Introduction to Smart Textiles

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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 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 e.g. 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

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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 firefighters. Their unobtrusive character makes smart garments particular 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 multi-modal 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 result 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 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.

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.

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 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.

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 ear-plug, and a small hand-made 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 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]).

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

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 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 multi-national 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 challenges regarding the interpretation of garment-sensors is their varying attachment depending on movement and body shape. Harms et al. provides an overview on a prediction framework dealing with errors due to loose fitting in orientation, skin contact, and strain sensing [31].

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 **[CHAPTER #17]** .

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 **[CHAPTER #2]**). Each production technique combined with the used yarn type impacts wearability of the garment differently, thus generating different mechanical properties, such as stretchability.

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. Using touch-resistive textiles as pressure sensors, Zhou and Lukowicz **[CHAPTER #3]** and textiles capable of measuring the bend angle of joints, Lorussi et al. **[CHAPTER #4]**) highlight two types of textile sensors and solutions to integrating the sensors into textiles. On the output side, visual output has gained center stage as shown in the work of Peiris **[CHAPTER #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 **[CHAPTER #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 **[CHAPTER #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 **[CHAPTER #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 **[CHAPTER #10]** . They present different approaches and discuss their advantages and disadvantages.

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, etc. Besides reversible methods such as push buttons, magnets, or hooks, more advanced multi-channel methods such as ball-grid connectors [35] have shown promising results. Mehmann et al. provide an overview on different types of connectors in **[CHAPTER #9]** .

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 **[CHAPTER #7]** . Alternatively, the garment-attached electronics are connected to a mobile phone or base station. Used interfaces include SPI (synchronous 1:N communication), 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.

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 **[CHAPTER #11]** . Focusing on the user, Hkkil presents a set of design studies in which the user experience of textiles is explored **[CHAPTER #12]** . In contrast, Honauer focuses on interactive costumes for professional stage appearances and derive a set of requirements from different design probes **[CHAPTER #13]** .

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 regards 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 **[CHAPTER #16]** . Additionally, smart textiles enables novel types of protective gears which are pro-actively protecting users. Chen and Lawo provide examples in this domain **[CHAPTER #15]** .

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.

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*.

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,e.g., 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.

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 lab studies. However, facing real-life challenges with smart textiles is an essential step towards 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 lab.

Taking field evaluation one step further, research trough 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 textiles evaluations will need to implement field studies to fully understand the symbiosis between user and textile.

6 Current and Future Challenges for Smart Textiles

6.1 Fabrication

A key challenge towards 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 towards a generic base textile are 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.

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.

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 towards estimating garment design and sensor realization options within the wide options 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.

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.

6.5 User-Centered Evaluations

While most smart textiles are nowadays evaluated with regards 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.

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Summary

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

- 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.

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