually forces to soften up the traditionally grown structures in theatre [9]. But the investigations described in this chapter also revealed that typical costume requirements already given for traditional costume design (compare [3]) endure and are important for (inter)active costumes, too. These are as follows:

- *Safety*: A costume must never be hazardous and has to ensure the physical integrity of its wearer and the people in the environment. This is a major issue, all other requirements are subordinated to it.
- *Robustness*: A costume becomes already very worn after a few hours of usage. For this reason, it should last excessive use on the stage during a season.
- *Cleanability*: A costume gets dirty through make-up, perspiration, stage blood, etc. Cleaning, drying and ironing it should be possible until the next show, or a copy of the costume should be available. Cleanability is related to robustness.
- *Aesthetics*: A costume is part of a whole performance. It should underline its mood, match up with the other costumes or elements of the show, and it needs to be visually pleasant.
- *Support of the role*: A costume is part of an actor's/actress' working tools. It should assist him/her in playing a character and express, e.g., a social status or historical contexts. Support of the role is related to aesthetics.
- *Changeability*: A costume can express the psychological or physical change of a character if needed. It should, for instance, demonstrate ageing or facilitate a body posture.
- *(Quick) undressing/dressing*: Sometimes an actor/actress has to change the costume during the performance. Then, the costume should not hinder a smooth execution of the whole performance, even if the appearance of another costume needs to be within a short time. (Quick) undressing/dressing is related to changeability.
- *Perceptibility*: A costume is to be seen and heard by the spectators independent of their location in the audience. Necessary details should not be too tiny or quiet.

13.4.2 Emerging Standards for Smart Costumes

The requirements described in Sect. 13.4.1 also have relevance for the creation of (inter)active costumes. The results of the investigations described in Sect. 13.3 emphasize that especially *safety*, *robustness*, *cleanability*, *aesthetics* and *perceptibility* are the aspects that need careful consideration [6, 9]. An (inter)active costume must be safe and never be dangerous for the wearer or the environment, and the concept of the embedded electronic features should prevent risky situations. Likewise, the integrated technology should be robust enough to physically survive the use on stage because actors cannot take care of it, they are busy with acting. Cleaning (inter)active costumes is also an issue since electronic components are usually not washable.[4] It makes sense to design the computational components in a way that the technology is easily removable for the purpose of cleaning. Furthermore, an (inter)active costume should be aesthetically pleasing. Included tech components such as wires,

[4]Some manufacturers, like those of the LilyPad Arduino, claim that their sewable electronics are washable, but they propose to clean them carefully or manually. The expert interviews discovered that this will not work in every case. Additionally, I think the maintaining procedure behind the stage is not (yet) prepared to clean computational clothes.

microcontrollers or battery packs should be hidden instead of distracting the spectators with unnecessary details. The (inter)active effects are to be perceivable for the audience members, e.g., it makes no sense to use a few not very bright LEDs that cannot be seen from the last rows in the audience or that are washed out by the stage lightning. Above that, there are some more conditions that are important for the production of (inter)active costumes. These are:

- *Functionality*: The idea behind an (inter)active costume should be translated properly into a customized solution. The defined specifications should result in a reliable construction with consistently working functions and expectable interaction qualities for the actor/actress. Functionality is related to robustness.
- *Prototyping*: An (inter)active costume needs much more time to be designed and engineered than the creation of a conventional costume requires. Thus, ideation and development should start earlier (in the pre-rehearsal period) to ensure a working prototype that can already be tested and improved when the rehearsals start.
- *Interdisciplinarity*: An (inter)active costume is the symbiosis of fashion design and physical computing. A mutual understanding on both sides is absolutely necessary for succeeding, designers and engineers should work together from the beginning. Interdisciplinarity is related to prototyping.
- *Rehearsing*: Wearing and testing an (inter)active costume is essential in order to identify weak points in the concept design and to give the actor/actress the chance to get familiar with it. The wearer's feedback may also be helpful for the production cycle. That is why rehearsing with the (inter)active costume should commence early enough. Rehearsing is related to prototyping.
- *Maintenance*: Maintenance is related to cleanability but using an (inter)active costume for stage performances over a seasonal period of time means not only that it has to be cleaned. Staff members need to charge batteries, and possibly modify or repair electronic features. That should not be too difficult or time-consuming in comparison with other maintaining cycles, and responsibilities should be assigned clearly to a person's profile inside the institutional structures.

13.5 Conclusion

Designing (inter)active costumes is to be approached carefully because building costumes with integrated tech features impacts the creation process and staging. I have shown how this influences the whole production process, and challenges traditionally grown infrastructures as well as given procedures in theatre (Sect. 13.3.2). Considerations have to be made with respect to all involved parts—the costume design, the technical development, the integration of both, the actors as wearers, the staff that takes care of the costumes' maintenance and of course the overall gestalt of the performance. The requirements of (inter)active costumes extracted in Sect. 13.4.2 are especially important for performances on professional stages such as theatre or ballet.

The final outcome of a piece has high priority for every production and the (inter)active costumes need to support the message as well as the aesthetics of the overall show. A performance is made for the audience who acknowledges its value. (Inter)active costumes should create emotions and the spectators should be able to recognize the (inter)active effects of the costumes whether visually, acoustically or with any other sense.

Further, an (inter)active costume is part of an actor's/actress' work equipment and has to underline the role he/she is playing. It must be safe and work reliable. The technical operations have to cause predictable effects for the wearer and the components need to be embedded properly. Acting with an (inter)active costume needs to be as easy as it is to act with a conventional costume. Triggering the (inter)active effects must not catch an actor's/actress' full attention. Dressing and undressing has to be uncomplicated and, if needed, quick changes have to be possible.

If actors have only little sense of (inter)active costumes, more rehearsal time than usually is needed. An actor/actress has to rehearse the (inter)active costume and explore its features. Early dress rehearsal informs the design and development process since the users' feedback can reveal necessary changes a designer or engineer cannot imagine. Furthermore, (inter)active costumes are to be built interdisciplinary by designers and engineers. The earlier creatives and technicians come together, the better the integration of computational elements into the garments will turn out. Being open-minded for the other side is needed to gain a mutual understanding. Likewise, a costume has to allow for cleaning and technical components need to be pluggable. The creators of an (inter)active costume should keep close contact to those staff members that help crafting (e.g., cutters and stitchers), staging (e.g., light and sound technicians) or maintaining (e.g., wardrobe assistant and dresser) it.

The insights gained in this chapter may also have relevance for the creation of smart clothing in other application fields. Some of the outlined requirements, such as functionality, interdisciplinarity and maintenance, are similarly important when creating, for example, smart garments for sport or medical purposes. Future research may survey their importance and relevance for other areas. For instance, e-textiles for sport and medicine might also need to be functional and work properly. Some of the descriptions used in this chapter might then have slightly changed terms and meanings. Nevertheless, it makes sense if interdisciplinary teams (consisting of, e.g., medical scientists or sports therapist, engineers, fashion designer and patients or athletes) build the textile application collaboratively, and maintaining the clothes should whether be described in detail in a kind of manual or to be done with the support of experts.

Summary

(Inter)active costumes are clothes with integrated tech features worn by actors, dancers or singers at the stage. This chapter analyses the design process of this innovative type of costume. Introductorily, it overviews related works and outlines the lack of research on the design process of (inter)active costumes. By giving a few examples, this chapter further shows that (inter)active costumes are already being used in professional environments for many years. Nevertheless, the described studies and the preliminary results of initial expert interviews reveal that the creation of (inter)active costumes comes along with individual conditions and requires in almost all cases an adapted procedure. This challenges especially the traditional structures of theatre since the design process of conventional costumes is incorporated in a fixed schedule, responsible designers have a poor tech knowledge and collaborate lately with the technical staff.

Moreover, this chapter lists traditional costume requirements. These are *safety*, *robustness*, *cleanability*, *aesthetics*, *support of the role*, *changeability*, *(quick) undressing/dressing* and *perceptibility*. They are equally important for the design of (inter)active costumes. Our practice-based research found that *functionality*, *prototyping*, *interdisciplinarity*, *rehearsing* and *maintenance* are additional requirements when creating (inter)active costumes. They address the whole creation process, from ideation, over design and development, to staging and maintaining (inter)active costumes. This might support future projects in the field of theatre or ballet and enable these institutions to soften up their infrastructures.

Acknowledgements Thanks to Theaterhaus Jena and, in particular, costume designer V. Bleffert, who offered collaboration to us. Thanks to our enthusiastic project students (H. Abitz, G.D. Acay, M. Al-Hallak, S. Gottschlich, S. Luge, W. Mueller, T. Rueckert, H. Sahibzada and M. Schmandt), the drama educator/theatre pedagogue practitioner J. Hahn, and the actors (R. Ecker, C. Kneisz and M. Oehlke). The Frauenfoerderfonds of Bauhaus-Universitaet Weimar supported the interactive costumes project with funding. Furthermore, thanks to M. Waldemeyer and N. Vermeer who offered interesting insights into their professional projects. Last but not least, thanks to E. Hornecker for supporting my work.

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Chapter 14
Textile Building Blocks: Toward Simple, Modularized, and Standardized Smart Textile

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Abstract Textiles are pervasive in our life, covering human body and objects, as well as serving in industrial applications. In its everyday use of individuals, smart textile becomes a promising medium for monitoring, information retrieval, and interaction. While there are many applications in sport, health care, and industry, the state-of-the-art smart textile is still found only in niche markets. To gain mass-market capabilities,

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S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_14

we see the necessity of generalizing and modularizing smart textile production and application development, which on the one end lowers the production cost and on the other end enables easy deployment. In this chapter, we demonstrate our initial effort in modularization. By devising types of universal sensing fabrics for conductive and non-conductive patches, smart textile construction from basic, reusable components can be made. Using the fabric blocks, we present four types of sensing modalities, including resistive pressure, capacitive, bioimpedance, and biopotential. In addition, we present a multi-channel textile–electronics interface and various applications built on the top of the basic building blocks by 'cut and sew' principle.

14.1 Introduction

Smart textile provides additional functionality over classic textile materials by changing properties under physical or chemical stimuli, or providing monitoring and interaction features. Although smart textile has formed a solid area in wearable computing and ambient intelligence domains, with wide applications in sport, industry, health care, it is facing a chicken-and-egg problem: For the devices to be widely deployed, the price must come down, but for the price to come down, the devices must be mass-produced, i.e., widely deployed. Frequently, smart garments have been presented as single-purpose textiles with sensing and actuating capabilities that fit a desired use case. In this chapter, we report an approach to build whole-body sensing systems for interaction, physiological monitoring, and activity recognition. The work is inspired by the current fabrication processes used in the textile industry, which generalize and modularize textile and garment production. Thus, mass production could greatly reduce cost.

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14.1.1 Smart Textile as Building Blocks

The traditional textile industry has established countless applications of textiles, such as clothes, furniture covers, packaging material, carpets, and curtains that pervasively surround us. All types of textiles stem from a single component: fiber, which can be considered as the basic building block, out of which the mansions of textile applications are built. Whatever the final application is, traditional textile industry is segmented into four layers: fiber, yarn, fabric, and clothing. For example, cultivating and harvesting gives the cotton fiber, spinning turns fiber into yarn, weaving turns yarn into fabrics, and cutting and sewing gives a final jeans. A core principle that enables textile industry, or even the whole modern industry to function, is the division of labor, where:

1. Production process of a final product is divided clearly into several steps.
2. The methods used within each production step are limited.
3. The latter step, i.e., child step, takes the result of former steps, i.e., parent step, as building blocks. A child step cares mainly about the received building block characteristics and ask questions such as how it can be used. Production details of the former step, i.e., how it was made, are not important to the child step.
4. The category of functionality grows exponentially starting from the basic building blocks until the end products.

Taken traditional textile industry as a successful example, we expect the smart textile production to utilize similar procedures, should it go beyond laboratory prototypes or niche products of small-sized companies.

We envisioned that smart textile production can be divided into four building blocks [1]: Sensing fabric, garment, processing platform, and applications. Figure 14.1 shows the building blocks. First, mass-producible generic sensing fabrics are developed. Based on these fabrics, 'sensing-ready' garments can be made that are with respect to their properties, looks, production process, and price, virtually indistinguishable from today's standard garments. The new smart garment functions as one sensor, one sensor array, or combination of multiple sensors and sensor arrays.

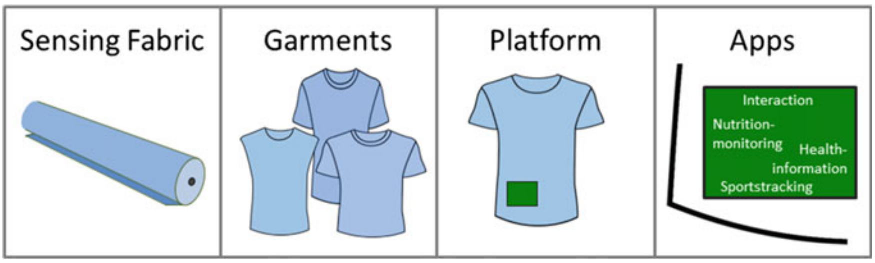

Fig. 14.1 Separation of the smart textile production process into fabric, garment, platform, and application

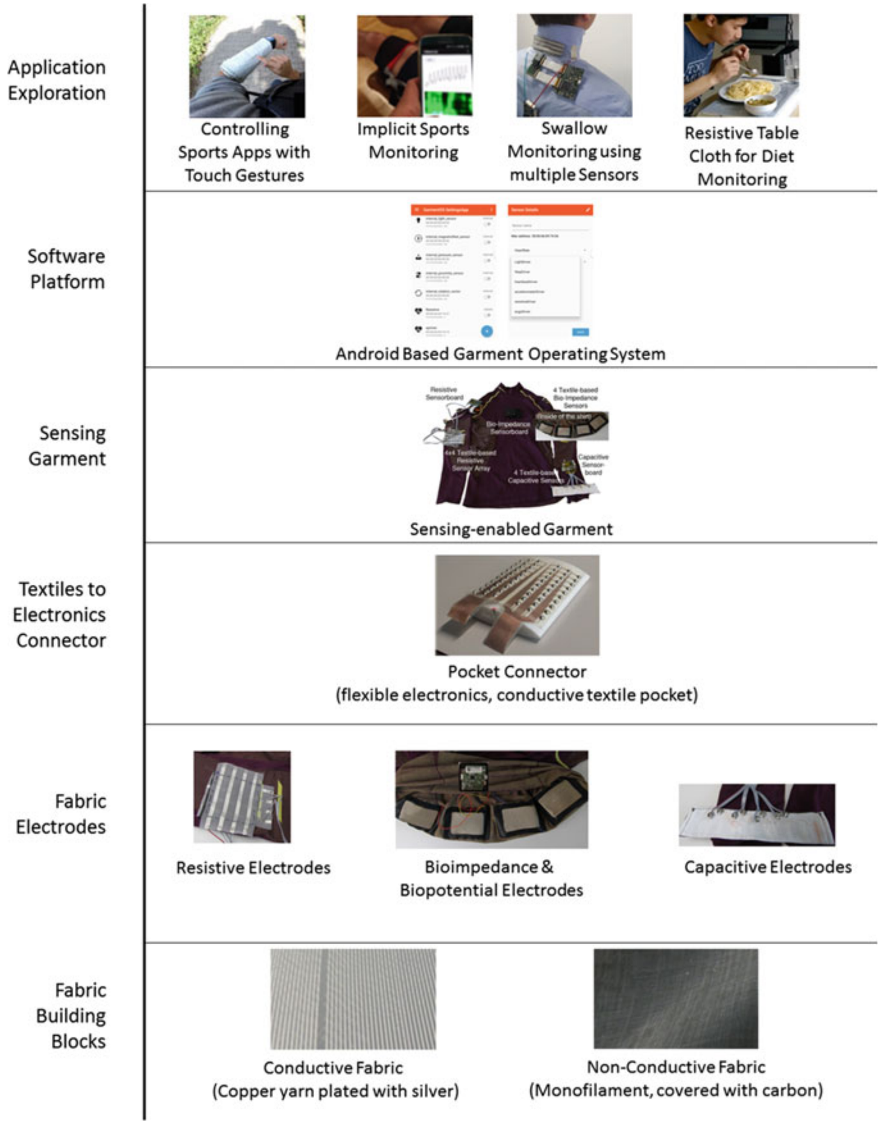

Fig. 14.2 Smart textile building blocks as developed in the SimpleSkin project: Fabric, platform, and garment are considered as building blocks that enable a variety of applications

By adding a sensor data processing hardware, it becomes part of an unobtrusive computing system that dynamically and adaptively processes input signals. A large variety of applications are thus created from limited types of fabrics and processing platforms. After 3 years of development within the EU FP7 project SimpleSkin, we have realized and standardized three blocks: two types of general sensing fabric, four instances of a processing platform, as well as methods for creating smart garments and textile–electronics interface out of the general sensing fabric. This chapter reports on the progress and applications that we already explored. An overview of the realized concept is provided in Fig. 14.2.

14.2 Related Work in Smart Textile Building Blocks

Frequently smart garments have been presented as single-purpose textiles with sensing or actuating capabilities that fit the desired application. One of the early examples is the sensor jacket [2]. Using 11 knitted stretch sensors placed over the joints served the authors to detect the user's upper-body posture, motion, and gestures in real time. Lorussi et al. built piezoresistive textile sensors by applying conductive polymer or carbon-filled rubber [3]. The strain-sensing fabric was implemented in sleeves, knee pads, and gloves to detect the posture of the arm, leg, and hand, respectively. Mattmann et al. proposed elastic strain-sensitive yarns and showed how the sensors could be used in monitoring back posture and sports movements with minimal hysteresis effects [4].

Smart textiles to monitor physiological data are among the most unobtrusive solutions to estimate health status continuously and in everyday life. The electrocardiogram (ECG) was widely explored as it is relevant for many applications. MagIC [5] is a smart garment for measuring the heart rate and respiration rate. It utilized two woven electrodes that obtained the ECG signal and a transducer measuring changes in thorax volume to assess the respiration rate. Paradiso et al. presented the WEALTHY system [6], combining movement detection via piezoresistive yarn sensors and fabric ECG electrodes. Several mechanical and chemical optimizations of fabric electrode were investigated in the MyHeart project, along with signal processing methods, to optimize the ECG signal obtained in daily life and sports settings [7]. A further example for garments measuring physiological properties is the SmartShirt by Lee and Chung [8]. In addition to ECG, the SmartShirt featured accelerometers that could be used for fall detection. However, one of the first approaches of a multi-purpose sensing garment was the Georgia Tech Wearable Motherboard [9]. The Wearable Motherboard garment was used for various physiological measurements, but not necessarily textile sensors, by providing plug-in interfaces for different sensors as well as preprocessing and communication possibilities [10]. Subsequently, Harms et al. introduced SMASH, a smart shirt with a network of generic processing units and wire-based communication channels built into a smart garment. The smart garment could be used with different sensor types via plug-in interfaces, while the generic processing infrastructure served to extract features from the sensor data [11].

Similar to the mentioned multi-sensor smart garments, we focus in this chapter on combining different sensing technologies that can be used as building blocks for creating smart garments. However, we investigate fabric sensor construction and mass-producible smart garments.

14.3 Universal Fabric

The very basic building block for smart textile is the generic sensing fabric. Depending on sensing principles, various weaving types have been used to produce appropriate fabrics. These fabrics consist of non-conductive, high-conductive, and semi-conductive fiber woven in the precisely defined directions and fabric patterns. In this section, we will show how the fabrics are produced in general and how the first fabric prototypes were prepared and used for sensing in SimpleSkin. The main challenge is to find proper material and processing method, based on which the fabric can be cheaply mass-produced at a high speed and simultaneously support multiple sensing modalities.

14.3.1 Fabric and Weave Types

Weave fabrics are textile products with a regular flat surface and are produced by means of weaving technology. The yarns running lengthwise along the weave direction are called warp yarns and the transverse ones weft yarns. The way in which the warp and weft yarns pass over and under each other is known as the weave. The number of yarns after which the weave pattern in the warp (x) and weft (y) directions repeats itself is called a repeat x:y weave. Warp, weft, and weave define the structure of a fabric. Three basic weave types are distinguished: plain, twill, and satin weave. Figure 14.3 provides an illustration. The simplest weave type is the plain weave with a repeat pattern of 1:1. It is symmetrical in both directions; warp and weft yarns are alternating going over and under each other. In twill weave, the weft yarns 'skip over' more warp yarns (and vice verse), resulting in a specific pattern. A similar structure arises in the third basic weave, satin weave, where warp passes over even more wefts and the points at which neighboring warps pass under the weft are not in physical contact with each other. The satin weave produces a particularly smooth surface. An even more complex technical fabric is the double-layer weave (DLW), which consists of two interwoven layers of fabrics comprised of yarns of different or equal thickness.

The manufacture of a product made of precision fabrics is composed of numerous process steps that fall under the two major production stages: (1) Fabric production—

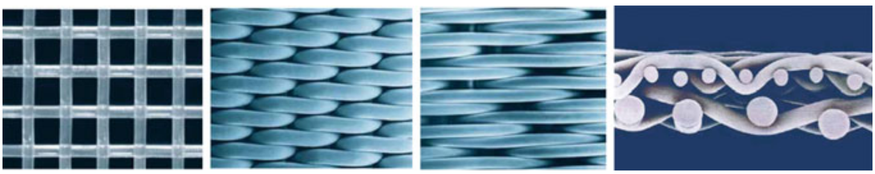

Fig. 14.3 Weave types from *left* to *right* plain, twill, satin, and double-layer weave (DLW)

involving warp preparation, drawing, mounting the warp on the loom, and weaving. (2) Finishing and making-up. Additional processes such as dyeing, heat treatment, calendaring, or processes to change surface properties, e.g., comfort, hydrophila, and abrasion resistance, are then added according to the application of the fabric. For details, see the work of Goenner et al. (Chap. 2).

14.3.2 Conductive Fabric Types for Multi-functional Sensing

Conductive fabrics are split into two branches: (1) Fabrics—whose conductive properties are embedded during manufacturing, e.g., weaving of metal wires; and (2) fabrics that are not intrinsically conductive, but their conductivity is enabled after manufacturing, e.g., by weaving, knitting, using an additional process.

A non-conductive fabric usually consists of polymer yarns such as polyester or polyamide, whereas conductive components ideally utilize good conductors such as silver and copper wires. The thin metal wire is treated as a separate thread. Using the conductive thread approach, no additional step after fabric manufacturing is required to establish conductivity.

14.3.2.1 Fabrics with Conductive Stripes

In general, all fabric samples in SimpleSkin were woven using 64 μ PET monofilament fibers in the warp and weft direction. The electrical conductor used was a silver-plated copper yarn consisting of 12 single wires, each 0.05 mm thick.

Usually 30 parallel conductive stripes, each having 3 mm width, were woven in the PET fabric. Figure 14.4 shows the smart textile design and construction. The

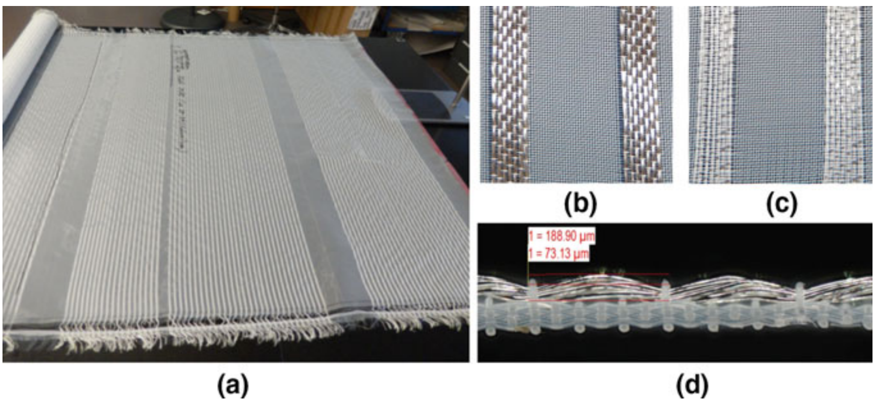

Fig. 14.4 SimpleSkin fabric with conductive stripes. **a** A roll of fabric. **b–d** Detailed view of the *front* (conductive) *side* and the *back* (non-conductive) side and cross section

Fig. 14.5 SEFAR CARBOTEX material used as semi-conductive fabric. The fabric was used as intermediate layer in the resistive sensor design, down to yarn having only $7 \times 50\,\mu m$ fiber in string

Cu-Ag yarns were woven into the fabric as close as possible to each other in order to obtain a very dense conductive strip with the best possible planar surfaces. The fabric types were woven in such a way that there are differences in conductivity on the front side and back side of the fabrics. The front side (sensor contact side) has extensively more conductive area than the back side as the conductive yarns protrude from the PET fabric on this side. The back side of the fabric is relatively less conductive, which can be seen already in the visual comparison as well as under conductivity measurements.

14.3.2.2 Semi-conductive Fabrics

SEFAR CARBOTEX 03-82 CF fabric [12, 13] served as sensing units in resistive sensing. Figure 14.5 shows the material. The fiber used is actually PA monofilament, covered with a layer of carbon particles, denoted by CF in the fabric identifier. SEFAR CARBOTEX fabrics are available in a wide range of mesh openings, 82 stands for $82\,\mu m$ opening.

The CARBOTEX fabric was weaved using plain 1:1 weave that provides the largest stability. CARBOTEX fabric is very flexible and air-permeable, which improves wearing comfort in comparison with non-permeable interlayer types. Using the CARBOTEX fabric as an intermediate layer in the resistive sensor design provided the best sensor properties, in particular having the most sensitive pressure response. Resistance changes at each measurement point are obtained already at very low pressure and can be registered by small pressure variations too.

To obtain a softer body feeling of the sensor assembly, the PET fiber of $64\,\mu m$ diameter was successively reduced to $30\,\mu m$ in further analyses. Similar, the conductive yarn having previously $12 \times 50\,\mu m$ fiber in string was replaced with yarn having only $7 \times 50\,\mu m$ fiber in string. Details on the resistive sensing are presented in Sect. 14.4.1.

14.4 Processing Platform and Sensor Types

The two types of generic fabrics presented above form the base for multiple sensor types. We explored four types of sensors by 'cutting and sewing' either the fabric with conductive stripes or both fabrics, then connecting them with a sensor signal processing platform. The textile–electronics interface is also built utilizing the generic fabric with conductive stripes. The central challenge here is the selection and realization of proper sensing function and of the driving circuits.

In this section, we focus on different sensor types for monitoring human activity and physiology, including the following: 1) the resistive sensing, which measures the pressure distribution and its change as a result of human movements; 2) the capacitive sensing, which detects the inner structural change of human body from the body surface; 3) the biopotential sensing, which picks up the electronic signals that initiate the muscle activities; and 4) and the bioimpedance sensing, which detects the impedance changes within the body tissue.

14.4.1 Resistive Pressure Sensing

Resistance-based pressure mapping is based on force-sensitive resistors (FSRs), e.g., carbon polymer sheets or CARBOTEX. The electrical resistance of the sheets changes as external forces cause material deformations.

The currently commercially available resistance-based pressure mapping products [14] are mostly polymer sheet deposited with metallic and carbon materials, which are flexible but not soft and air-permeable as textile or fabric. Some medical products [15] with elastic fabric knitting have emerged on the market. Our approach has been focused on providing flexibility, scalability, high-analogue resolution, and fast scanning rate in a platform to explore different application scenarios.

By applying two perpendicular groups of parallel conductive stripe electrodes on both sides of the CarbonTex material, thus forming a grid, we can measure the resistance distribution of the material. One electrode group actively supplies the scanning voltage; the other group is passive, connected to analogue–digital converters (ADCs) after a voltage-dividing resistor at each electrode. For optimal real-time implementation and flexible scalability, we designed a high-performance testing platform using a field-programmable gate array (FPGA) as control and driving device and dedicated 24-bit ADCs. Figure 14.6 shows a diagram of the hardware architecture. With the application parameters (channel numbers, scan rate, and analogue resolution) being selected, the system can be implemented on mixed-signal microcontrollers with sufficient ADC inputs to minimize power consumption (Fig. 14.7).

The resulting data have similar properties to monochromatic digital video. A continuous stream of frames representing the pressure distribution is obtained, each frame being a n-by-m matrix of integers, where n and m equal to the two electrode group counts. During our study, we used a high-performance FPGA platform, dedicated ADCs, and USB data connections, to ensure a constant frame rate of 40 fps across all frame scales. The frame rate showed to be sufficient for many human activ-

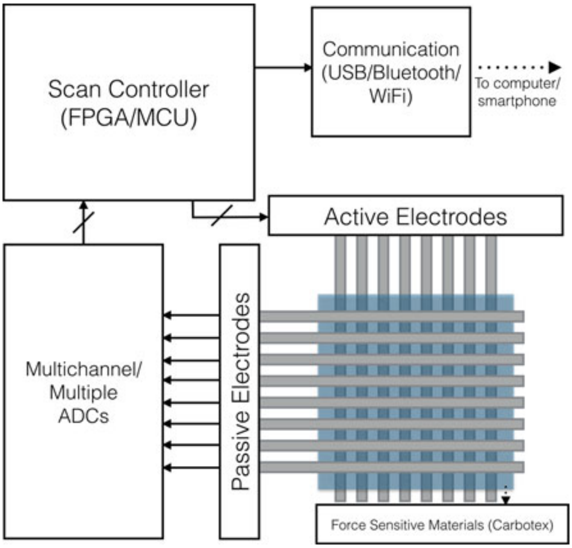

Fig. 14.6 Hardware architecture of resistive sensor type

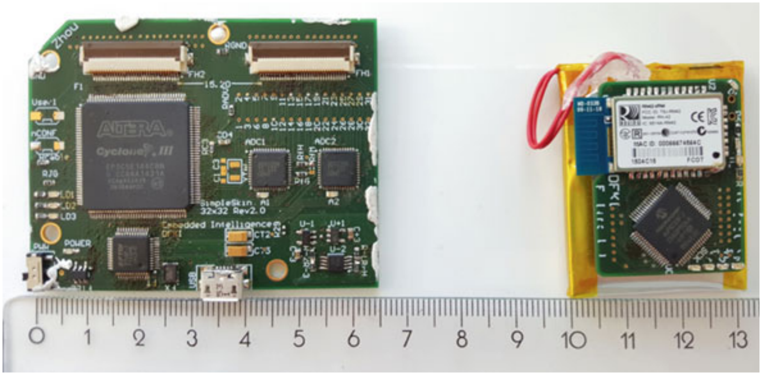

Fig. 14.7 Example of a 32-by-32 resistive sensing hardware. *Left* High-performance platform measurement using FPGA, dedicated ADCs, and USB data/power connection. *Right* Optimized version with microcontroller, Bluetooth connection, and a Li-Po battery underneath

ity detection tasks. Image processing and computer vision algorithms can be adapted in the data mining process to detect activities.

14.4.2 Capacitive Sensing

Capacitive sensing and the bioimpedance and biopotential sensing platforms (see Sects. 14.4.3 and 14.4.4) are using the generic fabric with conductive stripes only.

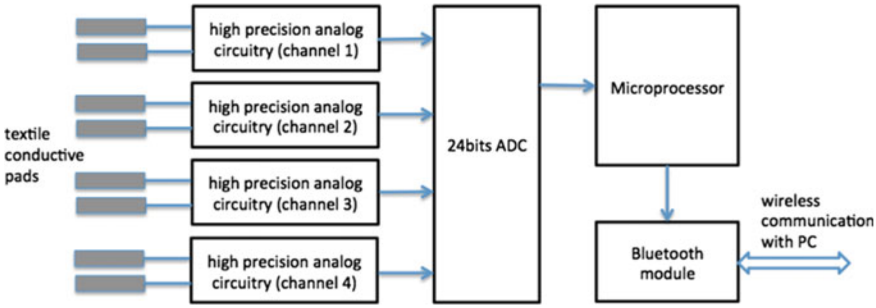

Fig. 14.8 Block diagram of capacitive sensing platform. The detailed front analogue design has been described elsewhere [16]

The conductive stripes function as the sensor pads and the non-conductive PET fiber serves as isolation. The capacitive sensor uses the electronic field with the conductive stripes serving as 'probes' to generate and pick up electrical potential. Alternatively, potential pick up could be made from the body-generated field too.

One capacitive sensor is formed of two conductive pads and the isolating material between the pads. The two conductive pads can be directly cut out of the generic fabric. When further embedded into clothes, the human body underneath the pads becomes also part of the capacitor. Any mechanical change in the pads and the clothes beneath them, also any mechanical or material change of the body tissue, results in a change of capacitance. Using capacitive sensing with textile material for contactless on-body sensing implies multiple challenges: (1) *Low amplitude*, as the overall capacitance is small, ~10 pF due to limited pad size; (2) *Large dynamic range*, as the capacitance change can be as small, e.g., in the ~fF range for a pulse, and as big as the overall capacitance, i.e., ~10 pF, when the sensor is removed from the body; (3) The relationship between the signal measured and the physical phenomena behind the capacitance change is complex. Using active capacitive sensing with electric field simulation and low-noise analogue driving circuit, we aimed to address these challenges [16]. When several stripes are cut and embedded into clothes, an array of capacitive sensors is created. Arrays can be used to detect mechanical changes in clothes, skin, and muscles due to physical and physiological activities.

Figure 14.8 presents the processing platform for capacitive sensing. The high-precision analogue circuitry generates a high-frequency electronic field and monitors its change, which reflects the change in capacitance. The output of multiple channels are digitized by a 24-bit ADC and then transmitted to the computer or mobile through a Bluetooth Low Energy module.

The textile conductive stripes can be embedded into elastic or semi-elastic bands, which could attach to neck, wrist, leg, ankle, or other parts of human body, to detect muscle movements and also the corresponding clothes/skin changes as the result of muscle movements, see Fig. 14.9.

All prototypes were built during the process of the generic fabric development. Alternatively, commercially available stretchable conductive fabric and conductive yarns could be used to create conductive pads. Because capacitive sensing requires

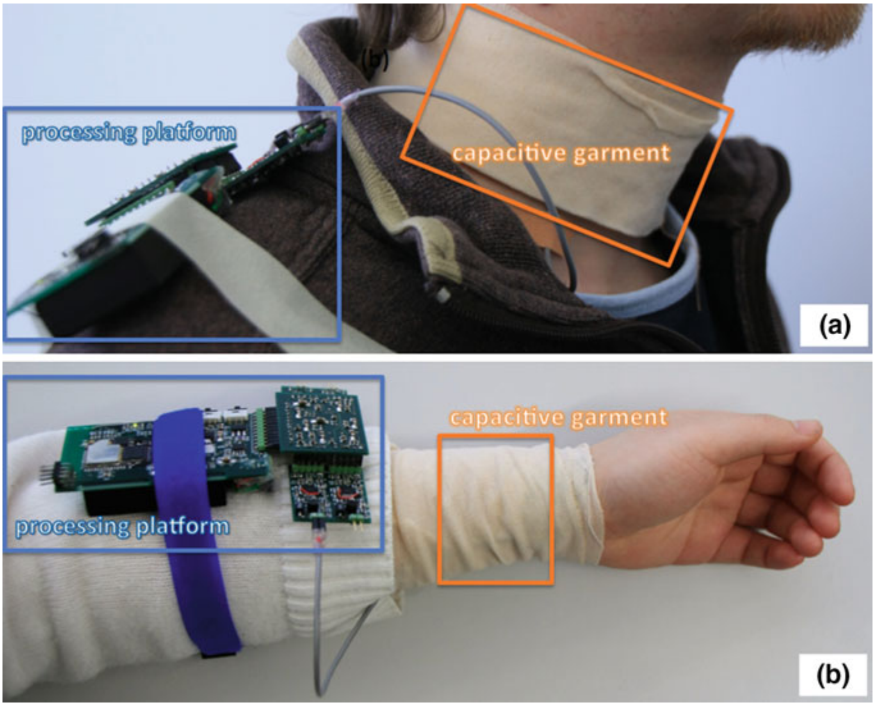

Fig. 14.9 Two prototypes of capacitive garment. **a** Neckband. **b** Wristband. The same processing platform was used for both, while the garment is designed differently regarding the conductive pad dimension and position

a limited surface area with of high conductivity only, there is no critical difference to be expected between signals detected using stretchable conductive fabrics versus the signals from a garment using the generic fabric.

14.4.3 Electrical Bioimpedance Sensing

Electrical bioimpedance sensing is generally used for non-invasive monitoring of physiological and pathological processes in humans. Bioimpedance measurements can vary regarding modalities, sampling rate, spectrum, and channel count depending on application and environmental conditions. It is precisely the versatility, combined with unobtrusive, small size, and relatively low cost, which make the key factor for the proliferation of bioimpedance prototypes implementing wearable biomedical sensing solutions.

The principle of bioimpedance measurement is based on the passive electrolytic and dielectrical properties of biological tissue that support the flow of electric current and propagation of electrical field. The properties are provided by both the intrinsic

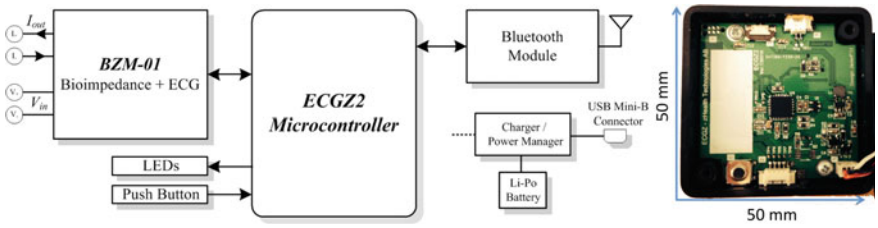

Fig. 14.10 Block diagram and one example of bioimpedance-sensing hardware

tissue constituents at ionic, molecular, and cellular level, and the biophysical structure of organelles, cell membranes, cell aggregation, etc. Further details can be found in [17]. Different tissues exhibit specific impedance spectra that can be exploit for tissue characterization. Differentiation and physiological or pathological processes that modify the tissue composition or structure can be studied by the change produced in the tissue bioimpedance.

Bioimpedance sensing is based on deflection measurements [18], i.e., stimulating with an electrical stimulus and sensing the tissue response. Often bioimpedance is measured through voltammetry, studying the relationship between the voltage and the corresponding current, known as transimpedance function. Typically, the electrical stimulus is applied as current using a current source [19–23], and the voltage response is measured by a differential amplifier circuit with a high input impedance, e.g., instrumentation amplifier.

In SimpleSkin, the ECGZ2 impedance recorder was used [24] to measure continuous 4-electrode single-channel bioimpedance based on the System On-chip AD5933 from Analog Devices Inc. and an analogue customized 4-electrode front-end [25–27]. The ECGZ2 estimates a new value of impedance every 4 ms, thus sampling at 250 Hz.

The ECGZ2 measures bioimpedance by injecting an imperceptible AC current between two electrodes and by sensing the voltage produced in the volume conducted from the surface. The electrodes used for the measurements are textile electrodes made of conductive yarn. Figure 14.10 shows the processing platform for bioimpedance sensing.

14.4.4 Biopotential Sensing

To record the electrical field produced for the bioelectrical endogenic activity, bioelectrical potential of the body and organs is frequently measured, when monitoring a patient or studying pathophysiological effects of a condition. The origin of the endogenic bioelectrical activity is the action potential that propagates through the body's excitable cells typically present in nerve, muscle, cardiac, and brain tissues. The biopotential is generated at the membrane of cells and has an ionic origin, i.e., there is a change in the concentration of ionic species between both sides of the cell membrane, which produces an electrochemical-induced change in the resting potential of the cell [28, 29]. Potential differences can be sensed from the skin surface, which allows biopotential sensing to be non-invasive using skin-contact electrodes.

Through biopotential, the cardiac function can be studied using ECG. Furthermore, brain function and the musculature system using electromyography (EMG) can be analyzed. Since heart rate is controlled by autonomic nervous system [30–32], it also possible to study ANS activity by analyzing the extracted heart rate data from the ECG signal [33].

In SimpleSkin, we recorded ECG using the ECGZ device described above. The recording device provides a single lead of cardiogenic bioelectrical potential, commonly know as cardiac biopotential, sampled at 1 kHz. An ECG recording has been obtained using a single measurement lead over the thorax (Lead I), using textile electrodes. Lead I ECG is well suited for further extraction of the heart rate by implementing R-peak detection algorithms [34, 35].

14.5 Garment–Platform Interface

Having the garment out of generic fabrics and the corresponding processing platforms at hand, the connection between textile and electronics becomes essentially important if the smart textile is to be used in real life outside laboratories. On the one side is the cheap textile that will be worn from day to day, often washed and from time to time replaced; on the other side is a relatively expensive electronic platform that need to be charged, often saved from water contamination, e.g., washing, and replaced at a lower frequency. The common connector between both sides should meet several requirements:

- ***Large number of connections***. To support multi-channel sensing or parallel sampling of multiple sensor types, the number of connections must be maximized. For example, for an $n \times m$ resistive matrix, at least $n + m$ connections between the garment and processing platform are needed if the matrix lines are operated via multiplexing. These connections must work in parallel.
- ***Minimal parasitic elements***. The connections serve as paths between (analogue) front-end in the garment and the processing platform. Electronic signals through the connectors typically have very limited driving capability; thus, signals are vulnerable to parasitic resistance, capacitance, and inductance. To avoid signal distortion, these parasitic elements of the connector should be much smaller than those of the garment sensor(s) and those of the electronic front-end.
- ***Easy to connect and detach***. Because garment and processing platform need to be separated and connected every time, the garment is washed and/or the platform is charged, a convenient and robust attachment is needed. Ideally, the large number of connections should be created or removed simultaneously with just one user action.
- ***Textile part is washable***. The garment and textile side of the connector is supposed to be machine-cleanable in a regular laundry process. The materials and fabrication

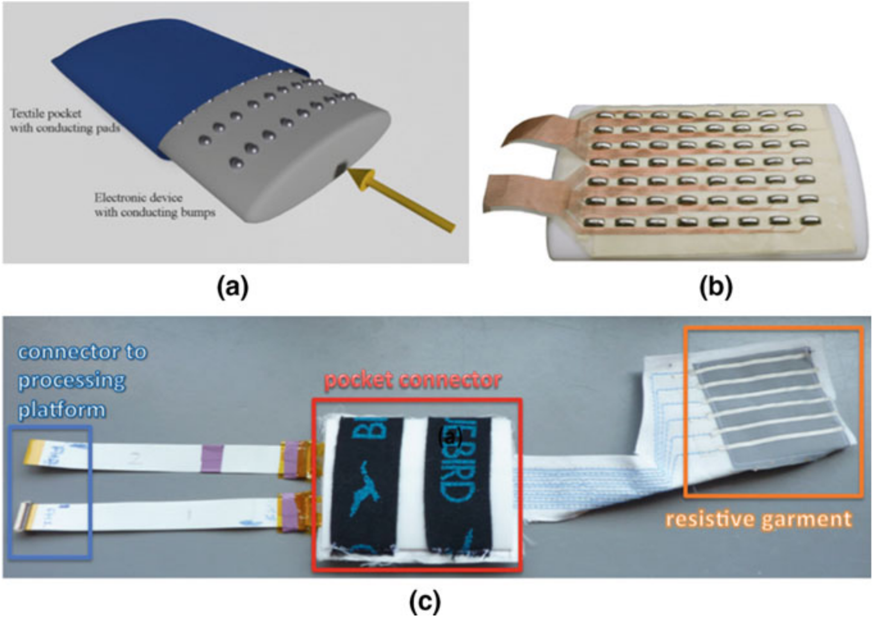

Fig. 14.11 SimpleSkin Pocket Connector as Garment–Platform Interface. **a** Device is inserted into the pocket, and each bump forms a connection with the conductive textile stripes in the pocket. **b** Connector electronics is made of a flexible print and is attached to a 3D-printed case. **c** Prototype of pocket connector. The pocket is attached to resistive garment and flexible flat cables, which can be connected to the resistive processing platform

processes used to derive the textile part of the connector should be standard in the textile industry for wearable electronics.

- ***Electronic platform is compact***. The electronic platform is directly connected to a garment and thus must be small, in less than tens of cm^2, thus maximizing wearability. All materials and processes should be standard in electronics manufacturing.

Various methods to connect textiles to electronics exist. Examples are snappers [36], plugs [37], zippers [38], hook and loop (Velcro R) [39], and magnetic connectors [40]. All rely either on using rigid parts or are not suited for many connections, i.e., connecting more than ten snappers or aligning hook and loop patches exactly will be cumbersome. We proposed a pocket connector to interface garment and electronic platform as shown in Fig. 14.11. The connector enables 56 connections on an area of $60 \times 100\,\text{mm}^2$, which is about the size of a smart phone. For more details on connectors, see the work of Mehmann and Varga (Chap. 9).

The pocket connector consists of two parts, based on the principle of zero insertion force ball grid arrays. The electronic part is made of a flexible printed circuit board with conductive bumps of solder tin and attached to a 3D-printed casing, which can hold the processing platform. The textile part is made of generic fabric with conductive stripes, which is divided into conductive pads by punching holes. The punched fabric is covered with elastic textile and fixed to normal textile to form a pocket. The textile pads match the conductive bumps and are pressed against each other when the device is slid into the pocket. The conductive textile pads are then rooted to textile sensors via insulated copper cables stitched onto dummy fabric.

We simulated the connector based on a mechanical model. Analyses showed that higher pressure is applied onto the conductive bumps than on the remaining surface of the 3D-printed casing: The pressure on the bumps is 3 to 4 times higher than on the remaining surface with bumps of height 0.7 mm, and this factor grows to 6 to 7 times when the bumps' height is increased to 1.5 mm. We further measured the electronic performance with a parameter analyzer. The Ohmic resistance of the connector is below 1.4 Ω for frequency below 10 kHz and below 3 Ω for frequency up to 100 kHz. The observed resistance is much smaller than the sensor resistance, e.g., several kΩ for resistive sensing and several hundred Ω for bioimpedance sensing. The detailed simulation and more measurement results can be found in [41].

The pocket connector thus enables convenient connection and disconnection of the garment and processing platform by sliding in the device into the pocket or dragging it out. The amount of connections and their performance supports the multi-channel sensing targeted in SimpleSkin.

14.6 Hardware and Software Systems

We produced two hardware and one software system that eases up the development of applications. These systems serve as an additional building block on the top of the garments and sensing electronics.

14.6.1 Hardware Systems

Within SimpleSkin, we created two prototypical multi-sensing garments that use multiple of the sensing techniques introduced before. First, we created a long-sleeved shirt [42] that incorporates resistive pressure, capacitive, and bioimpedance-sensing modalities. Figure 14.12 (left) shows the shirt. The bioimpedance sensor is placed on the chest part so that heart rate and respiration rate can be monitored. On the right sleeve, both remaining sensors were integrated. With the resistive sensor at the elbow, the arm bending angle can be observed. The capacitive sensor at the cuff was used to detect hand movement.

Second a multi-sensing collar shirt was created that combines the resistive, capacitive, and bioimpedance sensing around the neck. Figure 14.12 (right) illustrates the smart tie to monitor head gesture and swallowing too. Here, the capacitive and bioimpedance sensors catch both head motion and swallowing due to their sensitivity. Head and hyoid movements were furthermore detected by the resistive garment. Results showed that the information fusion of the sensing modalities provides improved swallowing event detection and head movements as well as other artifacts of each

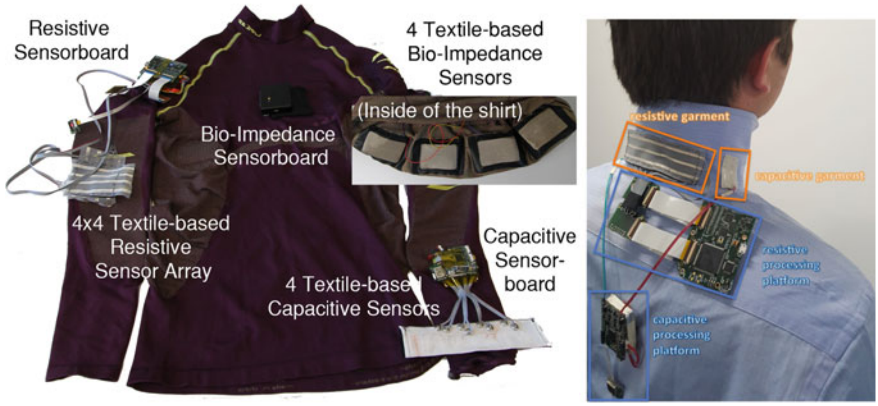

Fig. 14.12 Two SimpleSkin smart garment prototypes using capacitive, resistive, and bioimpedance sensing. *Left* Shirt with bioimpedance sensors at the chest part to monitor heart rate and respiration rate, resistive and capacitive sensors at the sleeve to monitor arm bending and hand gestures [42]. *Right* Collar shirt where all sensors are attached around the neck in the collar for monitoring swallowing [43]

individual sensor can be compensated in the recognition. More details on the multi-sensor collar shirt can be found in the work of Zhang et al. [43].

14.6.2 Software System

We strive to integrate multiple sensing modalities into a single smart textile or garment. To yield a scalable solution, it is essential to decouple applications from physical hardware so that applications can rely on an abstraction instead of particular physical sensors. Thus, a n:n mapping between sensors and applications is used: Several applications share the same sensor, and a single application utilizes several sensors. Both sharing options can be used, either time synchronous or time asynchronous. To realize the mapping, we use a middleware that collects all sensor values and provides application programmer interfaces (APIs) for developers, who want to access certain information. In particular, we developed an Android application called *Garment Operating System* supporting the following steps: First, it is managing the connection to the sensors using Bluetooth and Bluetooth LE connections. The incoming data are persisted and stored locally on the phone. On the top of the stored data, algorithms can be integrated that extract information out of the raw data. These data as well as the raw data can then be accessed via an interface for applications running on the same mobile phone.

14.7 Application Exploration

On the top of the proposed architecture, we explored various application scenarios which are realized using different conductive fabrics and electronic sensing platforms. We thereby used different input methods showing the capability of the proposed sensing modalities [44]. This section summarizes some of these applications for each sensor type and subsequently for sensor combinations.

14.7.1 Applications of Resistive Pressure Sensing

Including resistive sensing in garments allows measuring the pressure at different body parts. This pressure distribution changes depend on the performed activity or action. For example, while doing sports, the muscle contraction could be detected as a pressure shift between skin and a worn elastic garment. The relationship is not only observed directly, as in the aforementioned example, but also indirectly, if the force is propagated through a rigid object, such as dining containers or chairs. For example, the force between the feet and the floor of a four-feet chair was shown to be related to the chair user's static postures, but also dynamic activities [45]. The subtlety of the activities that can be recognized from pressure measurements exceeds conventional expectations. For example, while the feet of a standing person do not move, it is possible to recognize which cabinet the person is reaching and interacting with by a resistive pressure sensor matrix as a floor carpet [46]. The flexibility of the fabric material allows the sensor to be placed in various irregular shaped surfaces, resulting in novel implementations such as a force-touch gesture input on the couch surface [47].

Both wearable and ambient applications have been explored. Figure 14.13 illustrates the Smart Mat application example. An overview of the explored scenarios and detailed evaluation results can be found in [48].

- ***Smart tablecloth for dietary behavior monitoring***. When eating on a table, forces created by hands and food containers create different textures. For example, eating noodles and risotto results in distinct patterns of the force distribution measured between the table surface and the bottom of the plate. In a study with ten participants, each consuming a total of eight meals, eight activity classes were recognized based on the table location and the food-specific pressure texture, with accuracy up to 94% [49].
- ***Arbitrary touch input for smart devices***. A resistive pressure sensing matrix of 30-by-30, 0.5 cm pitch was placed on the sleeve [50]. This patch was used for detecting stroke gestures such as single strokes, circles, and squares. Particularly smart devices with a limited input space such as smartwatches and eyewear computer benefit from the decoupling and thus increase in potential input space. As application example, we developed a sports tracking application running on an Android-based smartwatch. In a user study, we show that input on the resistive patch outperforms input on the smartwatch itself.

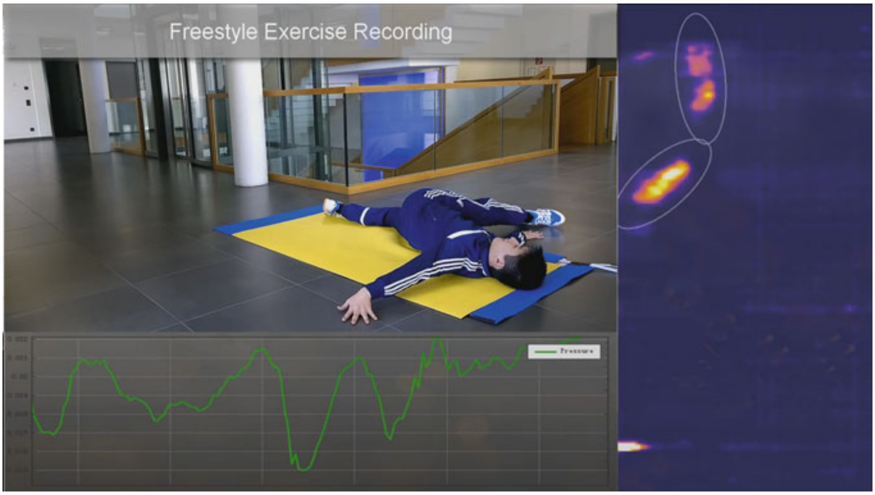

Fig. 14.13 Sport mat using resistive pressure mapping. Different exercises are detected based on the pressure distribution on the sport mat

- ***Sport mat for detecting exercises***. A sport mat with 80-by-80, 1cm pitch resistive pressure sensing matrix was used to recognize floor-centered, mostly body-weight-related exercises, e.g., push-ups, squats [51]. During exercises, the athlete's footprint does not change much in shape; however, the particular pattern of the force change and shifting of mass center can reveal information about the activity and repetition. From seven users and ten exercises classes, a recognition rate of 82.5% rate and counting accuracy of 89.9% were achieved.
- ***Sport band fixed on the thigh for evaluating gym leg exercises***. The resistive pressure sensing has major advantages over other wearable devices as (1) it is robust against shifting with the high amount of sensitive elements, and (2) it does not require direct physical contact or electrical coupling to the user's skin. Both items address practical concerns of wearable devices such as extreme, long-term movement, sensor readjustment, and intensive perspiration. The pressure matrix can be shielded with water proof/absorbing covers. We placed a 16-by-8, 1cm pitch matrix inside a elastic sport band to cover the frontal side of the quadriceps while the users do intensive weighted leg exercises in a real gym [52]. The result is a system that recognizes whether the user is doing a particular leg exercise from several options: idle, adjusting machines, or walking, with 93.3% recognition accuracy from six users. The system further observed the muscle expansion during warm-up exercises. Qualitative evaluation was done by comparing the consistency of the force among repetitions.

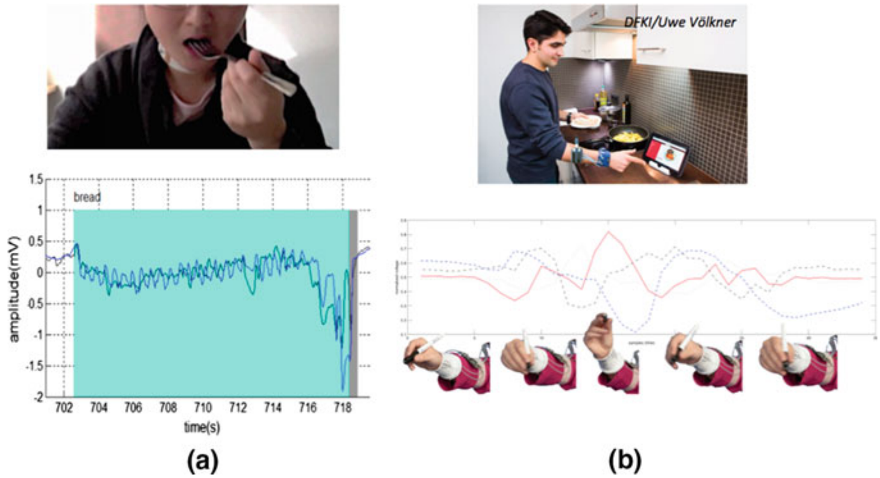

Fig. 14.14 Capacitive sensing applications with demonstrating scenario and representative signals: **a** nutrition monitoring with a neckband, **b** single-hand command input with a wristband

14.7.2 Applications of Capacitive Sensing

The textile capacitive sensing in SimpleSkin suits to detect minor mechanic changes in the body surface. Two application examples are demonstrated in Fig. 14.14). In the first application, a capacitive neckband records the skin/muscle movement on the neck, which reflects the throat movement when food or liquid is swallowed. In the exemplar signal, the whole intake process when eating a piece of bread is clearly visible, starting from the repetitive pattern of chewing (703–716s, marked with green), followed by the process of bolus forming and transferring (716–718s, marked with green), then the swallowing reflex (the deep value 716–716.2s, marked with green), and in the end the bolus entering the esophagus. In the second application, the user needs to operate a computer or mobile while the hand should be free; this could happen, for example, when the user wants to browse through a cookbook while the hands are wet due to food preparing, or, for example, when a doctor needs to retrieve and check medical ultrasound images while operating the patient. In the exemplar, the user wrote the number ‘2’ in the air, and the skin/muscle movements at the wrist are picked up by the four textile capacitive sensors embedded in the wrist band.

To sum up, we have explored the following applications:

- ***Nutrition monitoring***. The neckband can analyze the physical movement in the swallowing process and also monitor the daily food intake habit. In an exploration experiment, we created a data set of 138 h recorded from three subjects. We were able to detect 24 out of 25 ‘big’ (breakfast, lunch, dinner) meals with just 3 false positives. When smaller meals (e.g., eat a banana) were included, we detect 46 out of 64 with 136 false positives. Beyond eating, the next interesting result is the ability to distinguish between just being absolutely quiet (no motion) and actually sleeping, as periodic 'empty swallows' occur more seldom when a person is sleeping [53].

- ***Hand-free interface***. Besides the wristband, which can be used to input simple hand gestures, letters, and digits [54], the neckband can be used for head gesture and posture recognition too. A study involving 12 subjects was carried out, recording data from 15 head gestures and 19 different postures. Quantitative evaluation achieved an overall accuracy of 79.1% for head gesture recognition and 40.4% for distinguishing between head postures (69.9% when merging the most adjacent positions) [55].
- ***Gait analyses***. When embedded into a sock, thus worn around the ankle, the sensors can tell not only footsteps, but also different gait modes when the user walks normally, uphill, or downhill. Also the ground information (normal road or uneven meadow) is visible in the gait. Representative signals were presented in [16].
- ***Physiological signals***. The skin movement caused by thoracic skeleton movement while breathing can be picked up from the chest or the back. To a certain degree, this can be detected from other body parts too. For example, breathing is visible from the wrist, when the user sits next to a table and lies the hand quietly on the table surface. Pulse can be picked up from shallow arteries under the skin, for example, from external carotid artery with a neckband or from radial artery with a wristband. Representative signals from the wrist are presented in the former work [16].

14.7.3 Applications of Bioimpedance Sensing

We developed several sensorized garments with textile-integrated sensors that when combined with continuous impedance recorders enable several monitoring scenarios from well-known and well-spread applications including impedance pneumography [56] for respiration function, sleep apnea, and respiration rate monitoring [57], to impedance pharyngography [58] to assess swallowing function or impedance myography [59] for muscle function [60] and activity [61] or evaluation of neuromuscular diseases [62] and muscle injury [63].

Figure 14.15 shows an impedance pharyngography recording obtained during swallowing with the sensorized neck strap. Another impedance pneumography recording obtained with a sensorized T-shirt is shown in Fig. 14.16. In both examples, the targeted action, i.e., swallowing and breathing function, respectively, could be clearly identified.

Smart garments with bioimpedance electrodes can provide bioimpedance measurements supporting the development of pervasive healthcare-monitoring applications for chronic patient and therapy management as well as early detection of disease symptoms. Swallowing monitoring is further discussed in Sect. 14.7.5. Moreover, sensorized garments for bioimpedance monitoring have the potential to support the development of novel applications in other fields such as professional training, lifestyle, healthy aging, disease prevention, or health at work. The applications

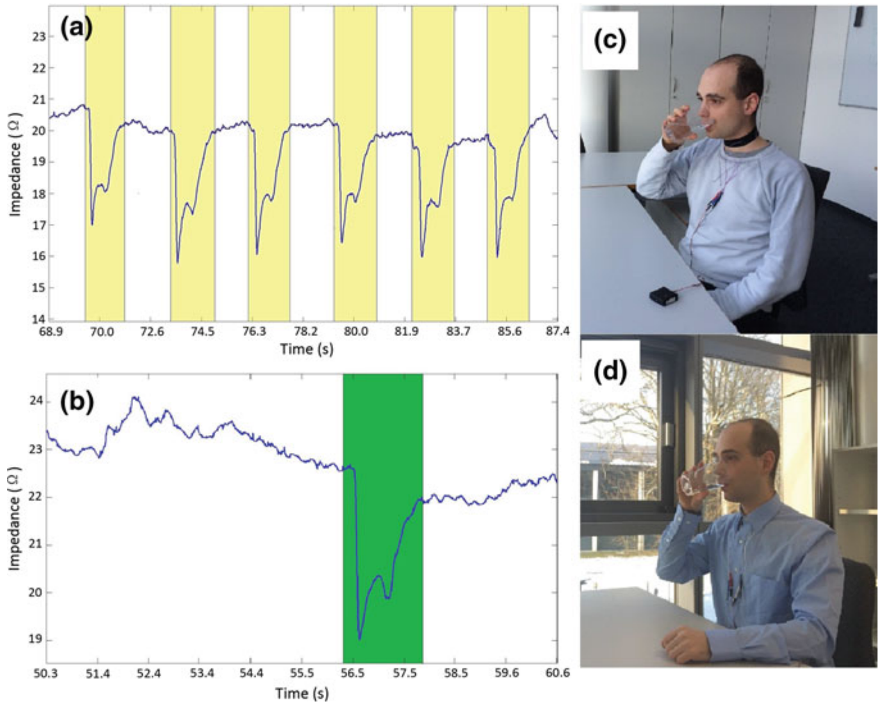

Fig. 14.15 Swallowing analysis using bioimpedance measurements made with fabric electrodes integrated into a neckband and shirt. Colored time series segments indicate swallows. **a** Measured impedance time series of a swallowing sequence during continuous drinking of mineral water. **b** Example impedance signal of swallowing water. **c** Measurement scenario with neckband. **d** Measurement scenario with custom-made shirt

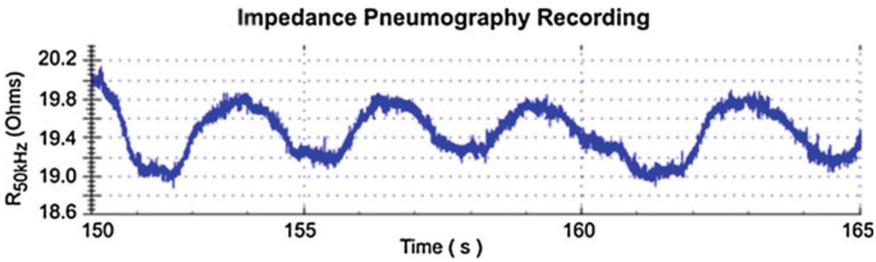

Fig. 14.16 Impedance Pneumography recording obtained from a raw resistance measurement of the thorax performed at 50 kHz oscillation frequency during normal respiration rate of 20 breaths per minute approximately

listed above are limited to the use of continuous and single-frequency bioimpedance recording only. Bioimpedance spectroscopy measurements in smart garments with already available wearable bioimpedance spectrometers could further increase the number of applications.

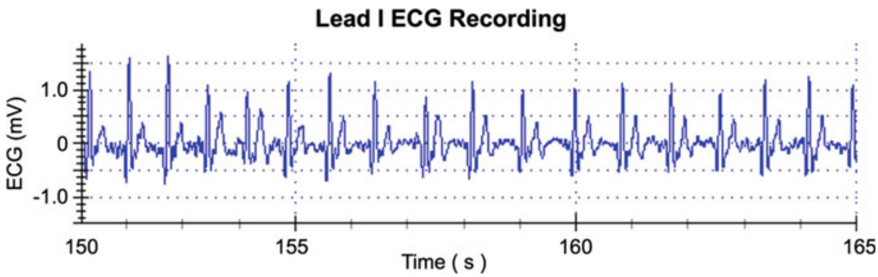

Fig. 14.17 ECG recorded with textile electrodes over the chest in a Lead I configuration. The QRS is easily observable

14.7.4 Applications of Biopotential Sensing

Applications of biopotential sensing with sensorized garments have been reported for more than a decade, e.g., by Rita Paradiso et al. [64], and currently several commercial products are entering the field of active lifestyle [65], professional training [66], and health care [67]. Moreover, novel applications in the field of personal protective equipment for potential early detector of mental and emotional stress have been reported. Often smart garments have been realized with a Lead I ECG signal. while Lead I ECG signal is insufficient for advanced ECG diagnostics, it is useful for arrhythmia monitoring as Holter [68] and extraction of the QRS complex, R-wave, and R-peak detection for heart rate analysis. Applications include stress assessment [24, 69–71] and cardiac performance during professional training [72–75] among others. The multi-modal smart garment developed in SimpleSkin has been confectioned to be used in all of the aforementioned applications. Figure 14.17 shows the ECG signal recorded with textile electrodes.

14.7.5 Applications with Combined Sensing Modalities

In addition to using a single sensing modality, using the developed hardware and software platforms, we propose multi-sensor applications (n:1), using sensors for multi application (1:n), and a mixture of both (n:n). More generally, the following applications areas benefit from multiple, multi-modal sensing in smart textiles:

- ***Multiple Sensor Application***. Mid-air interaction is one of the main interaction techniques for interacting in public spaces [76]. While many current systems use vision-based methods to track user movement, smart garments could realize gesture-based interaction without interfering with the user's privacy concerns, i.e., when monitored by cameras. By combining resistive patches at the elbow and the capacitive sensor at the cuff of the shirt, we were able to track almost the full arm. As shown in the application scenarios for the individual sensors before, resistive sensors achieve adequate results for detecting the movements of the joints and the capacitive sensor is well suited for detecting hand movement. Their combination allowed us to detect mid-air gestures performed by the user such as waving or pointing. The concept behind the application is thus that distributed sensors in a smart garment can be combined to reveal information, in this example more complex movement interaction.

- ***Multiple Application Sensor***. As an example shows the use of multiple application for a single sensor, the resistive sensor matrix at the forearm shall be considered. First, a wearer can perform forearm gestures including taps or drawing simple geometric shapes, e.g., circle and stroke. Gestures can be used to control smart devices such as smart watches or smart glasses. At the same time, the resistive sensor can detect the wearer's hand shape to authenticate to these smart devices. As soon as users touch their forearms with their flat hand, the system recognizes the user and unlocks the device.
- ***Multi-modal Sensor Application***. The benefit of multi-modal sensing is that the errors of individual sensors are independent; thus, the sensor fusion could potentially eliminate errors in the information fusion stage of processing signals. Swallowing detection is a challenging application as the neck region is centrally involved in head movements, artery-related motion, respiration, speaking, besides swallowing. By integrating resistive pressure to capture hyoid motion at the neck front, capacitive sensors to detect tissue changes, and bioimpedance to monitor structural variation, multiple data views onto the swallowing act can be obtained. The improved swallowing recognition results obtained by the information fusion clearly confirm that the modalities contribute independent errors [43].

14.8 Conclusions

In this paper, we presented a vision and initial efforts on generalizing and modulating smart textile production and usage. The core idea is to divide smart textile production into several layers and take the result of the former step as basic building blocks of the next by simple 'cut and sew'. We reported two types of generic fabric, four types of sensing modalities, and a textile–electronics interface. Across various applications, the unique benefits of smart textiles and garments were shown.

We believe that the easy combination of generic textile and sensing modalities will enable designers to create a wide variety of smart textile applications. The approach can lower challenges in smart textile development through the whole process from fabric manufacturing to the final software app development. Ultimately, the approach will enhance the price–performance ratio so that the smart textiles can indeed replace today's classic textiles.

Summary

This chapter presents a generalization of smart textile development and realization, which is essential to move from individual niche applications with different sensor requirements to mass-producible and affordable solutions. It is essential to partition the smart textile production into steps and devise basic building blocks at each step. By combining mass-producible building blocks, a variety of applications can be realized.

- **Fabric building blocks**. For smart textiles, both conductive and non-conductive fabrics are needed. Conductive properties can be embedded during manufacturing, e.g., weaving of metal wires. Non-conductive fabrics could be controlled regarding their conductivity in an additional process after manufacturing, e.g., by weaving, knitting.
- **Sensing building blocks**. Sensor functions can be derived by combining the conductive and non-conductive fabrics in different ways. For resistive pressure sensing, a non-conductive carbon polymer fabric can be used to create a pressure-sensitive matrix. Capacitive, bioimpedance, and biopotential sensing need textile electrodes that are made of highly conductive fabric materials.
- **Connector building block**. The connection between fabric material and electronics needed to process sensor data is a critical concern in any smart textile design. The connection needs to maintain excellent electrical properties, multiple connections, while obeying to textile-handling processes, e.g., bending and washing. A pocket connector made of a flexible printed circuit board for the electronics and conductive fabric stripes for the textile provided adequate performance in the applications considered.
- **GarmentOS middleware**. To realize a flexible mapping between hardware, i.e., sensors, and application software, a middleware is needed that provides APIs to abstract from the smart textile implementation details. A n:n mapping between sensors and applications seems appropriate.
- **Multiple sensors, multi-modal monitoring**. Depending on the application and set sensor data interpretation objective, different sensor combinations and data processing strategies are needed. While single-sensor implementation with multiple applications provides already some flexibility regarding the smart textile use, the benefit of multiple sensors, sensor arrays, and multi-modal monitoring is a key benefit of smart textiles.

Acknowledgements This work is supported by the collaborative project SimpleSkin under contract with the European Commission (#323849) in the FP7 FET Open framework. The support is gratefully acknowledged.

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Chapter 15
Smart Textiles and Smart Personnel Protective Equipment

Dongyi Chen and Michael Lawo

Abstract Wearable computing and smart textiles are the enablers for smartPPE (Personnel Protective Equipment). Was wearable computing first the idea to integrate computing power into clothing to, e.g., access information, we observe in recent years a split into two domains: wearable computers as smartphones, glasses and wristbands on one side and smart textiles on the other side. The research here described in some detail deals with a specific domain where these two developments meet: the smartPPE where the smart textile gathers sensor information and the wearable computer automatically generates context information to protect the health status of the person wearing the smart textile. This can be necessary due to perilous environments or chronic diseases.

15.1 Introduction

Wearable computing and smart textiles are the enablers for smartPPE (Personnel Protective Equipment). Wearable computing was first integrating computing power into clothing to, e.g., access information. Today, we have a clear split as follows: (1) wearable computers as smartphones, smart glasses and smart wristbands on one side and (2) smart textiles on the other side as reported by Reiss and Amft [1].

Parts of our past research described here in some detail deal with a specific domain where these two developments connect with the smartPPE where the smart textile gathers sensor information and the wearable computer generates context information to protect the health status of the person wearing the smart textile. This can be necessary due to perilous environments or chronic diseases. Examples of applications

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S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_15

are those of temperature-sensing protective gloves for firefighters, protective trousers for people using a chainsaw and protective shoes for people tracked for their own safety in indoor environments.

In all these applications, textile became smart by just adding electronics for sensing and communication to monitor the user with respect to the environmental working conditions and the tasks performed. We had in these applications healthy people as target group of our research. However, these people were willing to use technology-enhanced clothing to keep their healthy and safe state.

Another target group of our research is people with chronic diseases such as COPD (chronic obstructive pulmonary disease), CKD (chronic kidney disease), Parkinson's disease or MS (multiple sclerosis). Although the main research was in the field of AI (artificial intelligence) and machine learning-based context detection, a nanomaterial-based scarf to monitor swallowing is a smart textile.

In the following, we will briefly explain our journey from wearable computing towards smart Personnel Protective Equipment and derive our vision of this as an important topic for the Internet of Things (IoT) [2].

15.2 Wearable Computing

Wearable computing is not only a technical development, but also an entirely new paradigm of computing. Of particular interest is the aspect that the goal of wearable computing generally is to shift the way of actively operating computer machine to being a secondary task. The wearable computer shall rather actively assist the operator in carrying out a task in the physical environment or on-site. Ideally, operator must neither feel such a fact that he is carrying a computing system on him nor need to operate a machine. What does wearable computing devices mean we know today best, if we think of gadgets such as the Google Glass or the Fitbit by naming just two consumer products? Besides pure hardware difference, user interface and the way users deal with the systems are different. The ideal is that there is no longer any explicit interaction of the user with the system but that wearable system supports the users' activities as a personal assistance in a completely unobtrusive way. This goes far beyond the normal use of mobile computing today.

Today's mobile systems give access to their integrated sensors, and we can compute contextual information based on the sensed data. However, their interaction still follows the paradigm of the desktop computing with the full attention to the system required when in use. Here, wearable computers and, in particular, their user interface are built of a different type of hardware requiring sensors and the validation of their signals for tasks the user performs or is intended to perform. Only if the system does not need further user's explicit input it can fulfil the purpose of unobtrusive support for the user and becomes ideal wearable computer, which supports our concept of a smart personal protective equipment (smartPPE).

Fig. 15.1 WINSPECT glove 2006 (Image University Bremen - TZI)

The key is to find out the sufficient sensor-based information to completely detecting the user context. In our research (e.g., [3–7]), we focused on working environments. These environments require in many cases the users to follow prescribed procedures. This allows to segment tasks into elementary microtasks [8]. The microtasks require modelling and evaluation with respect to their potential of monitoring by sensors. There was a lot of research in this field during the last couple of years with very valuable results by Dey et al. [9], Bannach et al. [10], Roggen et al. [11] and Kurz et al. [12]. An outcome of the research at TZI was the TZI context framework developed by Iben that allows developers to simply deal with the information provided by task descriptions and different wearable (on-body) or environmental sensors for context detection [13, 14].

However, from the very beginning, we also looked for textile components when designing interaction gloves and wristbands (see Fig. 15.1) [15, 16].

15.3 Producing Smart Textiles

The material and structural characteristics largely determine the fabric performance. To design a high-performance fabric, we need to improve the properties of fibres and yarns. Traditional textile fibres are generally flexible with a certain strength. The physical properties of the fabric include maintainability, durability and comfort. Smart fabrics do not only have similar properties, but very specific requirements concerning maintenance (cleaning and operational maintenance) and production. There are specific requirements concerning mechanical optical, dielectric and thermal properties. Smart fabrics use smart fibres.

The processability of yarn or wire structures has an important influence on the choice of the appropriate textile technology. Wires easily break during weaving and knitting. Composite yarns too close to adjacent wires easily cause dead shorts. Lower resistance wires have less elasticity and strength.

There are several ways producing fabric out of fibres and yarns: weaving, knitting, embroidery, fitting and sewing. One applies these methods as well for functional as smart fabrics.

When thinking of a textile-etched wiring board, different technologies for processed materials are at hand such as (woven) jacquard, non-woven embroidery and knitted material. They all have different properties concerning, e.g., robustness, flexibility or wearing comfort. The fabric structure of jacquard is, e.g., stable, but requires a production process of some complexity. The process of embroidery compared to this is simple.

Actually, most popular technology for smart textiles as described in the report of TITV [17] uses embroidery when electronic components connect to each other by conductive yarns resulting in electric circuits. Linz et al. [18] describe how the embroidered conductive yarn provides the energy for the electronic components. TITV Greiz developed this technology and widely used it in research as Linz et al. describe in [19]. With this approach, it is possible to prepare textiles for later manual placement of the electronic components. An automatic placement as known from PCB equipping and final placement is still not available. Some approaches from the literature (e.g., [20–24]) as also described in this handbook give an idea of future developments. However, there is no large-scale automatic assembly known despite existing industrial property rights [25–27].

The application of conductive fibres is applicable in electronic textile as reported by Nagaraju et al. [28]. Conductive fibres are the standard electronic module in textile interconnection circuits. We need to consider the flexibility and processability of conductive fibres, when processed into smart textiles. Currently, one finds copper, silver, aluminium and iron as stainless steel and other metal conductive wires in production. These wires have small diameters, high electrical conductivity and good stability. However, the flexibility is poor. The conductivity of these pure metal fibres range from about 0.5 Ω/m to several k Ω/m reported by Randell et al. [29]. Silver-plated copper and brass one actually apply in production. Table 15.1 gives the electrical properties of wires from different materials of the Swiss company Elektrisola Feindraht AG (Escholzmatt, Switzerland) [30].

Table 15.1 Electrical properties of metal monofilament fibres [30]

Material	Conductivity ($S \cdot m/mm^2$)	Resistivity ($\Omega \cdot mm^2/m$)	Thermal coefficient of resistance ($10^{-6}\,K^{-1}$)		
			Min	Typical	Max
Cu	58.5	0.0171	3900	3930	4000
Cu/Ag	58.5	0.0171	3900	4100	4300
Ag99%	62.5	0.0160	3800	3950	4100
Ms*70	16.0	0.0625	1400	1500	1600
Ms/Ag	16.0	0.0625	1400	1500	1600
AgCu	57.5	0.0174	3800	3950	4100
Bronze	7.5	0.1333	600	650	700
Steel 304	1.4	0.7300		1020	
Steel 316L	1.3	0.7300		1020	

With conductive yarns like the ELITEX®-yarn [31] and an embroidery machine is it in principle possible to produce conductor boards in an industrial scale. For the placement of the electronic components, the FSD-Technology (functional sequin device) [32]—actually only used to place conventional sequins—offers an option not only for LEDs but also for sensors.

Base yarns such as cotton, polyester, polyamides and aramids incorporate metal monofilaments made from copper, brass, bronze, silver, gold and aluminium. They have a good stability and flexibility. However, with larger diameters, the conductivity decreases significantly. Rattflt et al. [33] describe conductive fibres of 20% stainless steel and 80% polyester. Metal monofilaments of Elektrisola Feindraht [30] are miscible with all sorts of fibres for direct use in weaving and knitting.

Another way to produce electrically conductive fabrics is just coating the fibres with metals, galvanic substances or metallic salts. One coats the surface of fibres, yarns or even fabrics to create electrically conductive textiles. Common textile-coating processes include electroless plating, evaporative deposition, sputtering and coating the textile with a conductive polymer.

Scheibner et al. [21] describe a support structure with woven conductive yarns and subsequent contacting. The report of TITV [20] describes constructing an electronic component structure on conductive yarns using thin-film technology (e.g., precipitation of coating systems to create a transistor or OLED) for later weaving. In the same report [20], one also finds the technique of contacting electronic components on conductive yarns for later incorporation in fabric.

Some references claim the industrial fabrication. Interactive wear [34] offers textile compatible snap fasteners with LED connected via textile leads. Forster Rohner Textile Innovations [35] use embroidery for connecting LEDs in textile structures. Industrial manufactured integrated sensors one needs when monitoring the apparelled becomes part of any workaday clothes.

However, to integrate sensors into textile structures is today more or less still a topic of design studies or research when it goes beyond heart rate monitoring. Paradiso et al. [36], e.g., report on a smart textile for detecting physiological signals when monitoring the health status. Coosemans et al. detect ECG [37], Linz et al. EMG [38] or Lofhede et al. EEG [39, 40]. Physiological signals monitored by athletes or patients can guide training or rehabilitation. With fabrics incorporating thermocouples, Sibinski et al. can measure the body temperature [41]. Electronic textile business applications include the iPod control, or displays and keyboards integrated into fabric as Jung et al. describe [42]. Omenetto et al. [43] report of light-emitting elements integrated into the fabric for so-called biophoton sensing. Shape-sensitive fabrics can sense motion. Combined with EMG sensors, one deduces the muscle health status as Meyer et al. describe [44].

Currently, there are three typical wearable electronic textile design and production methods. The first is a flexible screen printing method, which means a conductive material and sensing printed directly on the fabric substrate. The second is weaving, knitting or embroidery for conductive sensing and insulating fibres or filaments woven directly into the sensor. The third is sewing where one uses conductive yarn to contact ready-made circuit boards as tiny silicon chips woven into clothing or sensors applied on clothing. Using state-of-the-art technology, each of the three methods has its advantage.

Planar fashionable circuit boards are a novel flexible electrode technology. It uses soft and flexible plain-woven fabrics as the base and print circuits on the substrate. Its appearance is not different from general clothing as Stoppa and Chiolerio outline [45]. Kim et al. [46] directly use the epoxy screen printing or sputtering gold deposit on fabrics block. The integrated circuit placed on the fabric has wire bonding to the electrode pattern. One packages the integrated circuit with a non-conductive epoxy.

Lee et al. [47] developed at the Korea Institute of Science and Technology a multilayer fabric circuit. Kim et al. [48] describe a method of making a printed circuit of a fabric determining and analysing their electrical characteristics.

Marculescu et al. [49] designed at the Georgia Institute of Technology a wearable motherboard and McFarland et al. [50] protective clothing able to absorb infrared in explosive atmospheres. A team of the wearable computing laboratory at Eidgenoessische Technische Hochschule (ETH) Zurich developed sensor elements and conductive yarn embroidery for a fabric with 16 capacitive pressure sensors. They integrated a new type of thermoplastic elastic strain sensor into clothing for monitoring clothing strain identifying different body postures by Bayesian classifier methods and using the fact that sensor resistance and resilience have a linear relationship.

Meyer et al. [44] apply this approach to detect muscle activity and human motion. Eight testers showed 27 different body postures. Single tester's action classification rate reached 97%, and all testers' action classification rate reached 84%. Mattmann et al. [51] claim to apply this technology to rehabilitation of patients and athletes training.

At the E-Textile Lab of Virginia Tech [52], a team designed a coat for gait recognition.

The researchers of National Centre for Sensor Research, Dublin City University (Ireland), used wearable chemical sensors to monitor people and their surroundings. The chemical sensor was able to measure and analyse sweat in real time on the body. They have developed a microchip version of the platform to measure changes in the pH of sweat. Placing a surface mount (SMT) LED and photodiode module on either side of the chip allows interpreting the colour change of the pH-sensitive fabric by aligning with the pH-sensitive fabric. The final device with 180 m thickness is flexible and can adapt to the body. Chi and Cauwenberghs integrated sensors on flexible fabric substrate and designed metal plate dry electrode ECG chest strap in this way [53].

15.4 Security in Working Environments

In many working environments such as rescue service or foundry or one of the firefighters and lumbermen, workers expose themselves to threats arising from the environment and the activities. Many of these risks remain without consequences and do not evolve to such situations in which the worker is injured or endangered or has an accident.

This is because in addition to the individual experience of the worker, organizational measures and especially the wearing of personal protective equipment (PPE) contribute to this fortunate circumstance for the worker. However, a snapshot of the Federal Institute for Occupational Safety and Health (BAuA) from 2013 shows that despite the various measures available to protect the workers, a significant number of industrial accidents lead to personal injury, employment losses and in the worst case to death [54].

Indeed, the number of industrial accidents recorded by the BAuA in the years 1960–2013 shows a downward trend. In spite of all the improvements in technical and organizational safeguards, each year nearly one million occupational accidents happen of which more than 600 are fatal. Especially, workers in the timber and woodworking industry and the construction industry are particularly at risk, while the chemical industry generally regarded as a high-risk industry stands out by a small number of accidents. Here, new technological developments such as wearable computing and, in general, the IoT open up a new approach to improve safeguarding using smart textiles.

Previous research identified and mastered some of the challenges arising from this. In the following we will report on some smart textile applications our research groups developed during the last couple of years.

15.5 Threats to Physical Integrity and Conventional PPE

Humans protect themselves in several ways from damage. Even some of the functions of the human body protect itself. In particular, the skin protects against mechanical, physical and chemical influences. However, the humans' own protective functions are highly adjusted to the natural environment. Both the size of the load and the type of load that is able to withstand the natural protective functions range within narrow limits. Non-natural loads are often much stronger than natural ones or are of such a nature that the body's own protection does not recognize them and therefore cannot respond as Bischoff et al. [55] and Haddadin et al. [56] outline.

To avoid damage from such loads or at least weaken them, a human surrounds himself with a protective sleeve by wearing clothes. While the everyday clothing contributes only minor protection functions, particularly the personal protective equipment (PPE) as work wear is highly tailored to the respective risks of different jobs. Through the textile properties, a human may move in environments he could, otherwise only enter for very short periods without harming him- or herself or even not at all.

A principal characteristic of conventional PPE is its passivity. The protection functions are only effective when a risk occurs and damages the body or its surrounding hull. The example of the cut protection illustrates this: only when the running saw contacts the cut-resistant trousers, the function of the textile unfolds. Once the saw has penetrated the outer fabric, the long and tear-resistant fibres only loosely woven into the trousers that wrap around the drive of the saw, thereby stopping it. In any case, the chain violates the fabric of the cut-resistant trousers; sometimes, even the workers does not remain completely unharmed, too. In any case, one cannot use the trousers after an accident ever again.

15.6 Introduction

As explained above, wearable computing needs the situational context of the worker in its work environment; only then, it can effectively support. This requires information from different sources with respect to the place of work, the interaction actually performed, the required information related to the environment (machines, running processes), to protect the action of the worker as the physical condition.

The utilization of the opportunities provided by wearable computing for the protection of the workers allows overcoming the passivity of the previous conventional PPE. In fact, smart PPE can take an active role as a new generation of personal protective equipment in different ways:

- By drawing the workers attention to harmful influences from the environment before they pose a danger to the worker.
- By notifying the worker in highly stressful situations that his physical condition drifts into a threatening area.
- By influencing the work environment in a way to prevent situations harmful to the worker in advance.

Ultimately, such active protective equipment leads to enhanced protection concepts even applicable in human–robot collaboration [57, 58]. In the above-mentioned cut protective clothing, as an example, the "smart" safety trousers would already stop the chain before the contact with the trousers itself occurs; the advantages of such behaviour are obvious.

15.6.1 Scenarios for the Possibilities of SmartPPE

One can reflect the new characteristic of the activity of protective equipment and the resulting possibilities in scenarios, which cover a wide range of applications.

15.6.1.1 Scenario 1: Protection by (Augmented) Information

In this simplest scenario, one uses the existing possibilities of wearable computing solutions to increase the safety of the worker through information and communication. The information on the status of the worker himself, his surroundings and the equipment put the worker in a position to decide whether he stops his current operations for his own protection or adapts to the changing threat. The built-in communications allow the worker to communicate with the control centre and colleagues in the work environment to submit and examine the own situation assessment. This scenario does not require a protective function of the smart textile.

15.6.1.2 Scenario 2: Protection Against External Threats

This scenario extends the conventional PPE. The basis of the protective function is the role of the (smart) textile equipment. This points to the passive characteristic of conventional PPE and intervenes especially in those cases when the advanced "smart" protective functions are insufficient. As in scenario 1, the textile system becomes smart and offers information and communication as a protective mechanism, too. However, this happens on a much larger scale. The smartPPE automatically communicates with the working environment: if the smartPPE detects the presence of a possible threat, it tries to influence the neighbouring environment and its machines and processes by preventing a threat in advance. For example, the smartPPE triggers a production robot to adapt its working movement so that it moves around the worker. Even self-regulation of equipment is possible in this scenario by, e.g., cooling features directed into the interior of the equipment and activated when the outside temperature rises.

Thereby, one can extend the dwell time for the worker in a hazardous situation when informed about the dangerous situation and the action that his smartPPE has caused. It makes sense to also alerting the control centre and the neighbouring peers. Necessarily, such protection scenario needs the smartPPE to have

- appropriate environmental sensors,
- a standardized communication with the working environment such as machines, equipment and running processes and
- a model about hazards and possible damage, to trigger corresponding protective functions.

15.6.1.3 Scenario 3: Protection Against Internal Threats

While scenario 2 directs the protective functions to the dangers from the outside, scenario 3 directs the protective functions to the inside. This requires that the smartPPE explicitly registers the physical condition of the worker and the climate within the equipment and processes them. Particularly, those applications are of interest in which the worker has closed heavy and/or bulky suits. Here, the burden on the worker increases by an enlarged effort in the movement as well as by rising temperature and humidity caused by higher transpiration. Both these factors mean that the worker cannot perform work with such equipment as long as he could under normal conditions. Information about his condition and possible impact on developing harmful climate in the interior of the equipment works against a possible collapse of the worker.

15.6.1.4 Scenario 4: Protection by Active Physical Assistance

The previous scenario already introduced an active characteristic in the smartPPE through its advanced protection features. Scenario 4 further strengthens this by besides sensors integrating actuators into the equipment going beyond scenario 2, and the self-regulation of the equipment addressed there for heating and cooling. Here, we see special actuators that directly influence and strengthen the wearer of the equipment beyond the own personal strength. We consider exoskeleton systems as visionary examples of such smart textiles, where the change of its energy potential influences the form. This way, an influence on the movement of the worker is conceivable by indicating the harmfulness and hindering the execution. In addition, other human abilities concern hearing or vision we consider with active assistance.

15.6.1.5 Scenario 5: Protection by Active Training and Instruction

The smartPPE of all previous scenarios supports and protects the worker while performing assigned duties. The final scenario is set earlier and will use new ways to ensure that the worker can find an active safety briefing. This creates an active learning environment that helps to better understand and remember the information conveyed. Furthermore, it can foster a greater awareness of the topic of protective behaviour and equipment often perceived as annoying. In this scenario, one may think of the registration of the real operations of the worker, without the protective functions of smartPPE to intervene. The system interprets recorded readings and processes them appropriately. Afterwards, the worker receives an assessment of the execution of his activities with the resulting harmful load. With advice on the impact of these loads on the body over a long period, one can provide instruction on how to prevent such exposure and to improve the behaviour requires encouragement.

15.6.2 Requirements for the Development and Use of SmartPPE

As depicted above, we add the enhanced protection of smartPPE to the context detection feature already used in wearable computing.

Beyond the technical requirements for the development and the benefits of smartPPE, we have additional requirements from a safety as well as social and psychological perspective. Of course, ultimately, the business requirements are further there.

- Transparency, reliability and stability: In terms of security, it is necessary that the protective properties are transparent so that the worker recognizes how the smartPPE responds. Moreover, the protection capabilities must be reliable and always available in the same context. The protection systems and in particular the parts that are based on computer components have to run stable to ensure the protection functions.
- Redundancy: Also from a safety perspective, it is necessary at least for basic case-specific security goals to provide redundancy through textile protective properties besides the technical protection features.
- Acceptability, reliability and comfort: Usability is an important issue for acceptance by its respective wearers. This includes that the carrier permits the influence of the equipment to its working environment and may allow the execution of activities. It requires trust by the wearer in the reliability of the smartPPE to feel protected. In addition, the smartPPE must at least meet basic comfort requirements.
- Cost-benefit: The acquisition and maintenance of smartPPE must be proportionate to the new security goals and the created benefits for workers and businesses.

15.7 Examples of SmartPPE

We evaluated the concept of smartPPE described above in a couple of applications for which we had two target groups in mind: (1) healthy people in dangerous environments providing protection towards hazards as described in scenario 2 mainly and (2) people with chronic diseases providing a protection with respect to the disease related to hazards as described in scenario 3. Besides we covered also aspects of the other scenarios.

We will describe in some detail three applications and refer to the underlying research papers: (1) *A temperature-sensing protective glove*, e.g., for firefighters; we address here issues of the above smartPPE scenarios two and five, (2) *protective trousers* for people using a chainsaw addressing scenario two and (3) *protective shoes* for people tracked for their own safety in indoor environments where we address scenario one.

In all these applications, the textile became smart by just adding electronics for sensing and communication to monitor the user with respect to the environmental working conditions and the tasks performed. We found it very difficult to integrate efficiently smart textiles, as such, into the applications due to still missing features, robustness, maintainability and availability.

However, as mentioned above, in our research in smartPPE for people with chronic diseases, we succeeded at least with a nanomaterial-based scarf to monitor swallowing by smart textiles as an application of scenario three.

15.7.1 Protective Glove GloveNet

The first example desires to protect firefighters by temperature warnings and retreat messages during operations using a network of wireless sensor nodes and haptic feedback integrated in gloves for firefighters. This protective glove was an outcome of the *GloveNet* project [59].

The protection functionalities should increase the safety of the acting firefighter at the site of operation by the early detection and avoidance of threats giving a definite feedback to the acting firefighters (see Fig. 15.2 for the concept). There exist historic sight signals such as *attention, withdrawal or person located*. The system architectural concept has to take into account that there exists a hierarchy for different scenarios: the emergency scenarios have high priority; the distance control has medium priority; and the temperature control has low priority as claimed in stakeholder workshops [60].

The glove (Fig. 15.3) fulfils the European standard for protective gloves for firefighters EN 659. The sensors of the glove measure environmental and vital parameters of the firefighter, and two miniature vibration motors provide haptic feedback. The communication uses an 802.15.4 ZigBee module [61]. Two accelerometers interpret hand signals or immobility. An analogue reference temperature sensor monitors the human temperature on the back of the hand, and a thermocouple measures contact heat.

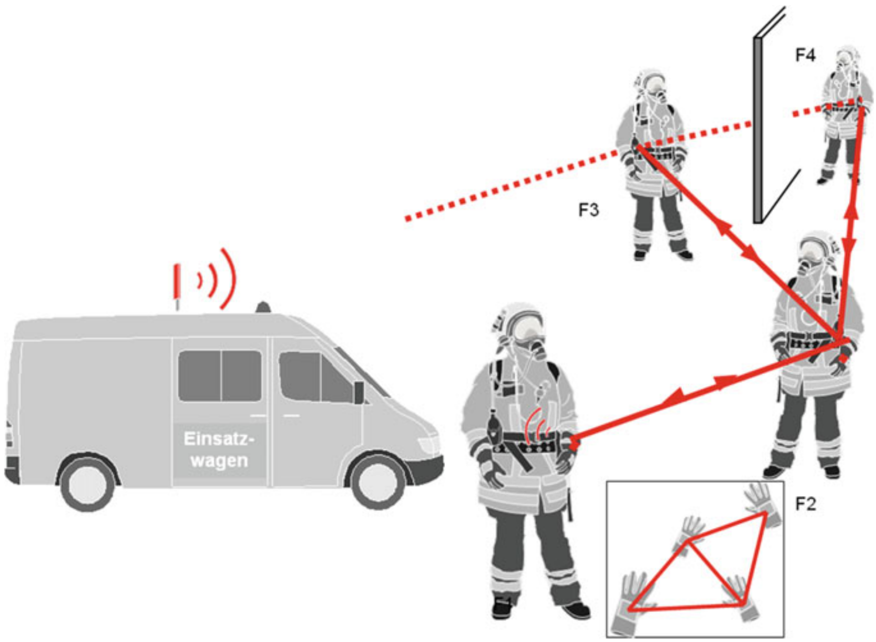

Fig. 15.2 *GloveNet* architectural concept (Image University Bremen - TZI)

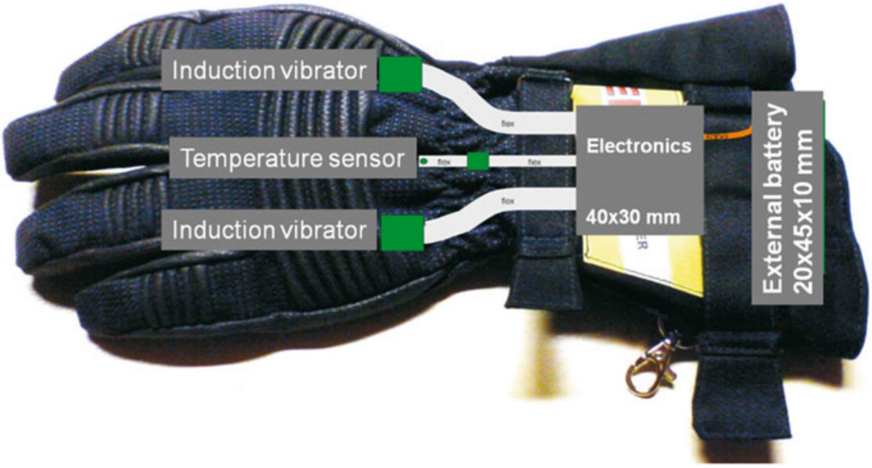

Fig. 15.3 Smart protective glove (Image University Bremen - TZI)

For the design of the electronics integrated into the glove was the main challenge to avoid any thermal bridge between the outer sensing part and the electronic components within the smart textile as temperatures of touched surfaces can reach 200 °C.

Different layers of the textile cover all electrical parts placed inside the glove. Behind the first carbon cloth layer near the skin, one finds the main board to ensure the same protection for the electronic as for the hand. Figure 15.4 shows the main board design with a flexible connection to the vibration motors (see [62] for details).

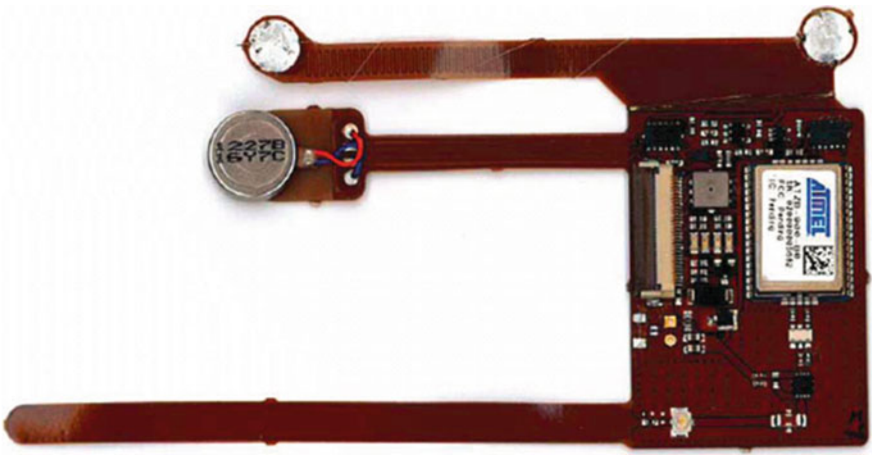

Fig. 15.4 *GloveNet* flexible electronics (Image University Bremen - TZI)

The technological requirements concerning robustness and reliability required the specific stiff-flex design without any textile component.

There is a need to check periodically, e.g., the environmental temperature, the air pressure around the firefighter and the life sign of each firefighter to let the command post monitor the status of each firefighter.

Other signals are event driven like the gestures. One therefore classifies signals thus into periodical and non-periodical data. However, it is not necessary to transmit each reading of periodical data to the command post. Temperature readings are, e.g., divided into four fuzzy levels, i.e. normal, high, very high and dangerous. The thermocouple and the analogue reference sensor inside the glove use this classification providing eight values to reflect the environmental and human temperature variation. Air pressure readings and life signs use the same approach with only two values representing normal or abnormal status.

As the gloves are stiff, the vibration motor has a flexible connection for good haptic feedback (see upper part of Fig. 15.4). One method of feedback is to give digital voltage impulses on the vibration motor via general purpose output (GPO) distinguishing between the lengths of impulses for standard information feedback and hazard warnings. In user studies with firefighters, they could only distinguish reliably four vibration patterns. The frequency of the vibration varies from short impulses over long to continuous impulse. Details of this research are in the dissertations of Breckenfelder [60] and Mrugala [62] and the project-related user study [63].

In this example, we faced the challenge of flexible electronics and the missing availability of textile electronics. Thus, the result is a smart textile in the form of a *smartPPE* with split functionalities: (1) the textile protects as well the vested human as the electronics integrated into the textile due to the hazardous environment and (2) a separate stiff-flex electronic with sensors, actuators, computing and communication functionality.

15.7.2 Protective Shoe InoTrack

The second example is on a protective shoe for firefighters or security personnel within disaster management using the digital network tetra to provide the command post of the rescue team with information on the actual location within unknown indoor environments. This protective shoe was an outcome of the *InoTrack* project [64].

When localizing people, one distinguishes between systems using an existing infrastructure such as WLAN or GPS and those using inertial measurement units (IMU) worn by people, e.g., as part of smart textiles like shoes and today already integrated into most smartphones. When localizing or even tracking, people pedestrian dead reckoning (PDR) is the state-of-the-art approach [65].

Using the three accelerations, angular velocities and directions provided by the accelerometer, gyroscope and magnetometer of an IMU, one can calculate the relative

Fig. 15.5 Smart protective boot (Image University Bremen - TZI)

direction, speed and orientation of a person moving from a known starting point as well within as outside of buildings.

Within the joint project, we developed a protective boot (see Fig. 15.5). One challenge was a robust and reliable integration of the electronics into the textile beside issues concerning the software application of localization and communication towards the command post.

Based on the far-reaching state of the art in shoe-integrated sensors for pedestrian dead reckoning [66–69], we used in this project the approach of Beauregard [70, 71] with gyro information and Nabneys-specific calibration technique [72]. Beauregard proved [65] that using his approach, general step patterns as observed in firefighters' intervention scenarios became detectable in three-dimensional indoor and outdoor environments.

An approach to integrate the IMU into the heel were not appropriate as the protective boot has a metal reinforcement defending any wireless communication. The wireless transmission of data to the radio set and further the command post were other issues not solved at that time, although we also experimented with a wireless IMU [73].

However, as in the previous example, there was no possibility adding the functionality of the IMU in anyway to the textile part of the smartPPE. The functionality of the textile was solely to protect the human and the electronics responsible for sensing, computation and communication functionality.

15.7.3 Protective Trousers HORST

The basic concept behind the smart protective trousers is to provide an early guard in a hazardous logging situation of forestry avoiding any health risk and loss of material by stopping a chainsaw before touching the textile. Because of the study of accidental scenarios and user involvement, it became clear that a minimal "aura"

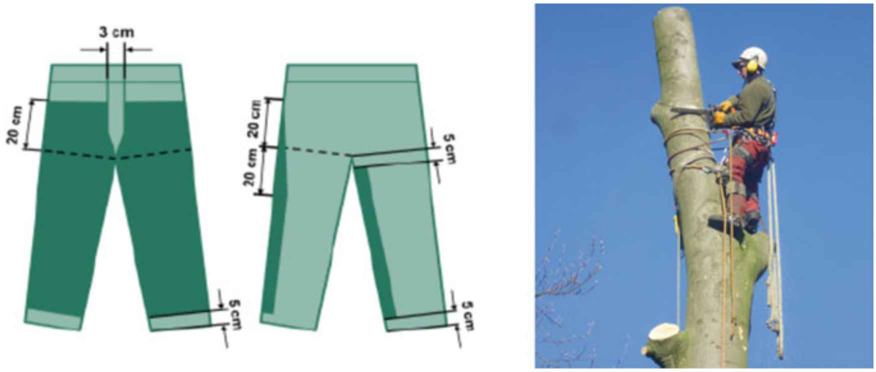

Fig. 15.6 Logging in forestry and protective trousers (Image University Bremen - TZI)

Fig. 15.7 HORST chainsaw slide with permanent magnets and reed contacts on textile layer integrated into the protective trousers (Image University Bremen - TZI)

between the trousers and the chainsaw of 5–10 cm exists, in which the chain should stop at anytime. The left upper leg and knee are most in danger, and limbing is the most dangerous task of logging in forestry (see Fig. 15.6).

The utmost challenging task was to identify an appropriate sensing principal for the working clearance taking the distance between the slide of the chain and the aura on one side and the time to stop the chain on the other side into account. As a result, the time for signal processing and transmission requires a minimal distance of 6 cm for the aura. The solution described extensively by Breckenfelder [60] and briefly in the final report [74] uses a coupling of permanent magnets in the slide of the chainsaw and reed contacts integrated into the protective trousers. The reed contacts have a double x–y pattern as in Fig. 15.7.

To ensure the serviceability of the textile with the reed sensors, professional textile care cycles included washing, cleaning and drying proving robustness without loss of functionality. The smart textile with the reed contacts became the second layer of the trousers just below the upper cloth as a protective shield of the forefront of the trousers.

In this example, we integrated the reed contacts into the textile creating a partially smartPPE. The smart textile was one of the layer for electronic components providing sensing but also a part of the clothing protecting the human and the electronics providing computation and communication functionality.

15.7.4 Protective SlimScarf

Swallowing is the important foundation of the human body to maintain normal physiological metabolism of the body. There exist different approaches: Passler and Fischer [75, 76] used the combination of signals from two microphones to suppress the interference signals and got relatively pure chewing and swallowing sound signals. Sardini et al. [77] embedded sensors in the oral cavity and detected the signal by wireless communication. Amft and Trster [78] combined many sensors for on-body dietary sensing. Amft et al. monitored in [79] each feeding action and the body weight (the sudden increase of body weight after eating). Amft et al. detected also swallowing and chewing sound [80], as heartbeat, body temperature and gastrointestinal reactions after eating. Nagae and Suzuki used in [81] sound signals to detect swallowing. However, their approach is not very efficient as many external sounds and voice signals are part of their detection but not relevant for the monitoring of swallowing.

A variety of organs and muscles under the control of neuromuscular coordination make up this physical movement. Ertekin et al. [82] found in their study that every swallow makes the throat move up and down twice. The throat moves up, closes and relocates to the original position. From the anatomical physiology perspective, one divides the whole process of swallowing into three stages: oral cavity stage, pharynx stage and oesophagus stage as Reddy et al. outline [83]. In pharynx stage, the lower jaw is closed and fixed, hyoid muscle applies a contraction force on the hyoid bone, and finally the throat moves. In the passage from the hyoid–throat complex process, the movement time of throat and its stability plays a vital role in judging whether swallowing is regular. Inspired by our common work on a smart scarf for pulse signal monitoring using a flexible pressure nanosensor [84], we monitor swallowing by a highly sensitive pressure sensor determining the time of the hyoid–throat complex movement (see Fig. 15.8).

At the pharynx stage of swallowing—moving up or down—the thyroid cartilage will relatively move the sensor on the skin surface; as a result, the surface pressure of the sensor will change. The sensor converts the changing pressure into changing voltage. The time interval of the two pressure changes indicates the duration of the throat swallowing process. Sounds and chewing will cause vibrations on the skin of the cervix. The vibration of the skin peristalsis will change the pressure on the sensor and result in changing voltage.

As the movement of the throat is a fine activity, ordinary piezoelectric sensors are not suitable for measurements. The designed SlimScarf uses a new type of nanomaterial pressure sensors as described by Pang et al. [85]. It has a rich PDMS

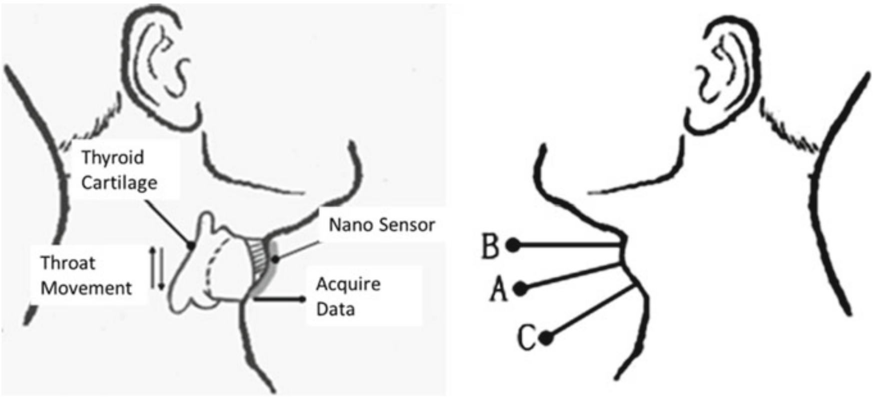

Fig. 15.8 Swallowing detection principle and sensor positions *A*, *B*, *C*

(polydimethylsiloxane) microsurface structure of high density, good mechanical strength and ductility. It is foldable with good skin compatibility as Wang et al. show in [86]. The sensor is made of two layers of SWNTs (single-walled carbon nanotubes) and 0.9–1.2 mm thick, flexible and non-irritant to skin.

The position of the sensor above (B), below (C) and in the middle (A) of the thyroid cartilage (Fig. 15.8 right) is important for the signal quality; the optimal placement is a result of extensive user testing [87]. Signals captured at position (A) have a better stability and repeatability and the largest amplitude. In SlimScarf, the sensor position is thus in the centre of the thyroid cartilage detecting swallowing movements, regular vibrations of chewing and sound signals generated while speaking and caused by head movement. During unconscious swallowing head movement, swallowing or chewing will not happen. Alike, unconscious chewing will not cause the other three behaviours. One can thus neglect the influence from other signals during long-time tests [87].

To ensure user acceptance, the system is an ordinary scarf accessory with the hardware completely integrated into the scarf clip with braided wires connecting the modules of Bluetooth (38 * 18 mm), band filter (25 * 25 mm), signal capturing (36 * 28 mm) and power (29 * 35 mm) as clips (see Fig. 15.9).

The nanomaterial sensors of *SlimScarf* collect physiological signals and transform them into electrical signals. With a cut-off frequency of 300 Hz as Reddy et al. state [83, 88] and a low-pass filter, the analog signals have a high signal-to-noise ratio. Twelve ADC (analog-to-digital converter) sample at a frequency of 1 kHz the analog signals. We stored them through the STM32 SPI interface on a Micro-SD card or sent them to a mobile device using an ultra-low power Bluetooth module. Signal feature extraction and recognition was one subsequently (see Fig. 15.10).

To analyse and judge the signals characteristics requires a suitable signal recognition mechanism for chewing, liquid swallowing and solid food swallowing and sound. From ten volunteers and twenty experiments one used data from chewing gum, drinking water, eating bread and reading a book. Further details of this are in [87].

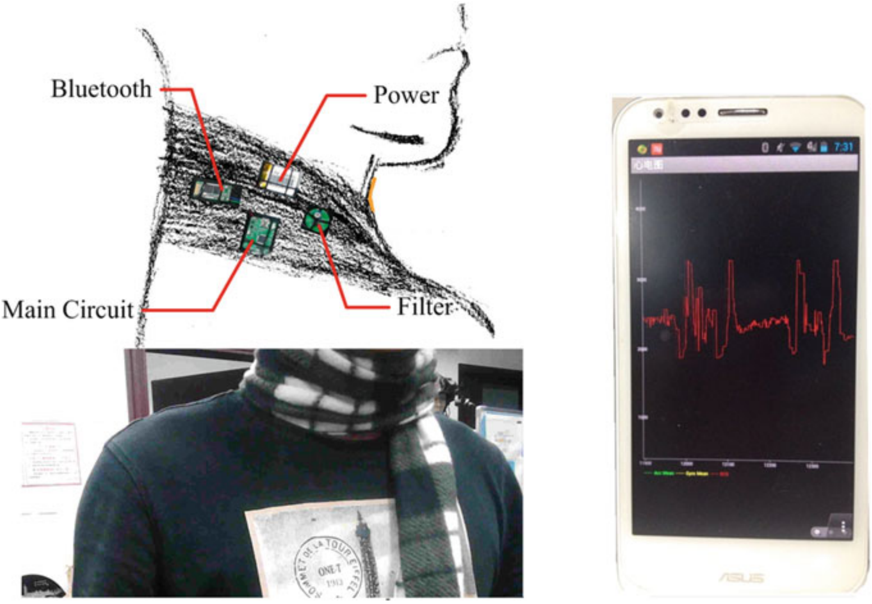

Fig. 15.9 *SlimScarf* with user interface (Image UESTC-MCC)

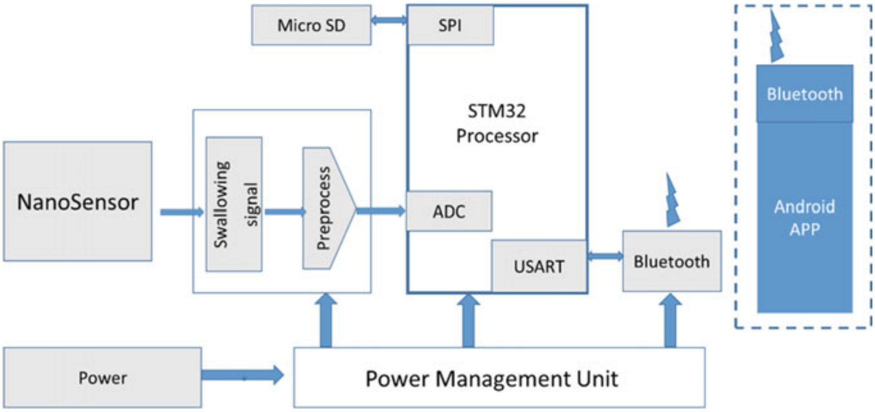

Fig. 15.10 *SlimScarf* overall system architecture

The frequency of sound is much higher than the other three signals. The two signals of liquids swallowing and solid swallowing are similar. However for solid food, before the swallowing signal must be a chewing signal other than swallowing liquids. Chewing signals in the time domain are easy to distinguish from solid- and liquid-swallowing signals.

A normal person swallows 600–2000 times a day (see Denk et al. [89]), and each swallowing action lasts in average 0.86 s due to Amft and Trster [90] or between

300 and 1000 sampling points. In total, the effective time of swallowing is only 516–1720 s per day. The straightforward approach of Nagae and Suzuki [81] does not consider that each sampled signal includes beside effective noise signals. As a result, computation is ineffective as most signals will not be those of swallowing. With our approach described in [87] in detail, we reduced the computational complexity and power consumption of the whole system. The recognition rates we got from tests with ten subjects were comparable to those of Nagae and Suzuki [81] sufficient, however, leaving still room for improvement especially to distinguish between swallowing of liquid and solid food. There is a great potential for non-invasive wearable systems using flexible nanomaterial pressure sensors for detecting swallowing signals but also other physiological signals, as body temperature or ECG. The example shows in anyway that one can gather at least some senor signals using textile components.

15.8 Challenges for SmartPPE

It is a matter of fact that sensors became smaller during recent years as a side effect of the smartphone development. The box with the inertial measuring unit being a part of our smart boot in the InoTrack project had a size of 58 mm $\times$ 58 mm $\times$ 22 mm. Those boxes of a motion suite we use today for motion tracking in human robot collaboration [57] measure 12.5 mm $\times$ 13.1 mm $\times$ 4.3 mm, which is less than one per cent of the volume. This reflects the development of ten years, and miniaturization of components and subsystems will continue. With this miniaturization, connections have to change.

Until today, the wireless body area network based on interconnected sensors and actuators with own energy supply and thus mounted without electric connections on the textile are still a vision. The energy supply is an issue existing since the early days of wearable computing. Progress is definitely there as Starner outlines [91]. However, the eventual breakthrough is still missing.

Batteries, processors or complex sensors like inertial measurement units are not available as textile subsystems. Moreover, for a robust and reliable design of systems consisting of rigid electronic components, even being very small on the in nature flexible textile layer the connection requires a lot of design attention. The electronics textile connectors and their standardization are an issue as ten years ago.

15.9 Conclusion

In this chapter, the focus is on an application of smart textile, namely as smart personal protective equipment. This is a special purpose of wearable computing and finds its field of application either in hazardous environments or as part of health care. The task for smart textiles is here the need to combine and integrate complex sensors and sensor subsystems, communication components and computing subsystems into a textile, which is a protective, basic ability of clothing. For hazardous environments, the clear focus is on protection. In health care, also issues of being comfortable and fashionable are beside protection of importance. The approach today is to integrate electronic components into the textile, and let the textile take the passive part of protection and the electronic components the decision to become active. However, beside miniaturization, future textiles will become smarter also in itself by anticipating sensor and actuator features usable in smart personal protective equipment as already seen in our last example. The workshop of Schneegass et al. [92] and this handbook are an attempt in the field of smart garments as urgently needed to innovate smart personal protective equipment towards smart textiles.

Summary

Wearable computing and smart textiles are the enablers for smartPPE (Personnel Protective Equipment). Was wearable computing first the idea to integrate computing power into clothing to, e.g., access information, we observe in recent years a split into two domains: wearable computers as smart phones, glasses and wristbands on one side and smart textiles on the other side.
The research here described in some detail deals with a specific domain where these two developments meet: the smartPPE where the smart textile gathers sensor information and the wearable computer automatically generates context information to protect the health status of the person wearing the smart textile. This can be necessary due to perilous environments or chronic diseases.

Acknowledgements Our thanks go to past and present co-workers being the foundation of the presented outcome: Chunlei An, Hannes Baumann, Stephane Beauregard, Michel Boronowsky, Dmitrij Boger, Stefan Brending, Christof Breckenfelder, Xiao Chen, Guo Chenggang, Christian Dils, Otthein Herzog, Peter Hoffmann, Zhiqi Huang, Hendrik Iben, Yi Kang, Andreas Kemnade, Holger Kenn, Ali Mehmood Khan, Peter Knackfu, Pierre Kirisci, Rdiger Leibrandt, Markus Modzelewski, Yehya Mohamad, Damian Mrugala, Xiahou Shiji, Tan Shuqiu, Hendrik Witt, Li Xinyu, Fan Xiong and Patrick Zeising.

The research had public funding from the European Commission, the German ministry of Research and Development and the German Ministry of Commerce, the Sino-German Research Foundation and many industrial partners mentioned in the cited references.

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Chapter 16
Textile Integrated Wearable Technologies for Sports and Medical Applications

Heike Leutheuser, Nadine R. Lang, Stefan Gradl, Matthias Struck, Andreas Tobola, Christian Hofmann, Lars Anneken and Bjoern M. Eskofier

Abstract Innovative and pervasive monitoring possibilities are given using textile integration of wearable computing components. We present the FitnessSHIRT (Fraunhofer IIS, Erlangen, Germany) as one example of a textile integrated wearable computing device. Using the FitnessSHIRT, the electric activity of the human heart and breathing characteristics can be determined. Within this chapter, we give an overview of the market situation, current application scenarios, and related work. We describe the technology and algorithms behind the wearable FitnessSHIRT as well as current application areas in sports and medicine. Challenges using textile integrated wearable devices are stated and addressed in experiments or in explicit recommendations. The applicability of the FitnessSHIRT is shown in user studies in sports and medicine. This chapter is concluded with perspectives for textile integrated wearable devices.

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S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_16

16.1 Introduction

Textile integration of wearable computing components lives up to the promise of offering innovative and pervasive monitoring possibilities. Relevant fields of application can be found in the military clothing sector, protection, and security area, and in the health, sports, and medical domain. In our example, we integrate measurements of the two biosignals (electrocardiogram and respiration) and position in the FitnessSHIRT (Fraunhofer IIS, Erlangen, Germany). It is a shirt for sports and medical applications and will allow more convenient monitoring solutions for both application areas. In the following, we will give an overview of the market situation, application scenarios, and related work. We will furthermore explain the FitnessSHIRT algorithms and hardware in detail and show its applicability in real user studies. We will also give an outlook of future application possibilities for textile integrated wearable technologies.

16.1.1 Market Situation

According to the IDC's Worldwide Quarterly Wearable Device Tracker [1], 76.1 million wearables have been sold worldwide by the end of 2015. This number includes both basic wearable devices (mostly activity and fitness trackers) and smart wearable devices, e.g., technologies such as smart eyeglasses, smart textiles, and smartwatches. It is estimated that 245 million will be sold in 2019. That is an increase of 300% compared to 2015. Wearable technologies and applications both belong to the most emerging segments of the technical industry since 2013, where sales were 3 billion euros in Europe alone. Analysts value the growth of the market in Europe with up to 9 billion euros until 2018. The prognosis for world sales until 2019 went up to 25 billion dollars and will probably increase to 70 billion until 2025 [2]. About 75% of the adults in the USA already own a device that can at least measure one fitness or health-related parameter. According to Ballhaus et al. [3], 60% of fitness wearable device owners are male and more than the half of them are below 34 years. There are already a lot of competitive companies in the wearable market that range from small start-ups to well-established companies like Apple (Apple Inc., Cupertino, California, USA) and Samsung (Samsung Group, Seoul, South Korea) that try to gain market share and to increase their growth.

When we talk about wearables as a gadget and not as a medical product, both issues seem to even be more important than absolute measurement accuracy. Chris Allen, CEO of iDevices, found that "it only takes one bad experience for the customer to say: I'm done with this product" [4]. When looking at smart textile integrated wearables, it can be shown that the current market sales, technical requirements, and user expectations are different to the general wearables' sales, requirements, and expectations mentioned above. This could have two reasons. First, the market for textile integrated wearables is just starting to grow, and thus, reliable prognoses are difficult. Second, textile integrated wearables have the potential to close the gap between sports or fitness applications and medical use cases, e.g., in injury prevention, medical diagnosis, and therapy. Therefore, a high measurement accuracy is mandatory and has to outweigh design decisions regarding user experience.

16.1.2 Application Scenarios

Major application areas for the textile integrated wearable technologies are in the field of sports and medicine. In sports, novel training support systems can be realized. In medicine, innovative solutions for cardiovascular health can be implemented. Both areas will be described in more detail in the following.

Over the last decade, personal fitness became more and more important, especially in the USA and great parts of Europe. In postindustrialized countries, an increasing number of people are interested in their personal health according to the motto: "A healthy mind lives in a healthy body." This can be observed in an increased number of members of sports clubs, a growing number of fitness studios, and a huge number of sports-associated support products, such as special food, clothes, or wearables. Moreover, the demographic evolution reminds people that they will grow much older than former generations, which comes with the fear of being helpless and sick for many years [5]. Therefore, personal health is directly linked to personal fitness [6]. With the increasing number of hobby athletes, the wearable technologies, simple to use and affordable, became more and more important and simultaneously developed into a huge market. Chest belts and pulse watches, for example polar systems (Polar Electro Oy, Kempele, Finland), suunto (Suunto Oy, Vantaa, Finland), or apple watch, are easy to use and allow a first insight into body signals. Via pulse analyses, running speed, or calorie consumption, people are able to interpret their body reactions but also alter sports intensity to an individual fitness level. Moreover, being able to see the numbers of how sports increases the personal fitness results in a higher motivation for doing workout sessions.

In an older growing population, solutions for medical care of elderly become more and more important. A parallel development of urbanization poses a great challenge for medical and health care, especially in rural areas. Since the reliability of data from wearable technology keeps growing, wearable technology can help in the struggle with modern healthcare challenges. For example, wearable cardiac monitoring systems that do not hinder patients in their daily behavior could be able to detect rhythm disorders at an early stage. Atrial fibrillation is the most frequent arrhythmia and can be detected by cardiac rhythm analysis. Furthermore, about 25% of strokes are caused by atrial fibrillation due to thrombosis. Patients who have to see doctors on a regular basis to check up their vital functions could be overseen from their homes with the help of wearables and communication interfaces which both, the doctor and patient, can use. There are several systems and projects that include wearables to perform intelligent, anticipation techniques. Examples are systems for collapse detection [7] and elderly care [8–10]. Yet, it is a relatively new field of research where much more work and development have to be done.

16.1.3 Challenges

With the increasing complexity and power of modern wearable systems, a crucial challenge emerges: the usability. It implies easy interaction with the wearable or textile while still providing profound insight into the human body. Due to the spread of wearables in every part of the society, developers and producers have to tackle a wide audience that can handle the new technology. This includes easy-to-use setups as well as self-explaining apps and data handling. Every user has to be able to acquire useful data, even the impatient one. Rather complicated systems, such as the determination of a specific training heart rate via the heart rate variability (HRV), have to be done prior to the training and demand a closer look into the manual. The easier and more self-explaining such a system is, the more it will be used. More complicated systems are usually used by either technically interested persons or athletes, who are keen on acquiring useful data. Among those usability aspects are, for example, unique color codings, when LEDs symbolize states of standby, shutdown, and data acquisition. Another aspect is to gain information about sports-specific positioning of the wearable. Additionally, the device should provide reliable data for a long time to the user. Signal quality should be excellent independent of the activity the user might want to perform. At all times, the textile should have an appealing appearance. The goal is to have an unobtrusive and comfortable wearing experience. The textile should be robust and last for several wash cycles. The associated algorithms should supply accurate and useful evaluations given the available signals, without misleading or false values, for example when determining step counts or burned calories.

16.1.4 Related Work

There has been quite a substantial amount of work both on algorithms and on systems for wearable health monitoring.

Reported in the American Journal of Medicine in 2014, Barrett et al. [11] demonstrated that 24/7 ECG monitoring can be performed with high quality in an unobtrusive fashion, using a small, wearable "patch" device attached to the chest. Their system was compared to a typical 24-h Holter monitor using 146 patients who referred to a cardiac investigation laboratory for ambulatory ECG monitoring [11]. The majority of patients considered the new device to be more comfortable than the Holter monitor. Both devices were able to detect a similar number of arrhythmias.

In 2012, Hu et al. [12] built iBoSen, a matchbox-sized sensor node that is able to record and analyze ECG, electroencephalogram (EEG), respiration, and body temperature in quasi real time using an additional smartphone connected via Bluetooth.

A similar concept, for ECG signals only, was presented in the same year by Gradl et al. [13] using off-the-shelf hardware and a different processing methodology. The popular Shimmer sensor platform was used in this case [14]. There are numerous other approaches that either focused on developing the software and/or hardware aspects of such systems [15–20].

A similar concept to the approach presented in this chapter is the work by Morrison et al. [21] from 2014. They described a textile integrated 12-lead ECG recording system built into a compression shirt. They also used dry electrodes as tissue interface and on-board signal processing. However, their system used a proprietary signal transmission concept which did not rely on existing standards such as Bluetooth variants.

16.2 Materials and Methods

In this section, we describe the hardware and software of the FitnessSHIRT, give recommendations for hardware/software codesign and for the development of mobile applications, and present recent sports and medical applications using wearable technologies.

16.2.1 Functionality of the FitnessSHIRT

16.2.1.1 Hardware

Hardware of wearable systems can be split into two parts: the textile part and the electronic units that compute and process the data. The latter have to be small, light, and removable and should not disturb the user. These are often realized in small units with push buttons (polar, garmin (GarminLtd., Schaffhausen, Schweiz), suunto) in the case of textile wearables. Another solution is integration of the wearables in wristbands (fitbit (Fitbit Inc., San Francisco, CA, USA), apple watch).

In our measurements, we used the Fraunhofer FitnessSHIRT. In the current version of the FitnessSHIRT, the hardware, namely the electronic units, is stored in a 5.0 cm × 8.2 cm × 1.3 cm plastic box (Fig. 16.1). Electronic contact to the sensors in the garment is made via six push buttons. Inside the plastic box, the ECG is processed using a differential coupling, whereas breathing activity is processed via resistance measurement in an AC/DC coupling. An ARM processor handles the incoming signals from ECG electrodes and the breathing band. Before the analog data are digitalized, the ECG is filtered with a Notch filter to eliminate frequencies at 50 Hz. The preprocessed data are subsequently sent via Bluetooth to a laptop or smartphone. To be able to combine vital data with precise position data, we developed the LokVitalTag, a round electronical unit (diameter 5.2 cm, height 1 cm, Fig. 16.1), that not only combines the before explained couplings to derive vital data, but is

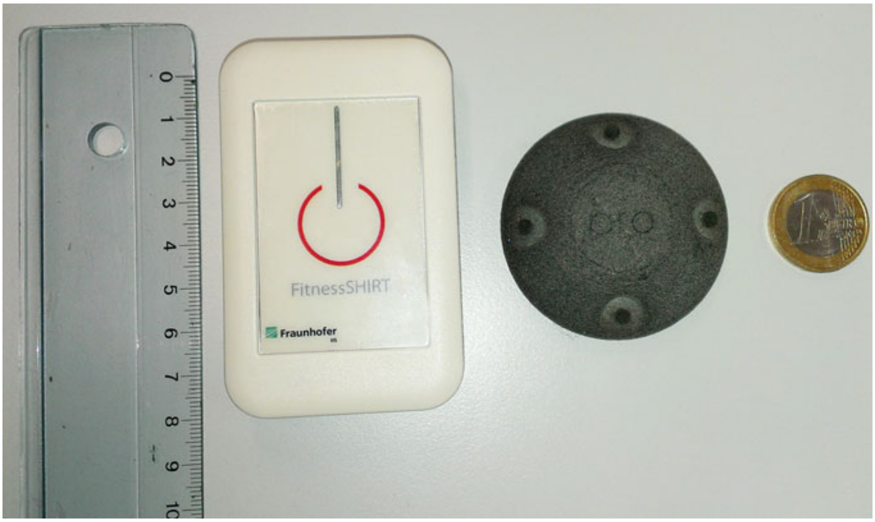


Fig. 16.1 Technical units of the FitnessSHIRT. From *left* to *right* current FitnessSHIRT technical unit, to acquire vital data; *middle* new LokVitalTag to acquire vital and position data; *right* 1 euro piece for scale reference

also communicating with an antenna system to detect position data. Via the time of arrival and time difference of arrival of the antenna/sender signals, the system is able to detect positions with a precision of a few centimeters. To be able to process these data in real time, the LokVitalTags are equipped with an 848-MHz data channel. This allows a high data rate as well as fast data processing.

Another central topic when talking about wearables is the textile integration. Standard systems to measure vital data, such as polar, garmin, or suunto, use chest belts for monitoring. However, these belts are not designed for long-term use as they can lead to skin irritations and are uncomfortable to wear [22]. Therefore, recent systems integrate sensors into shirts and other textile base layers (OM Signals, Hexoskin, Fraunhofer), which allows the user to wear vital tracking systems without noticing and without having to put on a piece of clothes which they usually do not wear. The textile basis of the current FitnessSHIRT version is a standard compression shirt from the brand under armor (Under Armour Inc., Baltimore, Maryland, USA) (Fig. 16.2). To guarantee the proper working of the sensors and a good data quality, the shirt has to be a tight fit. To derive a single-channel ECG, two textile electrodes are integrated into the shirt at both sides of the thorax approximately at the height of the 4th rip, matching the bipolar Nehb chest wall derivations. As an electrode material, we used the same material which is used for transcutaneous electrical nerve stimulation (TENS) products, where the conductivity is given from integrated stainless steel or silver yarns.

Fig. 16.2 FitnessSHIRT (Fraunhofer IIS, Erlangen, Germany). The Fraunhofer FitnessSHIRT has integrated ECG electrodes to measure a single-channel ECG. A semiflexible belt around the chest permits a measurement of the breathing rate. The basis textile is an off-the-shelf under armour compression shirt

When choosing the electrode material, it is important to mind not only the data quality but also the biocompatibility. As such, some electrode materials used in chest belts are roughened on a microscale for better skin contact. However, these belts lead to skin irritations when worn over several hours. The FitnessSHIRT concept, however, is based on a long-term use; therefore, we focused also on a skin-friendly material. Thoracic respiration acquisition is realized with two elastic bands sewed into the shirt at the lower costal arch. As material, an elastic silica band is used which is coated with graphite for conductivity.

16.2.1.2 Software

In principle, there are two modalities in which software can be used with wearables: (a) The software is embedded in the technical unit of the wearable and processes the raw data on that technical unit, supplying the user with analyzed data often in an app or a display in the wearable and (b) the raw data are sent from the technical units of the wearable via Bluetooth or another data transfer system and are analyzed on the target platform and presented to the user often via a certain interface or an app. Both modi come with advantages and disadvantages. Modus (a) needs more computing time on the mobile technical unit, leading to shorter battery runtimes. However, the raw data are relatively safe on the device (due to the missing network connection) and can be presented to the user without any further devices. Modus (b) provides raw data which enable the user to interpret and analyze the data in different ways (e.g., ECG and HRV). Moreover, when data analysis is done on more computing efficient platforms, the wearable can be used in a power-saving mode [23]. However, due to the network connection, the data can be compromised when not secured properly. Moreover, the user needs a second device to look at the analyzed data. In the following experiments, we used both modi, in dependence of the scope.

Still, software is a critical component of a wearable. It has to be fast and efficient in computing due to the low available power. At the same time, the software needs to be reliable especially in the context of medically interpreted data. When interpreting ECG data, it is important to correctly detect the R-peaks of the ECG. However, the obtained data are often corrupted by artifacts such as motion artifacts and artifacts that were introduced by wires and electrostatic charge from the textile components. This makes it necessary to filter the data before analyzing the R-peak positions. The frequency range of an ECG signal is defined between 0.67 and 40 Hz [24]. In the FitnessSHIRT, high frequencies are immediately filtered by an analog band-pass filter, implemented directly on the electronic units, followed by the analog/digital conversion. To compensate for electromagnetic irradiation, a 50-Hz single Notch filter is applied. However, as some artifacts are in the same frequency range than the ECG signal, it is necessary and reasonable to filter again prior to the R-peak detection. In the FitnessSHIRT software, we implemented a three-section second-order Butterworth IIR filter with cutoff frequencies of 8 and 45 Hz. Due to the nonlinear nature of the IIR filter, a phase shift is introduced. To eliminate the phase shift, the window of n forward-filtered samples is filtered in backwards direction with an IIR filter with the exact same filter coefficients as before. One advantage of an IIR filter over an FIR filter is the reduced number of filter coefficients which results in less operation per sample to reach comparable results, which makes it perfectly suitable for mobile applications.

For detection of the R-peaks, an adapted version of the detector proposed by Koehler et al. [25] is used, which is implemented directly on the FitnessSHIRT hardware for fast processing. This enabled a hardware-based R-peak detection. The method worked by overlaying the band-filtered signal from the previously explained processing with a sawtooth-like artificially generated sinusoidal signal. The number of zero crossings of the resulting signal is continuously counted. During a QRS complex, the filtered signal goes through a phase of high amplitude during which no zero crossings occur anymore. This can be detected as sharp downward slopes in the zero-crossing counting signal. There are several thresholds which control the behavior (e.g., sensitivity) of this detector. These thresholds were adapted for the signal produced by the FitnessSHIRT sensor and the respective filtering system. They are reported and explained in detail by Tantinger et al. [26].

16.2.2 Design Recommendations

16.2.2.1 Hardware/Software Codesign

Wearable sensors are implemented as complex mixed hardware–software systems. For correct functionality, hardware and software must fit exactly together building an integral functioning entity. However, a classical approach for developing mixed systems is to specify and develop hardware and software separately. Design and development are often done by separate groups of hardware and software engineers. Furthermore, it is common to verify hardware prototypes before starting software design. Using such a separated development approach causes problems in mixed designs [27].

A common design error of smart textiles is an unmatched bandwidth of the signal processing stages. This issue is often discovered late by software engineers when the hardware does not deliver the required information due to limited bandwidth required for the signal processing algorithms. Another design mistake is an unnecessary large sampling rate causing high energy cost and high computational complexity and reducing the battery runtime, which is a non-acceptable property for wearable systems [28].

Smart textiles are complex signal processing systems. All interfaces in hardware and software have to match perfectly to build a consistent signal processing chain. The signal processing starts with the contact of the sensors to the body (e.g., ECG electrodes), continued by the sensor front end (ECG amplifier), followed by signal conditioning (e.g., band-pass filtering and preparation for analog-to-digital conversion), connected to multiple signal processing algorithms in software (e.g., R-peak detection), and finally preparation for the radio transmission (e.g., Bluetooth), often continued by the processing steps at the radio receiver (e.g., visualization processing). All parts have to fit together to achieve satisfying results and to avoid expensive design setbacks. Therefore, the whole signal processing chain needs to be designed entirely from the electrodes to the last signal processing step regardless of the question of hardware and software.

Hardware/software codesign addresses these issues by providing several techniques for the concurrent design of hardware and software components. Codesign requires more time at the beginning of a project, but it reduces the risk of expensive design errors. To take the example above, an unmatched bandwidth requires a redesign of the hardware bringing high cost and delays. Investing more time to work out the codesign of the entire signal processing chain of a smart textile reduces the risk of those setbacks. This effort requires initially more time, yet it is an essential key factor for the project's success.

16.2.2.2 Specific and General Aspects for Mobile Applications

Applications (apps) for mobile devices such as smartphones and tablet PCs have become an integral part in today's software economy. The processing power of those devices has become comparable with standard desktop computers. With their benefits in portability and user interaction (touch screens, integrated gesture detection, etc.), they are the primary target platform to either present or even provide the evaluation for signals recorded from smart textiles. This approach is already state of the art as seen, for example, in the miCoach platform for smartphones (adidas AG, Herzogenaurach, Germany) which can provide a detailed analysis of the heart rate or movements during different sports. Those apps, however, are still limited by the hardware that is available to the everyday user for tracking his or her physiological signals. The FitnessSHIRT aims at providing an actual ECG lead signal to the receiving software. This allows an app not only to provide fitness-related estimated assessments, but also to actually detect clinically relevant abnormalities in those signals. This is the idea behind the "Hearty" application (Fig. 16.3), which was originally designed to allow real-time assessment of clinical parameters in the ECG as well as give medically relevant feedback to the end user [13]. This app is able to work with the FitnessSHIRT

Fig. 16.3 Screenshot of the Hearty application [13] running on a typical off-the-shelf Android tablet and processing an ECG record in quasi real time. In the *upper area* of the interface, typical ECG-related statistics are displayed (from *left* to *right* heart rate in beats per minute, RR interval in ms, QRS width in ms, the classification of the P wave, and the runtime of the current signal). In the *lower area* of the interface, the raw signal is displayed continuously. As soon as the processing algorithm detects an R-peak, the QRS width is extracted and the QRS complex colored in *light blue*. After detecting the P wave, it is colored in *light brown* with an arrow indicating the assumed P-peak position

either by postprocessing or by evaluating the hardware-filtered signal and hardware-detected heart rate, or using the raw ECG signal generated by the FitnessSHIRT hardware to filter and process it in the software to detect arrhythmias, as described in the following. For the second method, an adapted version of the knowledge-based QRS detector described by Mohamed Elgendi [18] is used.

16.2.3 Sports and Medical Applications of the FitnessSHIRT

Over all times, sports have been an integral component of human society. Sports competitions elate millions of people all over the world and the hunt for new human records, regardless of whether running, jumping, or team sports increase the pressure on athletes and trainers. Therefore, professional athletes and trainers always look for new methods to increase their performance. Due to the fact that wearables are usually small, light, and mobile, they offer great potential for applications in sports. Combining the FitnessSHIRT with the real-time position-tracking system, RedFIR enabled us, for example, to track vital data (e.g., ECG and respiration) as well as position data from complete soccer or ice hockey games. These data were analyzed to gain information of single athletes and their state of fitness as important indicator to prevent injuries. We determined how much effort it took for the athlete to perform a certain action, how long the distance was the athlete took during that action, and how fast the athlete was. In pretests, we equipped athletes with a FitnessSHIRT and numerous player beacons to be able to track not only the athlete himself (with the beacon on the back) but also the movement of the leg and the toes. The data showed that it is possible to resolve the movement of single body parts and that there are indeed great differences between toe and leg movement, allowing sports scientist to make statements of technomotoric abilities which are crucial for the position in which a soccer or ice hockey player plays.

Further, using algorithms for sports-related tactics, the system can analyze whether the performed action was actually the most effective one. General information on each athlete and individual player position such as defenders, midfielders, or attackers helps in analyzing the overall performance of the whole team. All this information can help to improve the performance in real time during a competition, provided that regulations for that sport allow for it. Nevertheless, training sessions can be monitored and recorded using the combination of RedFIR and FitnessSHIRT. The technology helps revealing weak spots that can be improved in future training sessions. Another application is an ongoing project in javelin throw, where we analyze dropping speed and vital data of the athlete in order to optimize training and competition preparation. Especially in javelin throw, the speed and the angle in which the javelin is thrown decide how far it will fly. Current versions of training support often work with video analysis, which is not automated and therefore time-consuming and does not offer a direct analysis for the athlete. With a real-time analysis, an athlete can, however, react directly with changes in body position, etc.

All of the above-mentioned aspects help improving the performance of the whole team by precisely analyzing the individual athletes and optimizing their capabilities. The same holds true for training sessions in which every athlete can work on their weak spots going through an individualized training session that is designed only for them. Based on the data recorded during a game or training session, athletes no longer have to go through the same training routine altogether but work more effectively and more efficiently to improve their skills.

However, not only professional athletes use wearables. Especially hobby athletes are a broad clientele for wearables, measuring vital data such as ECG, breathing rate, and speed. On the one hand, these ambitious hobby athletes want to monitor their own development, in terms of gained speed or shape. This includes also feedback from the system in terms of a “well-done” remark or a suggestion for better results, almost as if a personal trainer would be present. On the other hand, these wearables can also help to prevent injuries, due to physical overload or too hard beginning exercises.

Apart from sports and fitness applications, textile integrated wearable technologies such as the FitnessSHIRT have their usage in medical applications. To begin with, the medical background is briefly described. Afterward, the current state regarding cardiovascular applications using the FitnessSHIRT is given.

Heart rate or HRV analysis is the investigation of the current heart rate alone. Applications of HRV range from arrhythmia detection [29] and sudden cardiac death [30] to sports and training sciences [31]. HRV had been identified as a diagnostic marker for overtraining. Furthermore, HRV is used for assessing autonomic changes in endurance exercise training [31]. For this investigation, only the time instances of individual heartbeats have to be known. One common representation of the phenomenon HRV can be seen in the time domain in a tachogram. Here, the duration of individual RR intervals is plotted on the vertical axes where the time occurrence of these RR intervals is plotted on the horizontal axis. In healthy subjects, two consecutive RR intervals do not have the same duration and a sinusoidal oscillation of the RR intervals is visible. In the frequency domain, power spectral density (PSD) and other calculations show the power distribution over frequency related to this oscillation in the time domain. In both domains, standard parameters can be calculated [24]. HRV analysis addresses the phenomenon that consecutive RR intervals have different durations [24]. For this, accurate R-peak positions have to be known.

We suggested an early detection of arrhythmias using solely the RR interval signal [29]. Such an early detection could improve the identification of patients and their medical condition. We calculated features that regarded the oscillation of RR intervals due to respiration (respiratory sinus arrhythmia) and considered only the preceding individual RR intervals. We obtained mean class-dependent classification accuracies of 90% when using a naïve Bayes classifier. The prerequisite to this approach was that normal heartbeats preceded the abnormal heartbeat.

In order to have the most accurate approximation of the true HRV, it is necessary to refine the R-peaks found by any QRS detection algorithm. Therefore, we developed a peak refinement postprocessing step to find the actual R-peaks using the filtered and the raw ECG signal [32]. All ECG signals recorded with the current version of the FitnessSHIRT are derived from Einthoven's lead I. As such, given the natural variability between the orientation of human hearts, and the fact that also abnormal beats should be detected, a simple maximum search as peak refinement is not feasible. This is due to the fact that the R-peak is not necessarily the largest positive peak in any lead except the Einthoven lead II. Our refinement step searches for the maximum absolute difference between the median sample value and all samples found near the assumed R-peak position coming from the QRS detector, and this procedure is described in detail by Gradl et al. [32]. The benefit is that also negative or aberrant QRS complexes, as they are often seen in abnormal heartbeats originating from the ventricles, can be detected accurately.

Arrhythmia classification is currently performed in software on mobile devices, as a postprocessing step to the R-peak detection and refinement. There are two implementations for detecting arrhythmias. Either the RR intervals were checked for abnormalities, or the morphology of the heartbeat was evaluated. The first method has already been discussed in one of the last paragraphs [29]. For morphological evaluation, the raw ECG signal was used together with the filtered one (Fig. 16.4). From the refined R-peak positions, the Q and S waves and the P wave maximum, onset, and offset were extracted for each beat. For the Q and S waves, not only the wave peak but also the Q-onset and S-offset (J-point) were determined. Given those feature points, the width of the QRS complex, the height of the RS amplitude, the

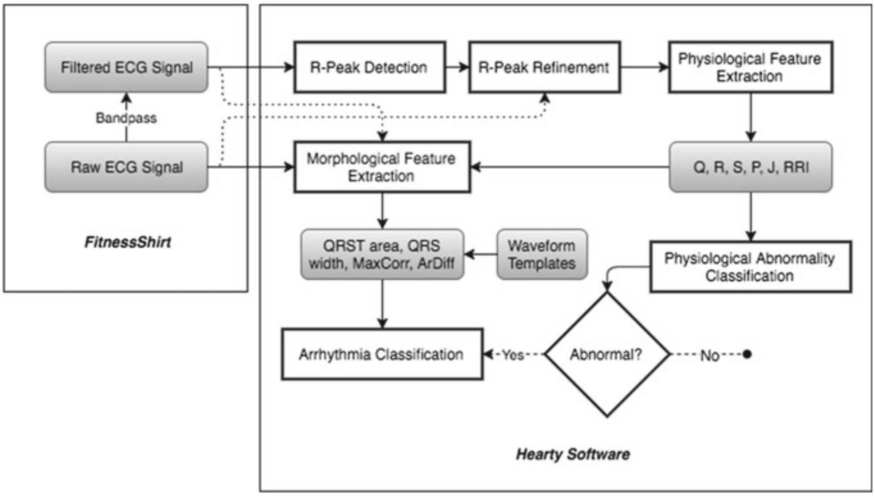


Fig. 16.4 Signal processing and arrhythmia detection pipeline as it is currently implemented in the FitnessSHIRT and in the mobile device processing software (Hearty). On the *left side* of the diagram, the steps performed in the embedded hardware are shown. The signal is then transmitted to a mobile device and further processed in software, which is shown on the *right side*. The morphological features that are calculated consist of the QRST (waveform) area, the QRS width, and two features derived from waveform templates of normal beats: the maximum correlation coefficient to the templates (MaxCorr) and the area difference (ArDiff) [13]

duration of the PQ interval, and the P- and Q-amplitudes were calculated. These features and the RR interval were used for a preliminary knowledge-based physiological classification which was adapted from clinical ECG analysis procedures [33]. If an abnormality was found in this step, an additional procedure classified the beat according to the method described by Gradl et al. [13]. For this step, four features were calculated and used. The first two features were the QRST waveform area and the already determined QRS width. The remaining two features were derived using initially generated waveform templates from normal beats: the maximum correlation coefficient to the templates (MaxCorr) and the area difference (ArDiff). An overview of the entire processing and classification pipeline is depicted in Fig. 16.4.

16.3 Experiments

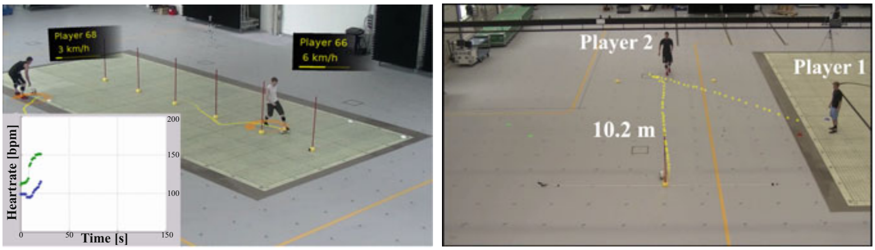
In this section, we describe experiments that were performed to demonstrate the applicability of the FitnessSHIRT in the previously mentioned application areas in sports and medicine.

16.3.1 Usability

We tested the usability of the FitnessSHIRT in a real environment. We considered the placing of the technical unit, the interaction with the user during data acquisition, and the user interface for analyzing the transmitted signal on the computer screen.

Using the FitnessSHIRT, athletes performed typical soccer experiments. One experiment was for exampling dribbling through a slalom route (Fig. 16.5a). Another experiment consisted of passing the ball to a second player who then shot at a cap to measure pass accuracy (Fig. 16.5b). Handling with the FitnessSHIRT showed that clipping the technical unit on the back of the player was reasonable in soccer, because soccer players also use the chest to stop the ball. This required a second person for placing the technical unit to ensure that the technical unit was switched on and was correctly acquiring data. Moreover, light signals indicated the status of the technical unit, e.g., standby, recording, or shutting down. These statuses need to be specific and easy to distinguish. Therefore, the technical unit is blinking in red while being in standby, in green while recording, showing a long red light while shutting down, and a long green light while switching on into power mode.

Moreover, when the vital data from these experiments were analyzed, the usability of the software, especially the user interface, became more important. Therefore, we are constantly developing attractive and self-explaining user interfaces (Fig. 16.6).



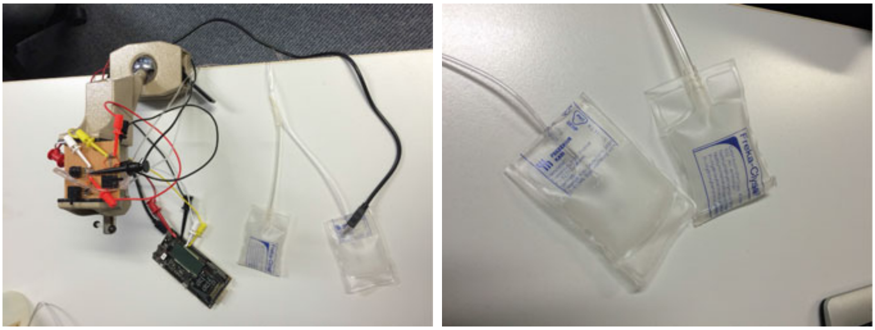
(a) Slalom parcours. **(b)** Passing exercise.

Fig. 16.5 Visualization of typical soccer experiments. Athletes are running through a slalom parcours (*left*, **a**). Heart rate, speed of the athletes, and running path are shown. *Yellow lines* indicate the running path of the players. Speed of players is given in the *black boxes* near the athletes. Heart rate of both players was monitored simultaneously (*inset* heart rate in *green* belongs to player 66 and heart rate in *blue* to player 68). The exercise raised the heart rate of the athletes. Athletes are performing passing exercises (*right*, **b**). Player 1 passed the ball to player 2 who subsequently shot at a pylon. *Yellow dotted line* indicates the path of the ball. The distance between player 2 and the pylon was 10.2 m

Fig. 16.6 FitnessSHIRT GUI. The user interface of the Fraunhofer FitnessSHIRT shows the ECG signal on the *upper left side* (in arbitrary units (a.u.) as it is a demo version) and the breathing rate (in a.u.) on the *lower left side*. On the *right side* are displayed the raw data of the acceleration sensors (*upper curve*) and the moving average over the activity (calculated from the acceleration sensors in x, y, and z directions, *lower curve*). Moreover, the persons' current heart rate and breathing rate are shown in beats/min (heart rate; *upper right side*) and breaths/minute (breathing rate; *upper right side*)

16.3.2 Contact Pressure

To obtain the high-quality data, the contact pressure of the ECG electrodes on the skin plays a crucial role. In this experiment, we measured the data quality in dependence on the contact pressure of the electrodes. We designed a pressure measurement device consisting of an air cushion for each electrode and a small circuit to be able to measure the different contact pressures on the electrodes in the textile (Fig. 16.7).



(a) Experimental setup. **(b)** Two air cushions with pressure sensors.

Fig. 16.7 Complete experimental setup of the pressure measurement device (*left*, **a**) and the air cushions for the electrodes (*right*, **b**). We measured the pressure with a bench vise and a small circuit

In this experiment, five subjects were equipped with the FitnessSHIRT and the measuring device and performed six running tests on a treadmill (Horizon Fitness, Johnson Health Tech GmbH, Trittau, Germany). During all the tests, the ECG was derived. After each running test, the contact pressure was increased. When the shirt and the measuring devices were completely attached to the subject, the subject started by a complete exhalation indicating the starting point of the measurement. After that, the subject slowly exhaled and inhaled for five times, signalizing rest. Simultaneously, the pressure was measured to be around 1 kPa. Afterward, the subject performed a 90-s protocol on a treadmill (Horizon Fitness, Johnson Health Tech GmbH, Trittau, Germany) (30-s standing, 30-s running at 6 km/h, 30-s running at 12 km/h). Subsequently, the contact pressure was raised about 1 kPA and the procedure was repeated. Altogether, pressure was raised six times reaching a maximum contact pressure of 6.62 kPa.

Analysis revealed that the quality of the data was defined as a clearly visible ECG with no signal saturation. The data showed clearly that the contact pressure directly correlates with the quality of the data. However, the exact contact pressure depends on the state of the skin and therefore cannot be set on a default value and has to be adjustable each time. As a conclusion of this experiment, we decided to integrate a stretchable belt to be able to customize the chest coverage of the shirt and therefore the pressure with which the ECG electrodes are pressed to the chest.

During the experiments concerning the contact pressure, we realized that derived data from some persons were noisy despite of a good contact pressure. We measured their skin conductivity and detected values far above the normal value of around 10 kΩ. Unfortunately, skin conductivity depends on the individual skin nature, products for body and bath, and sweat state and can vary not only from person to person, but also from day to day (for the same person) [34, 35].

16.3.3 *Hardware Evaluation*

16.3.3.1 Washability

We are currently performing a long-term washing test with a fixed protocol, different washing agents, and a subsequent comparison and analysis of raw data. Preliminary results showed that in order to guarantee the authentic data provided by the textile electrodes even after several washing cycles, we recommend to wash textiles with integrated electrodes such as the FitnessSHIRT always on a mild stage of the washing program (e.g., wool or silk) with a maximum turning rate of 800 rpm and maximum temperature of 30 °C. With respect to these instructions, the raw data should not have any obvious deficits in quality, even after several washing cycles.

16.3.3.2 Durability

We performed a durability test using the technical unit of the FitnessSHIRT. The test was performed in seven different modi: (1) off, (2) standby, (3) a data acquiring mode where the data were stored in the internal flash store, (4) a data acquiring mode where the data were sent immediately via Bluetooth Low Energy (BT4), (5) a mode where a serial port profile (SPP) connection is established, (6) a mode where the data were sent via SPP, and (7) a mode where data were sent via both SPP and BT4. We measured the power consumption using an oscilloscope and computed the theoretic runtime. Additional to the theoretic runtime, we provide the estimated runtime as 90% of the theoretic runtime. The estimated runtime is more realistic due to the fact that the power consumption grows at the end of battery runtime. Table 16.1 shows the results of the described durability test.

Table 16.1 Results of the durability test using the FitnessSHIRT in seven different modi

Mode	Current consumption (mA)	Theoretic runtime (h)	Estimated runtime (h)
Off	0.1	2479.3	2231.4
Standby	5.0	60.0	54.0
Data acquire flash[a]	10.0	30.0	27.0
Data acquire[b] and BT4	13.0	23.1	20.8
Established SPP connection	15.0	20.0	18.0
Data acquire and SPP transfer	32.0	9.4	8.5
Data acquire and SPP and BT4 transfer	32.0	9.4	8.5

Abbreviations: BT4: Bluetooth Low Energy; SPP: serial port profile
[a] Data acquiring mode where the data were stored in the internal flash store
[b] Data acquiring mode where the data were sent via BT4

16.3.4 Embedded Software Evaluation

We compared the performance of the embedded software as described in Sect. 16.2.1.2 with an open source Hamilton algorithm [36]. The database was a set of data acquired with the FitnessSHIRT where the test subjects had to perform an ergometer test. The ergometer exercise began at 130-W load followed by an increase of 30 W every 3 min until voluntary exhaustion. We took care that 65–70 rpm was kept constant. All subjects were healthy males of average fitness level with an average age of 31.6 years. We analyzed running data from 10 subjects and ergometer data from 25 subjects. ECG data were manually annotated.

We calculated the true-positive rate (TPR) and the positive predictive value (PPV) for comparison. To address the phase delays introduced with the filtering, detected R-peaks often did not exactly match the annotation. Therefore, we chose an acceptance radius around each annotation and employed the nearest neighbor search prior to distance thresholding to match annotations to detections and to decide for each of the above cases.

Comparing 20 sets of data with 8193 hand-annotated R-peaks, we obtained a TPR of 90.0% (on ergometer data) with acceptance radius of three samples, corresponding to an accuracy of 6 ms [36]. The Hamilton algorithm [37] revealed in this case only a TPR of 62.2%. When increasing the acceptance radius, the PPV of both algorithms raised. Our algorithm reached a TPR of over 99% for an acceptance radius bigger than 8 samples, whereas the Hamilton algorithm reached comparable detection rates earliest at a radius of 15, corresponding to about 30 ms.

This showed that our algorithm performed almost twice as accurate as Hamilton's algorithm under the conditions mentioned [36]. Note that the algorithm described by Pan and Tompkins [38] was established to find the position of QRS complexes, not necessarily R-peaks. If the aim is, however, to derive HRV features, the exact R-peak position has to be known. Moreover, the Hamilton algorithm [37] was developed to evaluate clinical ECG signal, whereas we used mobile-recorded data with motion artifacts using the FitnessSHIRT.

16.3.5 R-Peak Refinement Software Evaluation

The R-peak refinement was evaluated by determining the time distance between the reference annotation for an R-peak, made by cardiologists, and the R-peaks before and after refinement was applied [32]. As test set, all detectable beats from the MIT-BIH arrhythmia database [39] were used without leaving out any record. The average time distance between R-peaks and reference annotations from regular beats for the Elgendi QRS detector without refinement was 8.7 ms. With refinement, this dropped to 4 ms. For abnormal beats, the average time distance to the reference annotation without refinement was 13.4 ms, with refinement 6.7 ms.

This showed that the R-peak refinement algorithm improved the accurate detection of R-peaks. This is crucial for calculating HRV in application areas such as arrhythmia detection.

16.4 Outlook and Perspectives

Wearables are part of today's society. Textile integrated wearable technologies conquered and will further conquer the market. The FitnessSHIRT, in the current version, respects already several challenges that a textile integrated wearable technology should address. The different aspects of usability (e.g., interaction with the user while handling the technical unit or acquiring data) were tested in a real environment. The contact pressure relating to signal quality was assessed in a separate experiment. This relates to appropriate fitting sizes of the shirt. We could identify one perfect fitting shirt for every subject due to individual sewing lines. Especially athletes have different body shapes that are not consistent with standardized shirt sizes. The fitting shirt further has to be appealing and comfortable in wearing. The long-term usability of the device regarding washability and battery lifetime further has to be considered.

Within the project "Leistungszentrum Elektroniksysteme" (LZE), energy harvesting concepts are developed to provide the FitnessSHIRT (even in combination with the RedFIR system) with energy from thermal activity of the body or vibrations, typically accompanied by physical activity. Moreover, sophisticated concepts for acquiring, processing, and sending data are created to extend battery runtime. One aspect that is often disregarded is the problem of dropped hardware. Standardized norms (e.g., IEC 6060-1) suggest that a hardware for medical use has to operate correctly even when it was dropped repeatedly (20 times) from a free-fall height of 5 cm on a rigid surface. We recommend incorporating these fail-safe aspects in dependence on medical equipment to use in textile wearable integrated technologies.

We conclude this chapter with perspectives regarding textile integrated wearable technologies in the areas of biometric authentication, current-based measurements, and standards for data and platforms.

16.4.1 Biometrical Authentication

The use of biometric features for authentication becomes more and more important. Nowadays, different features such as the fingerprint, a face, or iris scan can be used for identity verification. Another biometric feature, which is unique for every individual, is the human heartbeat that can be measured with an ECG. There are several physiological reasons why the heartbeat differs for every human. The first reason for these differences is the individual structure of the human heart for every person. The Purkinje system, the muscle fiber orientation, and the electrical conductivity of the cardiovascular cells distinguish several individuals. Besides, the position of the heart in the human causes differences in the ECG patterns [40]. Other reasons are related to the sex, age, height, and body habitus of different subjects [41]. With a wearable detecting the ECG, it could be fast and easily possible to use the human heartbeat as a biometric authentication device. In a first study, using the FitnessSHIRT and authentication software based on a wavelet transform, we showed that an accuracy of about 89% was reached [42]. This suggests intensive investigation in this field of application.

16.4.2 Current-Based Measurements

Additional application scenarios for sensorized garments and in particular the FitnessSHIRT lie in the area of water-based activities. May it be for healthcare-related monitoring or professional sports training, keeping track of the heart activity and breathing patterns is just as valuable in wet environments as it is outside thereof. In order to not have to insulate the electrodes, which causes additional problems [43], a different kind of measurement circuitry can be used. The concept of non-insulated current-based measurement has already been successfully approached by Whitting and von Tscharner in 2014 [44] for electromyogram (EMG) signal measurement underwater and outside of it. In future, the same idea can be used for the FitnessSHIRT to enable to record underwater without any restrictions. Some preliminary experiments have shown that such a concept seems to provide the additional benefit of a much higher signal-to-noise ratio than with an insulated potential-based ECG system in fully submerged conditions.

16.4.3 Standards for Data and Platforms

With the advent of mass-produced photoplethysmography (PPG) sensors in the form of fitness gadgets (arm/chestbands, smartwatches, etc.), heart activity-related data recording is no longer the quasi-exclusive domain of clinical environments. From a scientific point of view, it is of great interest that all the data collected with those new kind of devices can be used for meaningful evaluations. It is desirable that a set of flexible standards exist that guide the way how these data are processed, stored, and transmitted, in particular when thinking about the trend toward a quantified self. When looking at ECG as an example, a multitude of different formats can be found to store such data. An overview of the most widely used file formats is described by Clifford et al. [33] and Trigo et al. [45]. Examples include the EDF+, HL7, WFDB, or FDA-XML format. All of which still have drawbacks and are either not flexible or lack usability. Usability is of concern here, since it is imaginable that at some point in future, the bulk of data used for fitness-related scientific evaluations come from the everyday user of (fitness) peripherals. These data need to be uploaded or committed to some forms of database such as Google Fit (Google Inc., Mountain

View, California, USA) or Apple Health. One of the major issues with this approach would be the problem of data anonymity which can only be guaranteed by transparent data formats so that the everyday user can understand what he/she sends into the cloud.

Right now, it is also still necessary for evaluation devices (like smartphones) to use proprietary driver software (or vendor-specific apps) to record, store, and transmit raw data. Although standards such as the Bluetooth Heart Rate Profile provide the means for an arbitrary platform interface, it is still very restrictive and assumes some preprocessing was done in the sensor hardware.

The future lies in unified interfacing methodologies that allow data to be accessed from any ubiquitous sensor nodes (e.g., in the Internet of Things) without restrictions. Bluetooth and near-field communication (NFC) are widely adopted, but especially in research and medical areas, a lot of proprietary solutions exist.

Summary

By now, wearable technologies and applications both are part of the most emerging segments of the technical industry. In this chapter, we focussed on presenting the FitnessSHIRT as textile integrated wearable technology and described the technology and algorithms behind this wearable together with application scenarios.

- Research and development enabled modern wearables to be accurate and opened up applications areas for textile integrated wearable technologies. We described the most important application areas in the sports and medical domains.
- The FitnessSHIRT is one example of a textile with integrated wearable technologies. We presented the hardware and the two different software modalities in detail. Various aspects have to be considered, e.g., the position of the electronics and sensors, the type of electrodes, or the contact pressure, for the creation of textile integrated wearable technologies.
- Key challenges of textile integrated wearable technologies (e.g., connectivity, reliability, and usability) were pointed out, and experiments to consider and test these challenges were described. We presented the study protocols and gave advice.
- We proposed recommendations for hardware/software codesign as well as sports and medical applications. The interaction between hardware and software (e.g., appropriate, fast, and computational efficient algorithms) is essential.

Acknowledgements We thank Titus Czyz for his feedback to application scenarios in sports. This contribution was supported by the Bavarian Ministry of Economic Affairs and Media, Energy and Technology as a part of the Bavarian project "Leistungszentrum Elektroniksysteme (LZE)." We thank Bjoern Schmitz, Ruslan Rybalko, Sven Feilner, and Andreas Huber for helpful discussion. We thank Fraunhofer Gesellschaft, BMBF, and DFG for financial support.

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Chapter 17
e-Garments: Future as “Second Skin”?

Aurora De Acutis and Danilo De Rossi

Abstract Wearing clothing is exclusively a human characteristic. Conventional garment has become the second skin of humans which they missed by nature for the protection purpose that over time transformed the human body into a social and cultural symbol. The history of clothing is immediately linked with the history of textiles, and they are changing every day in line with technological advances and market pressure. Since the 1990s, electronic textiles or e-textiles have been introduced as new emerging concepts and prototypes. Early published literature and journals on the fields of textiles, electronics, and advanced materials have indicated that e-textile-based garment would have a great impact in textile industry to fabricate human second skin replacing the traditional clothes when enhanced properties are needed. More than two decades have elapsed since researchers in this field have begun to work on e-garments achieving excellent results, but these findings have not taken off significantly in terms of market success and consumer adoption. In this chapter, we discuss that a transition from a technology-driven product to a human-driven product can make e-garments the e-second skin for a mass market.

17.1 Introduction

Animals are equipped with a sort of interface layer between themselves and the world, be it bare skin, skin with feathers, hair, scales, shells, or hide. In most cases, skins serve as a defense against predators and environmental hazards and provide protection, camouflage, and sexual distinction. Feeling inadequately protected from

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S. Schneegass and O. Amft (eds.), *Smart Textiles*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-50124-6_17

environmental conditions due to the loss of body hair around 1 million years ago, humans began clothing themselves.

Clothing was probably the basis for the survival of modern man outside the African continent, where the hominids of earlier millennia had failed. It is not certain when clothing was first developed, but some information has been obtained by studying lice [1]. When body lice started living in clothing undergo genetic modification from head lice about 1,00,000 years ago, suggesting the introduction of clothing can be traced back to around 42,000–72,000 BC [2]. Wearing clothing is exclusively a human characteristic, and garments have become the second skin of humans due to the acquisition of additional functions. In hot climates, clothing provides protection from sunburn, while in cold climates, it plays an important role with its thermal insulation properties. Clothing provides a protection against events that might damage the uncovered human body including rain, snow, wind, or other environmental hazards. Clothes also protect their wearers during work activities.

Clothing also has social and cultural implications, such as individual, occupational, and sexual differentiation and social status. The history of clothing is immediately linked with the history of textiles. The first clothes were made from natural artifacts such as animal skin, grasses, leaves, or bones. Leather and fur garments sewn with needles made out of animal bone date back to 30,000 years ago. The settled neolithic cultures discovered the utility of woven fibers over animal hides. Over time, humans developed the techniques and machines to make the fabrics for clothing. Today's fabrics are manufactured through weaving, knitting, and nonwoven technologies. Textiles and clothes are changing every day in line with technological advances and market pressure. The idea of fabrics with incorporated intelligence once seemed like science fiction; today, they may be the future of the textile industry. Since the 1990s, electronic textiles or e-textiles have been introduced as new emerging concepts and prototypes. In general terms, e-textiles are interactive smart fabrics with miniaturized electronic components, smart material, and modified textile fibers, thus providing garments with sensing, monitoring, communication, and self-adaptive functions. The early literature books and journals in the fields of textiles, electronics, and advanced materials indicated that e-textiles would have a great impact on the textile industry. Fabricating a second skin for humans and replacing the traditional garments with augmented functionalities is, however, a different argument. From the appearance of early prototypes, researchers have achieved excellent results in protective clothing, sports, and biomedical sector. However, their findings have not taken off significantly in terms of market success. Today, with technology dominating every sphere of daily life, e-textile-based garments (Fig. 17.1) could represent another way to change the modality people use to interact with technology.

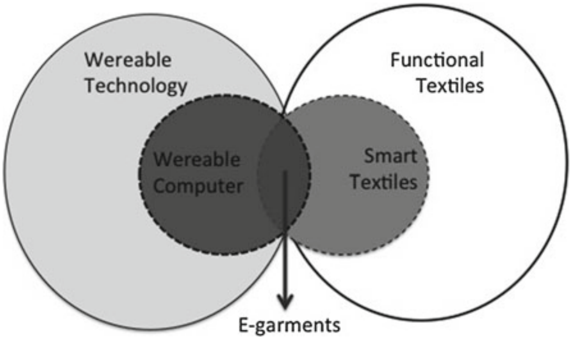

Fig. 17.1 Electronic garments represent an evolutionary fusion of developments in the field of wearable computers and in the field of smart textiles. In general, they are referred as intelligent clothing that allows the incorporation of technological elements, electronic devices, and computing resources in everyday cloths

17.2 The Naked Society and Its Needs for Clothing

The need to alter the natural appearance arises from the fact that human, unlike most mammals, is naked, except for the head and a few other parts of the body, of protective hair. Therefore, man is a naked animal, endowed with skin as the only interface with the external world. The skin is the largest organ in the human body, and the part of its function is to provide selective e-barriers to chemical, mechanical, and thermal insults from the outside world. It is probably the most versatile of all organ systems; it contains nerve endings, which provide the sense of touch; it skin also communicates emotional and physical states through hormonal signals.

However, the skin does not provide adequate resistance against abrasions, burns, and blows, nor provide sufficient thermal insulation in harsh environmental conditions. These deficiencies mean that human beings need to protect themselves with second skins or garments. Fabrics were developed to manufacture garments not only for practical purposes, but also for social needs, playing an important role in terms of communication as well as for expressing modesty, social identity, and personal identity such as age, gender, race, culture, and religion. Clothing has evolved to reveal a individual personality as well as their emotional state. The introduction of clothes to cover the body is also linked with the primitive forms of modesty and decency. Over time, clothes have also become a decorative tool to enhance the concept of beauty or the aesthetic appeal through strategies aimed at correcting and hiding the body’s weaknesses and to enhance stronger and more attractive bodies.

Another purpose for clothing has emerged for the prevention of injuries or loss of life for the professionals who work in hazardous conditions. As Flugel mentions in his book [3], clothes have evolved as for animals; in centuries, they are changed gradually, but always maintaining the same basic structure. Therefore, reflecting on the needs for protection/prevention and comfort that led the man to procure the means for covering himself, they have remained unchanged over the years; one can state that mass adoption of systems based on e-garments could perhaps occur when they will fulfill in a unique way new human needs.

17.3 From Textiles to e-Textiles

Humans created the technology that enabled them to achieve a second skin as protection, and which over time transformed the human body into a social and cultural symbol, humans constantly developed new textiles to match the technological anthropic surroundings. This evolution was possible thanks to the constant research for new materials and new production techniques to provide added value to the wearer. The textile industry grew significantly during the Industrial Revolution with the introduction of manufacturing machinery.

A major step came forward after the Second World War with the introduction of synthetic fibers. Over the last 20 years, advances in miniaturized electronics and communication have brought from the conception to an implementation of e-textiles. Technological advances have enabled electronics to become smaller and more powerful, thus paving the way for their transition from portable to wearable for innovative applications far from the conventional textile world. This is the case of the fusion of digital electronics and information technology onto textile substrates for a new reality defined as e-textiles or electronic textiles which synthesize active functionality, responsiveness, intelligence, and communication.

Current research has led to the creation of fibers with electronic properties as shown in Table 17.1. For other features, it is common to integrate traditional electronics into clothing, without altering its main characteristics. e-textiles have attracted considerable attention due to their potential revolutionary impacts on human life. They were originally perceived as being technological appliances with the potential of widespread applications through the integration of data storage system, communication, monitoring devices, miniaturized power sources, and energy harvesting system. As happens with all other technological appliances, the best products do not always succeed, because social and cultural limitations can dominate the

Table 17.1 Textile-based fibers and their applications

Application	Key materials	References
Fiber-based strain sensors	PPy, Pt nanofibers, carbon fibers, CNT	Scilingo et al. [4]
Fiber-based pressure sensors	CNT, PVDF, P(VDF-TrFe)	Wang et al. [5]
Fiber-based chemical sensor	PPy, CNT, optical fibers	Zhu et al. [6]
Fiber-based transistor	Textile monofilament-coated polythiophenen	Hamedi et al. [7], Locci et al. [8]

technology [9]. If the product does not satisfy the ordinary customers, they may reject it, how beneficial it may be.

Therefore, a question we may ask: Is our society ready to extend the intelligence to clothing, thus accepting them as the new second skin?

17.4 e-Garments: A Few Projects and Products

R.V. Gregory et al. carried out pioneering work in the field of e-textiles in 1989 with the development of the first conductive fibers by polymerizing pyrrole or aniline on the surface of fabrics, thus encasing each single fiber with a smooth layer of the electrically conductive polymer [10]. At the same time, early results using embroidery to realize interfaces from human–computer interaction were announced from a group of MIT Media Lab [11].

The first prototypes of e-textiles emerged in 1997 as a result of the work of independent groups around the world. The Wearable Motherboard was developed at Georgia Tech (Fig. 17.2), which was a smart undershirt implemented by integrating metal and optical fibers connected to an optoelectronic device to monitor the vital signs of a soldier and detect the bullet penetration [12].

In the same year, while researchers in Tokyo were developing textile electrodes for cardiopulmonary monitoring [13], the University of Pisa in Italy used thermo- and piezoresistive fabrics for recording biomechanical parameters in ergonomics and rehabilitation [14].

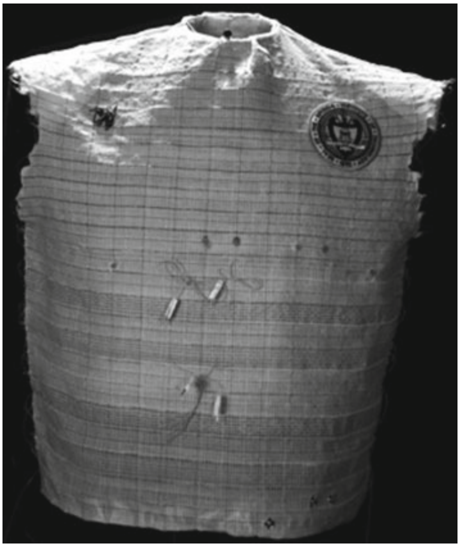

Fig. 17.2 The Georgia Tech Wearable Motherboard (GTWM) is one of the world's first wearable e-garments of the twentieth century. This Georgia Tech Wearable Motherboard incorporated sensing, monitoring, and information processing devices

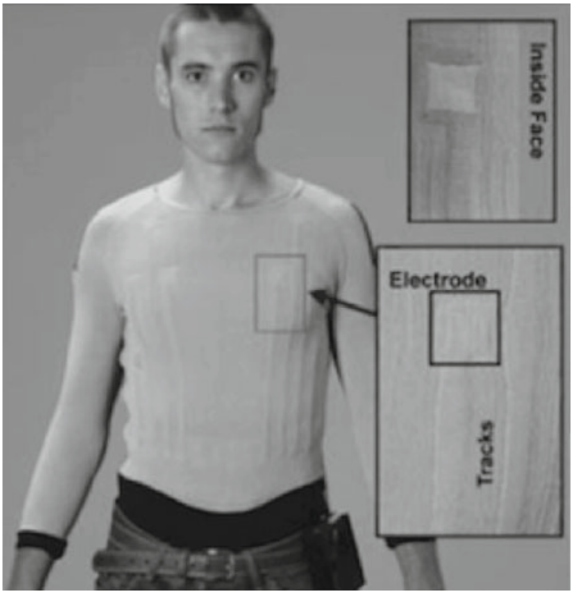

Fig. 17.3 One of MyHeart's prototypes

A few years later, Europe decided to invest in e-textiles, thus providing significant research and development funding for personal health monitoring. In 2005, the EC-funded Wealthy project was completed, with the development of an undershirt, aimed at providing a comfortable solution to monitor cardiopulmonary conditions. The Wealthy platform represented a very high level of integration between textile technology and a wearable electronic unit, endowed with wearable onboard processing and modern wireless communication system [15]. The MyHeart project was one of the largest biomedical and healthcare research projects within the European community. MyHeart through the collaboration between academia, research institutions, and industry developed functional clothing for the prevention and management of chronic cardiovascular disease (Fig. 17.3). The approach of the MyHeart project was to monitor vital body signs with e-textile-based wearable technology, to process the measured data and to give the user the right therapy [16].

The original focus on vital signs monitoring (body temperature, electrocardiogram, breath rhythm, etc.) was extended by Biotex. Biotex was one of the most recent EU-funded projects in the field of biosensing textiles to support health management that for the first time developed dedicated biochemical-sensing techniques integrated into to tackle very important health issues [17]. Some solutions have also been proposed for baby health monitoring, such as Mimo, the sensorized baby pajamas.[1] Mimo uses sensors to tell how the baby is breathing as well as their body position, sleeping temperature, and activity level, and provides alerts to a smartphone.

[1] http://mimobaby.com/.

Several e-textile-based garments have also been developed for protection, sport, well-being, and fashion. Focusing on the protection field, PROETEX, a 6th Framework IST Integrated Project that developed under/outer garments, uses specifically textile-based technologies [18]. These garments were for firefighters and specialized personnel for disaster management. One of the most recent projects for protection/safety applications is the TIIWS project, funded under 7th framework program (FWP). The main aim of this project is to integrate advanced polymers with piezoelectric and electrostrictive properties in textiles to develop advanced garments and footwear.

In the sports sector, companies including Adidas, Nike, Omsignal,[2] Bodytruck, AiQ, Hexoskin,[3] and Sensoria,[4] have marketed e-textile-based t-shirts as fitness tracking devices. OMsignal developed a conductive fabric-based t-shirt, the Biometric Shirt, which ensures the comfort and the accurate acquisition of physiological signals to get more out of workouts. It is connected to an advanced reading technology, acting as a personal coach, aimed at making fitness more fun. Thanks to funding from a crowdfunding campaign, Sensoria recently developed sensor-filled socks to analyze the way in which the foot rests on the ground, thus aimed at correcting the gait and preventing injury. Another example is the bionic bra developed at the Innovation Campus at the University of Wollongong.[5] The bra is shaped like a traditional bra but contains sensors and actuators to detect breast movement and reduce its bouncing when the wearer is moving so much.

In 2006, Philips’s designers introduced the Bubelle Dress,[6] the first emotion sensing garment. This dress consists of two layers: The inner layer contains biometric sensors that pick up a person’s emotions and projects them in colors onto the outer layer. In this way, the Bubelle Dress (Fig. 17.4) changes the look instantaneously according to the individuals’ emotional state.

Lastly, e-garments have also been proposed in the field of fashion. A recent example is the Smoke Dress[7] designed by Anouk Wipprecht and 3D printed by Materialise, which automatically creates a veil of smoke to protect the personal space of the wearer. Finally, in a world where everything is interconnected, many projects, such as the wear-A_BAN cofunded by EUs FP7, or the Jacquard[8] launched by Google, are working to bring e-garments into the Internet of Things scenario.

[2]http://omsignal.com/pages.

[3]http://www.hexoskin.com/.

[4]http://www.sensoriafitness.com/.

[5]http://smah.uow.edu.au/brl/bra/index.html.

[6]http://www.lucymcrae.net/philips-design-probes/.

[7]http://www.materialise.com/cases/smoke-dress-hits-the-volkswagen-catwalk.

[8]https://atap.google.com/jacquard/.

Fig. 17.4 The Bubelle Dress. As part of the skin probe project, philips design created wearable prototypes such as bubelle. This garment demonstrated how electronics can be incorporated into fabrics and garments in order to communicate the wearer's emotion. Illustration adopted from http://www.lucymcrae.net/philips-design-probes/

17.5 e-Garments: Electronic Appliances for Clothings in the Chasm

According to Norman [9], as happens with other technological products, e-garments have a life cycle as they progress from birth through maturity. During this cycle, the customer segment varies. In its early days, an electronic appliance can only meet the needs of the so-called early adopters, which represent a small section of the potential marketplace. These adopters are fans of technology, usually buying almost every new item, and they are willing to pay a high price. They demand advanced technologies and high performance. The early users drive the initial market of an appliance with the result of leading to a technology-driven product.

In terms of the sheer size of the market, the late adopters dominate; they are pragmatic and conservative; and they do not buy new products, until the technology has proven itself and has met their needs. Late adopters look beyond the technology itself by demanding value, user experience, and products that simplify their daily life. After a period in which the electronic appliance relies on pure engineering and grows by technological enhancements, there is a transition phase where the technology satisfies the basic customer needs. As shown in Fig. 17.5, in this phase, defined by Moore [19] as the chasm, the product reaches its maturity from the technological point of view and begins to attract the most demanding customer, the late adopters. From this moment, if the appliance is to survive in the market and be successful, it has to move from a technology-centered to human-centered product. This is a necessary step because these new customers take technology for granted, they want value, easy to use, reliability, and the right balance between cost and benefit. Although

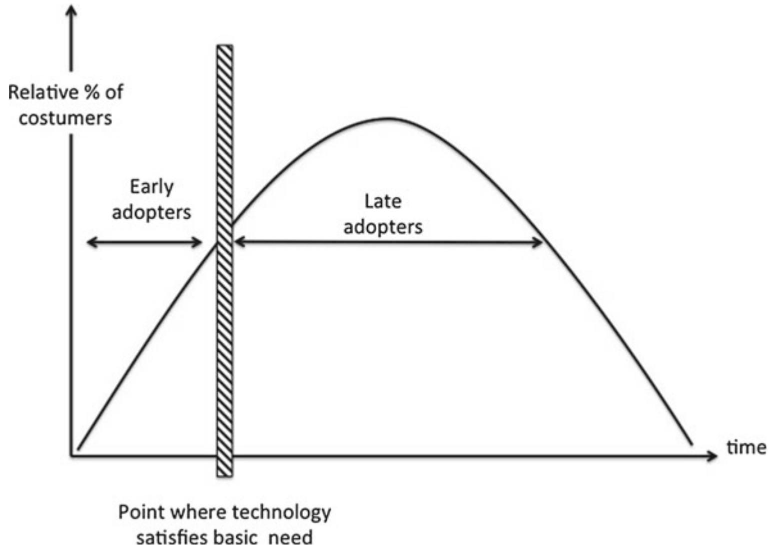

Fig. 17.5 Representation of the technology life cycle. Illustration adapted from “The invisible computer” by D. Norman

e-garments have been around for over a decade, they can be characterized as being in the chasm of their life cycle. This is because from the end of the twentieth century, when engineers began to match electronics with textiles, there has been more importance on the technological improvements, rather than on the user.

Thus e-textiles in clothing have not yet passed the state of being good enough for most consumers whose market has not yet reached the mass scale. To attract the attention of the main market, companies have to change the way a product is developed as well as the design and marketing, bearing in mind that it does not matter whether or not its technology is superior, it only matters that whether what is being offered and if what the customer is looking for fulfills its needs [9]. According to Norman, moving to a customer-driven product is difficult, because a technological change is hard, while cultural and social changes are even harder. To promote this transition and encourage the use of intelligent clothes as second human skins, e-textiles need a large set of skills.

17.6 e-Garments Toward a Human-Centered Production

To date, there have been relatively few e-textile commercial successes, and much of the sector remains niche-based and relatively low volume. Now, it is the time to think about their potential impact and take appropriate action. To make the transition from niche products to mass markets, in order to make e-garments the human second skin, companies need to manufacture their products using a triad of skills: technology, marketing, and user experience. These act as three supporting legs of the product, and if they are not well-balanced, the product will not be able meet the right expectations [9].

17.6.1 Focus on Technology

Without the right technology, e-garments will not have the great impact that was expected. When we talk about technologies associated with e-textiles, we need to distinguish between the manufacturing technology of the product and the technology embedded into the product to make it intelligent. Almost everything about the embedded technology in textiles is the result of academic or SMEs research. Current advances in new materials, new fibers, and miniaturized electronics are what have driven e-textiles in clothing until now, with new functions and better quality. The key goal could be to make the technology invisible for the wearer by integrating it into clothing. Unfortunately, most research and commercial development projects are hybrids where the clothing is wired with cables, or one or more strands of conductive fibers are integrated into the fabric substrate to form a textile connection to external batteries or electronic devices. Batteries on a fiber could be the solution, because they store more electricity than supercapacitors, but they are less popular due to the cost and reliability when on a fiber. Although e-textile technology has reached some level of maturity, the poor integration is partly ascribable to the limits imposed by the manufacturing capability which is a barrier to e-textiles growth. In turn, the production capability is related to the manufacturing technology of the textile industry, which is very conservative, reluctant to change, and skeptical about these new products. This could be one of the reasons for the slow market growth. In order to bring e-textiles out of the chasm, textile industries must also contribute with more focus on technology by investing in e-textiles and investing in new equipment to introduce the intelligent garments in the normal manufacturing processes, thus making the market more favorable for new investors.

17.6.2 Focus on Marketing

Although e-garments have been developed for over two decades, the market has not yet reached the mass-scale tipping point because companies have not managed to coordinate successful marketing campaigns. Marketing covers a wide range of activities, but above all, it provides expert information on products for customers [9]. Good marketing ensures that the product meets the market expectations and features that appeal to users. e-textiles were originated from the two different areas of textiles and electronics, with different design strategies and priorities, so when the first e-textiles came on the market, the requirements of most consumers were not taken into consideration. Usually, consumers seek e-textile-based clothes that fit comfortably are affordable, low maintenance, mendable, washable, and easily and efficiently produced. e-textiles need to retain their functionalities over many washing cycles, and reducing the need for frequent battery charging can encourage the purchase of e-textiles. This is the point from which a new design concept develops: A variety of enabling technologies already exist for designers to make e-textile garments something people cannot imagine living without.

The key advances in the last five years have led to early commercial products, with a market of around $100 m in 2015. The proliferation of sophisticated e-textiles aimed at consumer mass markets is expected to take more time [20]. In 2014, an IDTechEx report suggested that the main addressable markets for e-textiles were the medical, health, fitness, wellness, and fashion sectors. The market segments of sports clothes, health, and lifestyle textiles have a potential sizable growth [20]. According to Kotrotsios et al., this is supported by the fact that the above segment operates through a business-to-business approach [21]. To rapidly accelerate the market growth for e-textiles, the hot spots of innovation still need to be identified [20].

Results from the Khler et al. [20] expert survey among e-textile developers indicated the current hot spots of innovation. The estimation of the possible market size varied depending on the respective application area. For the near future, the interviewees expected the highest market potential in the area of ambulatory/health monitoring. Confirming the results obtained by Andreas et al., IDTechEx forecasts that sports, fitness, and medical/health care will be the sectors with the greatest potential of success, whose market could reach over $3bn by 2026 [22]. We have previously seen such optimistic forecast.

17.6.3 Focus on User Experience

Understanding the clothing and its psychological significance can help realizing how important user experience is in the design of intelligent garments so that they are not rejected by the wearer because they are unnatural. Thus e-garments design has to follow a psychotechnological approach to make the e-textile clothes acceptable by users.

In order to make a garment that will be psychologically accepted by a customer, a designer has to take into account that there are many types of users from young to old with different levels of technical ability. e-textile clothes are intended to be attractive and comfortable, to enhance someone’s life and not inhibit their daily routine. How people perceive comfort and consider the comfort-related parameters during garment selection are complex processes which include physiological and psychological aspects.

According to Kaplan et al. [23], the five most important fabric/garment attributes influencing comfort are as follows: garment fit, sweat removal, thermal insulation, allergic problems, and design. The classification related to the basic aspects of comfort revealed that the aesthetic group including color, design, fit and weave was the category with greatest influence [23]. This highlights the importance of clothing in terms of the psychological and social lives of people. Comfort is not only the requirement for adopting e-garments to satisfy a customer, but also the personal discretion, subtlety, and a sense of privacy that plays an important role. During the design of wearable e-textiles, attention needs to be paid to these three factors, especially in case of underwear, which define the intimate space of a person.

17.7 Toward e-Second Skin

One of the biggest challenges for e-textile garment manufacturers is understanding how to reinvent their businesses and development process aimed at the successful deployment of electronic second skins.

From a technological point of view, there is a wide variety of artifacts and textile solutions or electronic components to choose from. On the other hand, the conservative and skeptical nature of textile manufacturers toward new opportunities in e-textile innovation makes it difficult to reduce the enormous mismatch between the textile, R&D, and the electronic industries. In terms of time of development, investments, and vision, another challenge is to develop common standards in the e-textile industry.

At the moment, the lack of common standards is one of the reasons holding back the commercial growth of wearable e-textiles. Standardization and interoperability are two conditions that are often regulated by international rules that do not currently exist in this field. One of the major causes of the lack of standardization of e-textiles products is connected to the fact that this area emerged from a high number of start-up, developed by government-sponsored projects. These spin-offs protect their products through patents. Although IP protects their ideas, it leads to develop specific products and solutions at the expense of standardization.

The scarce interest of consumers and user skepticism toward e-textile wearables is an another challenge. New consumers and users can only be attracted by reliability, good safety levels, good design, comfort, simplicity, quality, and added value. However, this alone is not enough to build loyalty and to engage consumers. These new electronic appliances must have an easy-to-use application interface to interact with a smartphone, watch, or tablet. Thus, in addition to transforming potential competitors into enabler products for wearable e-textiles, these e-garments will be able to enter the Internet of Things environment. However, companies that work in this data-driven environment will have to consider that protecting consumers and respecting privacy are key issues in order to be successful and gain the trust of consumers.

E-garments developers also have to focus on addressing real customer needs, rather than developing technology in search of an application or a market place [9]. This is the reason why e-textiles clothes have not yet gained social acceptance. Hence, the need for a consumer-centered approach to design new wearable e-textiles matches the consumer profiles, desired functionalities, and lifestyle sustainability. For the transition to a consumer-centered approach, developers must have a clear concept of how electronic devices and clothes are perceived, purchased, and employed in different ways. The added value of technology is not the first reason why e-textile clothes are bought. First of all, clothes are perceived and selected according to a fashion criteria, user experience, and individual personality, such as means of emotional and psychological communication, while electronic devices are chosen above all for their practical functionalities. This suggests that changing the users perception of a hybrid product, such as e-garments, is a challenge that can be tackled by designing an easy-to-use product that fulfills a real practical function as an electronic and unobtrusive device. At the same time, it would thus have the same usability, user experience, and emotional benefit as ordinary clothes.

Finally, these assumptions highlight that healthcare applications and sportswear are the optimal market segments for e-second skins, since they more suitable for the combination of features previously described. This is partly confirmed by market surveys that suggest that the medical, wellness, and fitness/sport settings and also the video games field will be the potential market segments for wearable e-textiles in the near future. E-garments could have a good potential in telemedicine as a support for home therapies in a virtual unit. However, telemedicine, which has been talked about for at least 40 years, has never taken off, and this is a problem for which no solution has yet been found. For e-textile wearables to be successfully used as medical devices, they need to demonstrate that they can be operated effectively and safely before being released to the end user in order to obtain the CE and/or FDA certification. An increase in the number of consumers that wish to continuously have information about their health status could make the wellness and sport market successful for e-garments. In the wellness or self-healthcare fields, e-textile clothes could be used to monitor the daily well-being of individual consumers. In terms of e-textiles in the fitness/sports field, consumers can measure their effort, track their progress to optimize their performance, and reduce the training injuries. Within the sports market, there are two subsegments: the amateur and professional markets. Due to this differentiation, these markets need to show a high degree of flexibility in terms of costs, performance, customization, and quality. Despite this, e-garments in the wellness/sport markets have greater potential for success than the medical sector, since they involve standardized products that do not require a high quality of recorded data. The success of health care or sport segments is also linked to the fact that the so-called e-undergarments can properly operate as functionalized second skins. Undergarments offer the advantage of being worn under normal clothing, so as not to affect nonverbal communication, and since they are developed according to structural standards, they will never be changed because they are unfashionable, but only when they will not work anymore.

In all other areas, where e-wearable garments were already introduced without a market criteria or a particular human-centered approach, these products will only represent the lure of a second skin. As long as our relationship with what we wear will not change or until other needs will not arise, the e-garments remain only a lure and functional garments will continue to prevail surely.

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