Towards Accepted Smart Interactive Textiles

The Interdisciplinary Project INTUITEX

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Abstract. Smart Interactive Textiles combine the warmth and omnipresence of textiles in our everyday lives with the benefits of modern information and communication technologies. The potential of innovation is not only based on technical ingenuity, but also on the consideration and embedding of peoples' fears, requirements, desires, and wishes regarding these innovative technologies. Thus, the development of smart interactive textiles requires the expertise of various disciplines. Foremost, appropriate conductive yarns must be selected and integrated into conventional fabrics. Sensors and actuators must be embedded in textiles in a way that they could be used as a user interface. The design of these textiles should meet human needs and should enable an intuitive, easy to learn, and effective interaction. To meet these requirements, potential users should be part of the development and evaluation processes of innovative smart textiles. In this article, we present a research framework that integrates several interdisciplinary perspectives (interface design, textile technology, integration and automation, communication and human factors). We realized three functional smart textile demonstrators (curtain, chair, jacket). We report on the results of this interdisciplinary research project as well as the research questions and key findings of the individual partners. In summary, this article demonstrates that interdisciplinary cooperation, user-centered and participatory design, and iterative product development are necessary for successful innovative technologies.

Keywords: Pervasive technology · Ubiquitous computing · Conductive yarn · Smart textiles · Smart interactive textiles · Design for all · Technology acceptance · Iterative product development

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1 Introduction

Since the dawn of mankind, textiles have been an integral part of the human culture tracing back to 30.000 B.C. [1, 2]. Textiles are perceived to be warm, soft, and pleasurable; they come in large variety of different forms, sizes, textures, and colors; and they are used for clothes, furniture, and decoration. In contrast, integrated circuits, microprocessors, and the subsequent advances towards the Internet of Things are rather novel developments originating in the 1950s [3, 4]. The convergence of these two developments is highly promising. Novel input and output devices may profit from the ubiquity and qualities of textiles (e.g., flexibility, warmth, aesthetics) to integrate seamlessly into our environments.

Numerous technical innovations fail when they reach the market as they are not accepted by consumers. Reasons for this are manifold and include development processes that are solely product-oriented and feature-driven with the lack of focus on potential customers and their requirements [5, 6]. To ensure high acceptance, high suitability, and high usability of future smart interactive textiles, interdisciplinary perspectives should unite to an integrative and iterative product development process. These perspectives include expertise from textile engineering and textile industry, systems integration and embedded development, computer science and media informatics, product design and marketing, as well as communication science and user experience research.

This holistic unification of these diverse perspectives was carried out in the research project "INTUITEX – Intuitive Textiles". The goal of this project was to explore and develop novel interactive textile interfaces that are (1) intuitive (easy to use and learn), (2) consider the wants and needs of an increasingly diverse user population, (3) address age related changes, (4) have an attractive design and a familiar form, and (5) can be seamlessly integrated into the human habitat.

2 Related Work

This section provides an overview of the disciplinary state of the art regarding smart interactive textiles. The section starts with the technical perspectives, continues with related work from product design, and concludes by describing various models for assessing humans' perception and acceptance of technical innovations.

2.1 Smart Textiles in Engineering

In addition to the conventional input devices (e.g., mouse, touchpad, multi-button remote control), which are usually embedded in rigid housings, there are devices which are realized by functional textiles (a.k.a. smart textiles [7]). Many research projects deal with the question of how information technology can continue to gain a foothold in everyday life by integrating itself into clothing and other textiles. Examples of this are "intelligent" clothing, which capture vital parameters, such as the heart rate and perspiration, or a step counter that is integrated in shoes and not visible to the user. Often, in wearable computing, old interaction concepts and input techniques from the desktop computer are transferred without reflecting on the new requirements of the device or context. For example, integrating buttons or touchscreens in gloves and jackets for controlling an MP3 player demands the user's visual attention and input precision in contexts where the user is continuously moving or engaged in other primary tasks. Until now, smart interactive textiles have been mainly developed in research labs and design studios without considering the manufacturing and industrial aspects of these novel products, with one exception [10]. To realize smart textile interfaces, there are still some electrical components that need to be connected to the fabric. Using typical electrical connection methods, such as soldering, is often not suitable for or possible with conductive yarns, leading to handmade connections. The usability of textiles depends highly on the reliability of their functionality and lifetime. Recent developments in conductive yarns provide highly conductive and washable materials at an industrial level. This motivates investigating the holistic development process of creating smart textile interfaces for public consumption.

2.2 Smart Textiles in Human-Computer Interaction

In recent years, researchers have been investigating ways to augment and re-appropriate textiles as interactive media. Early work [8, 9] examined the benefits of integrating a capacitive touchpad into clothing. The result is a rich eyes-free input device to, e.g., write text notes on a phone that is in a pocket. Today, touch enabled textiles are produced commercially, e.g., Project Jacquard [10], and are ready to enter the market. These textiles detect touch input (taps and gestures) like touch screens [11–14]. But unlike touchscreens, they have similar properties as regular textiles–they are flexible, warm, and just as comfortable to wear.

Leveraging the textile nature of many of the objects that surround us enables natural interaction with and seamless integration into our environment [11]. Lee et al. [15] defined a gesture alphabet of possible fold, bend, and distort gestures for paper, plastic, and stretchable fabric. Natural interact with fabric (e.g., pinch, stretch, squeeze, drape, etc.) has been recently motivated as an interaction metaphor for deformable user interfaces [16–18].

Pinstripe [19] uses a parallel pattern of conductive stripes integrated into the sleeve of a t-shirt to detect the size and displacement of a fold in the cloth. This information is then mapped to a one-dimensional continuous value change. Gioberto et al. [20] use stretch sensors to detect fabric bends and folds around a single axis, such as the knee. However, integrating a stretch sensor for each possible axis would overload the fabric making in heavier and less flexible.

So far, most textile sensors have been designed to be integrated into garments as interfaces for wearable devices. In this project, we also look at textile interfaces in the home environment, more specifically, curtains and armchairs. So far, augmenting the large surface of a curtain as an interactive surface has been realized using image-based technologies. Funk et al. [21] present a shower curtain that senses touch input using a thermal camera. This allows to select between different applications, such as weather information or controlling a music player. A number of interactive chairs have been developed as input devices for navigation in computer games [22] and controlling the mouse cursor in the desktop environment [23]. Probst et al. [30] equipped a flexible office chair with motion sensing functionality. The chair becomes an input device that detects the user's movements over the chair (tilting, rotating, or bouncing) to control the computer. However, most of these systems use inertial measurement units for detecting movement and do not appropriate the fabric of the chair as an interactive surface.

2.3 Design Parameters of Smart Textile Interfaces

From the design perspective, there are various design heuristics, guidelines, and parameters that must be considered [24–26]. Established design parameters for textile interfaces are: ergonomic parameters (e.g., size and accessibility of the textile interfaces), functional parameters, easy handling, and a simple and self-explanatory usage of the textile interface.

The shape of the interface should blend well with the object's form. In this way, the interface becomes an integral part of the object. The interface should offer feedforward clues (haptic, tactile, or visual). For example, embroidered lines and ornaments should guide the interaction with the textile interface for easy learning and usage. The material of the interface owe to be as simple as possible and the design should be minimalistic due to an inconspicuous integration of the interface in the specific object.

Finally, design requirements and production requirements must be balanced. Here, a tradeoff between effort and costs of industrial production and the haptic, texture, and visual appearance of the textile interface must be considered in the concept phase.

2.4 Acceptance of Innovative, Interactive, and Textile Technologies

To understand which user and system factors influence the adoption of novel technologies, a systematic and model-based research approach is necessary. Key theories are Roger's Diffusion of Innovations [6], Davis's Technology Acceptance Model (TAM) [27], or Venkatesh's Unified Theory of Acceptance and Use of Technology 2 (UTAUT2) [28] serve as a foundation for the investigation of acceptance of smart interactive textiles. Still, to reflect the product characteristics of novel textile interfaces, these models and theories must be adapted, evolved, and refined.

In the first step, qualitative methods are necessary to identify new factors that are relevant for acceptance. For example, Kranz, Holleis, and Schmidt [29] conducted first qualitative usability studies on interactive textiles and identified preferred designs of interactive surfaces, as well as accepted body areas for the interaction gestures.

Results revealed that the context-of-use shapes the acceptance of wearable smart textiles [30]. Dependability, functionality, and data security were shown to be key determinants for the success of wearable smart textiles. As potential consumers are characterized by a high heterogeneity, it is important to consider that user diversity, especially age and technical expertise, turned out to be key predictors for acceptance. It should be evaluated if these results are transferable to non-wearable textile interfaces or if other factors will be relevant for acceptance.

3 Interdisciplinary Research Approach

As outlined in the previous section, the development of accepted novel smart textile interfaces requires the expertise of various disciplines. Therefore, partners from academia and industry, the domains of textile engineering, information technology, product design, marketing, psychology and communication science collaborated in the interdisciplinary research project INTUITEX founded by Germany's Federal Ministry of Education and Research.

The overarching goal is to design, realize, and evaluate functional demonstrators. The focus of this project are questions from psychology and communication science (acceptance, usability, design), engineering (producibility, software, and hardware), economic and marketing (feasibility, affordability). Each of the partners has individual perspectives, priorities, and concepts that are continuously related, weighted, and harmonized in all phases of the iterative development process. This model enables the development of novel, integrative, and extendable methodology that facilitates the design of smart textile interfaces and considers technical and textile requirements, users' wants and needs, as well as aesthetics.

The following section presents the individual perspectives of the research partners:

- Institute for Textile Engineering, RWTH Aachen University (perspective of textile engineering)
- AFP Textilveredelungs- und Vertriebs GmbH (perspective of textile finishing)
- Chair for Media Informatics, RWTH Aachen University (perspective of human-computer interaction)
- BraunWagner GmbH (perspective of (communication) design)
- Enervision GmbH (perspective of system integration)
- Chair for Communication Science, RWTH Aachen University (perspective of psychology and technology acceptance)

3.1 Integrating Different Perspectives on Smart Interactive Textiles

Textile Engineering and Finishing: The design of interactive textiles deals with the selection of suitable materials (e.g., fabrics, yarns, …), the technical realization of the requested sensing (e.g., touch, folding,) and actuating functions (e.g., light, sound), and the manufacturing process. Smart textiles can be designed for various applications, yet the combination of the textile platform, i.e., the fabric, and the augmented and/or integrated electronics in the textile surface determines the overall suitability and producibility. The choice of material determines the properties of the textile platform, such as texture and deformability. The choice of functional material, such as the conductive yarn, determines the functional properties of the sensor, but also limits the design and producibility. This aspect of producibility is a very important factor, which is often insufficiently considered. Smart textile technology must be producible in a manufacturing process at scale or the industry would not adopt it because of the high manufacturing costs of single batch productions. Therefore, to increase the potential of the success, the aspect of producibility must be considered from the early stages of development. This also applies to contacting technologies, which are necessary to combine functional textile materials with electronic components [31, 32]. Furthermore, the user's requirements in smart textiles must be considered. For examples, smart textiles must be washable and should neither lose their electrical properties, nor their textile character.

The technology most often used to integrate conductive yarns into a fabric is embroidery [33]. Most embroidery companies are small and medium-sized enterprises (SMEs) and focus on products for a local market. Individualized products, up to small series are manufactured, using single or multiple head machines and given textile substrates. Fast processes are necessary, as it takes a few thousand stiches to embroider complex designs. For conductive yarns, this means to find process parameters that allow fast manufacturing and have the right friction and tension with the yarn (to avoid reduced conductivity due to mechanical abrasion or getting thread breaks). Using multifilament yarns cause too much friction resulting in lint formation or filament fraying leading to the failure of the process or short circuits later in the device.

Media Informatics: Fabric interfaces, especially in commercial products, often simply transfer known concepts to the textile domain, such as buttons [18] or touchpads [20, 21]. In this project, we as media computing experts focused on designing and developing textile sensors that enable natural user interaction borrowing metaphors from people's relations to surrounding fabric objects. Smart textiles, especially smart garments, share many of the challenges of wearable computing [34]. Textile sensors are expected to be visually unobtrusive [7] and socially acceptable in public contexts [35]. Holleis et al. [36] identified other factors such as the need for quick and easy eyes-free, one-handed interaction and methods to ensure that the sensor is robust against involuntary activation and garment shift. Existing systems, however, rarely address these issues, which are important for the general acceptance of such wearable controllers. This project proposes three textile user interfaces that build upon the natural affordances of fabric to address these challenges. We focus on the design of the smart textile layout, the input techniques, sensing technologies, and discuss some of the issues of textile integration into fabric.

System Integration: Smart home technologies still lack convenient human-machine-interfaces that keep pace with AI-driven innovations in mobile and connected applications. In project INTUITEX we look at how textile interfaces can become part of the smart home and wearables eco-systems. With a textile interface, one can seamlessly integrate system interfaces into readily available textile objects in order to enhance the user's comfort and preserve his sense of aesthetics and design in a given context.

Nowadays, there are dozens of different incompatible bus systems, many times, in a single building. In the future, integrating home, office, car, and personal devices will use protocols of the Internet of Things. But to verify the potential outcome of these trends, we must look at bridges between disparate technologies like LonWorks and Bluetooth.

Design: Smart textiles enable the seamless integration of interfaces as integral parts of objects. Consequently, the use of a conventional input device made of metal, glass, or plastics, such as mobile phones, tablets, or computers, becomes redundant. Entirely new haptic and visual user experiences can be implemented. The user is encouraged to interact with devices via individual shapes, graphics, and haptic elements.

Communication Science: Usability and studies on technology acceptance are often based on the evolution of fiction scenarios or of commercial products. By using the inherently interdisciplinary research approach, this discipline gains the potential to contribute towards the development of textile interfaces iteratively across all stages of the design process: From the design and evaluation of scenarios, over non-functional and then functional demonstrators. Along all these phases the user's requirements, acceptance, and diversity is integrated into the subsequent development steps, placing the human under the spotlight.

3.2 Disciplinary Research Challenges

To design textile interfaces, several aspects must be considered and solutions for research questions of different fields must be developed. First, the technical specifications must be known, such as the conductivity of the used yarn for signal transmission. It must be identified which fabrics can be used to integrate conductive yarns and electrical components while maintaining their original textile properties. Secondly, what processes are needed to enable the industrial manufacturing of reliable and economic textile interfaces. How to balance the design requirements with the constraints of manufacturing, e.g., cost, and technical implementation, e.g., electronics integration and conductive yarn. Finally, what aspects influence users decisions to purchase, use, and accept smart textile interfaces, e.g., the sensors' washability and durability, originality of the fabric (texture and deformability), and invisible integration.

Textile Engineering and Finishing: Weaving and embroidery are the most common textile integration technologies for conductive yarns. Processing parameters for the weaving technology are unknown yet. Here, the questions are, how close can the signal lines be laid out and how does the influence interaction design and product design. Regarding the embroidery, the friction behavior of the yarn during manufacture and post is essential because it determines the amount of mechanical stress onto the conductive material and how fast the yarns could loss of conductivity. To reduce yarn friction, production speed, e.g., the stitching speed of embroidery machines, must be controlled. Eventually, the technical specifications of conductive yarns and the production process could limit the creative freedom of both interaction and product designers.

Media Informatics: Working with smart textiles, we need to understand how the physical characteristic and the technical specifications of the yarn as well as the textile production process affect the design of textile sensors. We raise the following questions: How can the conductive thread be connected to the electronics in the PCB holding the sensing technology and intelligence that enable smart textiles? Can capacitive and/or resistive touch technologies with fabric be used? How can algorithms be developed to detect user input (e.g., touch, pinch) and to filter noise caused by fabric movements? How can we design textile sensors that are intuitive (easy to learn and use) and robust against accidental activation?

System Integration: One main obstacle in system integration is the automatic mapping between different technical systems. As the connection usually is of a more semantic nature, the improvements in the field of AI may help here to achieve better solutions. Furthermore, the overall performance of a solution is later relevant for acceptance in the market. As from the point of integration an entire integrated solution is seldom better than the weakest part. We look at the balanced quality and integrate-ability of solutions.

Design: From the design perspective, the following key research questions are of importance: First, what are some of the use cases of smart textile interfaces? Second, are shapes and graphics helpful to familiarize with the interface and ensure easy handling? Third, which ergonomic requirements need to be considered in the textile interface?

Communication Science: The role of user diversity in interaction and acceptance of textile surfaces is currently insufficiently understood. Although the body of technology-acceptance research models is constantly growing, there are currently no empirically validated models specifically tailored to textile input surfaces. Therefore, the new factors that might influence the projected and actual use of these interfaces must be identified, operationalized, and integrated into predictive research models. One key question is how the diversity of users, such as age, gender, affinity towards textiles, technical expertise, or mental models, shape the efficiency, effectivity, and satisfaction while using interactive textile surfaces. Based on these findings suitable interaction designs should be developed that facilitate a high usability and an overall acceptance of the proposed novel textile interfaces.

4 Key Findings

The following sections presents several engineering and research findings that have been generated during the project INTUITEX. Research and development started with experiments on interactive textile surfaces and eventually branched into three different application domains and an exemplary demonstrator for each domain.

4.1 Realized Demonstrators

Within this project we realized three different demonstrators to explore different levels of personal proximity to the interactive textile surface:

1. **Proximal textiles**, i.e. a wearable textile on or very near the body, such as a Smart T-Shirt or a Smart jacket.
2. **Extended surrounding area**, i.e., a textile that people frequently touch, use, or sit on, such as a Smart cushion, a sofa, or a bed.
3. **Surrounding space**, i.e., textiles that are present within the living or working environments that are usually not touched, used, or moved.

Demonstrator for Proximal Textiles: The Smart Jacket. This jacket can be used for sports and everyday situations. A stitching pattern (see Fig. 5, top row) is integrated into a jacket and offers two operation axles that can be grasped by hand. The two possible gestures are currently used for two different usage scenarios: (a) accepting or making a phone call; (b) stopping/playing the music or switching between songs. The interaction can be supported by an embroidered graphic as a haptic concretion on the fabric to enable the user to grope the handling area. Figure 1 illustrates the smart jacket in a user test.

Fig. 1. Proximal textiles demonstrator: smart jacket during user test: subject taking a phone call while riding a bike (left), focus group discussing the jacket's textile interface (right).

Demonstrator for the Extended Surrounding Area: Smart Armchair. An off-the-shelve armchair with motor-adjustable back- and footrest is augmented with an interactive textile interface. We realized different textile interfaces that are evaluated and compared to the conventional remote control. One of the interfaces is based on textile pleats that resemble the backrest and the footrest, respectively, integrated in the side of the chair. Either touching or bending (pushing) the pleat activates the motors and moves the rests upwards or downwards. Figure 2 presents the armchair with its smart pleats.

Fig. 2. Extended surrounding area demonstrator: motorized armchair with a textile interface.

Demonstrator for the Surrounding Space: Smart Curtain. As a demonstrator for the surrounding space we realized a smart curtain by integrating conductive yarns into a conventional curtain cloth (see Fig. 3). The yarn can be incorporated into textiles with different processes, such as embroidering and weaving. By touching and swiping across the respective areas, the curtain is opened or closed.

Fig. 3. Surrounding space demonstrator: Smart curtain.

4.2 Individual Research Contributions

Textile Engineering and Finishing: Within this project, the embroidery company AFP Textilveredelungs und –vertriebs GmbH, tested different conductive yarns on their multi-head embroidery machine from TAJIMA Type TFGN –910 (meaning 10 heads with 9 needles each) in cooperation with the Institute for Textile Engineering. Different conductive materials were tested and typical issues were yarn breaks, irregular appearance, slow running speed, lint formation or that the fabric is not processable. Tested yarns consist of copper multifilament wires, stainless steel yarn in different linear densities, silver coated yarns based on polyamide (PA) and twisted yarns made of polyester and silver coated PA-yarn and a spread between 100 and 560dtex. The best results were achieved with shieldex 117/17 dtex 2-ply HC+B from Statex and Silver-tech 120 from Amann. To get an impression of the different properties, some pictures of different conductive yarns can be seen in Fig. 4.

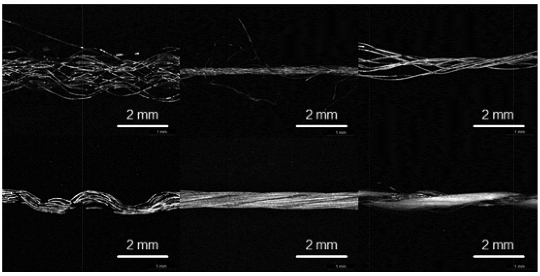
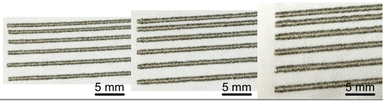
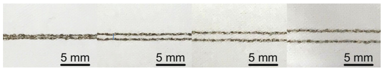
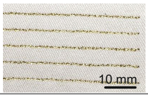
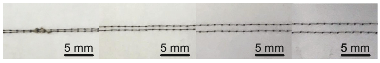
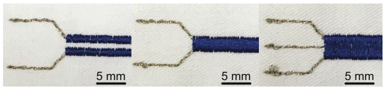


Fig. 4. Examples of different conductive fabrics, yarns, and process parameters.

Geometrical limitations regarding the distance between signal lines could reliably be decreased from 6 mm down to 2 mm. Due to the break of single filaments there were short circuits between several parallel lines. With better process parameters and a consideration during the punching in the embroidery software, the yarn could be processed without damaging it. This allows to create complex interface structures on a smaller area. Different kinds of stiches (flat stich, linear basting stitch, lock stitch or the use as lower thread) allow different haptic and electrical properties or protecting of signal lines. The back of embroidered devices is usually flamed, to avoid any lint and short circuits. Table 1 shows an excerpt of the design of experiments with different process parameters, stitching types, and yarns.

Table 1. Different conductive yarns with div. mechanical properties and stitching distances.

Stitch type	Variation parameter	Working limits	Samples pictures
Flat stitch	Stitch width: 1.2–1.6 mm Signal line distance: 1–3.5 mm	All working	
Linear basting stitch	Stitch length: 2–3.6 mm Signal line distance: 0.7–2.8 mm	All working, best results with 2.6 mm	
Offset	Stitch length: 2–3.6 mm	All working	
As lower thread (view from backside)	Stitch length: 2–3.6 mm Signal line distance: 0.7–2.8 mm	All length working, short circuits may occur below 1 mm	
Linear basting stitch, isolated with non conductive yarn	2–3 lines isolated together with flat stitch (distance 2 mm); single isolation (distance 3.3 mm)	All working	

After figuring out which yarns and parameters work best, the realization of devices started. Different variations were produced to test functionality borders and behavior in user conditions. The functionality is achieved through resistive or capacitive sensing. For linear input devices, single signal lines can be used, e.g., for controlling the curtain (the lines detect the user hand and send the data to the microcontroller) (see Fig. 5, bottom row). Long linear signal lines can be produced by weaving as well, which allow higher length (up to “endless”) and the use as platform material. Limitations are the unidirectional and parallel design; embroidery allows freedom in design but is much slower in production.

Stitched conductive bars are used as a haptic support for the user and to get wide signal detection areas. 2D-embroidered structures can be adapted to 3D-input-devices, similar to what we achieved with the Smart Armchair by folding the fabric and sewing pleats (see Fig. 5, middle row). A combination of different stitch types allows complex textile-based devices for detecting a 2D or 3D-folding and corresponding signals (see Fig. 5, top).

For more complex structures, one must consider that more signal transmission lines are necessary. However, as the required space on the substrate increases, the effort for designing the structure increases proportionally. For consumer products, textile manufacturing offers a lot of potential but must be inherently integrated into an iterative development cycle, as the technical realization is one critical factor for a product’s commercial success.

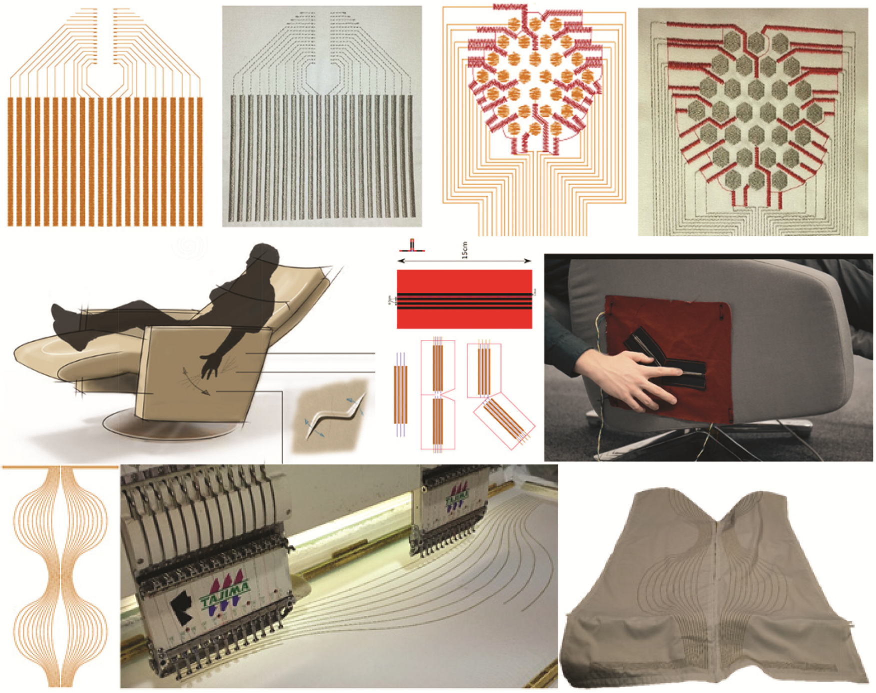


Fig. 5. Different stitch patterns for the three realized demonstrators (top: jacket, middle: armchair, bottom: curtain).

Media Informatics: The electrical connection between the conductive yarn and a PCB holding the electronics containing the intelligence of the smart textile is of great interest to research. Soldering conductive yarns onto a PCB is very challenging and error prone and for some yarns, e.g., silver-coated yarns, it is not possible. Linz et al. [38] suggested using flexible PCBs which can be stitched on fabric and connected directly with lines of conductive thread. This strong integration, however, requires the electronic components to be washable, which results in additional effort. In Project Jacquard [10], an industrial process is described to connect the conductive thread and completely seal the interconnections and electronic components.

We developed a clipping mechanism [39] to easily connect the ends of the conductive thread to a PCB. The clipping mechanism, depicted in Fig. 6, above and below the conductive lines are two horizontal holes to get the clip through the supporting fabric. The conductive thread is firmly pressed against the conductive plates on the bottom side of the PCB by a plastic clip. The plastic clips have raised edges between each connection point to prevent the threads from accidentally connecting with each other during, e.g., movement. This mechanism has the advantage that no sharp edges slowly cut into the yarn and thereby reduce its conductivity, and that the PCB can be removed before washing and clipped to another piece of fabric. One limitation is that the clip becomes bulky very quickly as we increase the number of connections.

Fig. 6. The orange clip provides bins for the endings of the conductive thread. The PCB just has simple contact areas on the bottom side and is pressed against the fabric by the orange plastic clip. The black part is the top case of the enclosure. (Color figure online)

Touch technologies, capacitive and resistive, enable a large input vocabulary that ranges from tapping, swiping, and gesturing on the fabric surface, to pinching and rolling the fabric between the fingers. We used capacitive touch technology to enable the curtain and the armchair. Both demonstrators have a 1D touch sensor that can detect swipes in two directions (curtain) or tap/touch (armchair). To detect these gestures, a microcontroller reads the difference in capacitance at each conductive thread and measures it against a threshold. The microcontroller filters noise by detecting permanent contacts, e.g., when the curtain folds touch, or when more than one touch area is activated on the armchair, e.g., when someone bumps into the side of the chair.

Capacitive sensing on clothing is very challenging. Searching for a capacitive touch-area cannot happen eyes-free since activation is triggered once the finger is near it. During movement the sensors deform and fold creating noise signal. Finally, the body capacitance makes it very difficult to place a sensor above the skin. The smart jacket uses resistive technology. The sensor consists of 30 pads of conductive yarn embroidered onto a piece of cloth (Fig. 7). When a user pinches a fold in the sensor, some of the pads come in contact with each other, which can easily be sensed by a microcontroller. Pinching is a natural gesture that is relevant to fabrics. It is an explicit gesture that activates the sensor and triggers an action at the same time, and it is robust against accidental activation. We used a machine learning algorithm, random forests, to classify

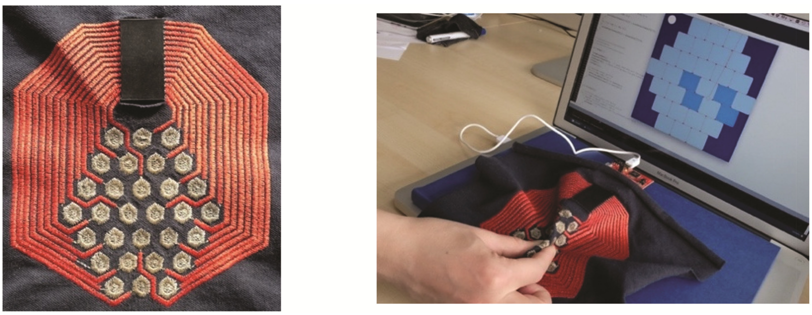


Fig. 7. The sensor consists of 30 pads of conductive thread embroidered onto a piece of cloth. When the user grabs a fold of the sensor, the interconnections are sensed by a microcontroller and mapped to relative 2D output.

at which angle the user is pinching the fabric relative to his body. We achieved 85% accuracy rate at 45° angle increments, and 90% accuracy at 90° angle increments [40].

Despite the limitations of the 2D embroidery structures, we could design visual and haptic affordances by manipulating the shape of embroidery and fabric. For example, in the armchair, we use fabric folds at two different angles to allow users to haptically determine, by swiping their hands across the side of the chair, which area controls the reclination of the back- or footrest of the seat. The direction of the touch is mapped naturally to the possible actions: pushing down on a fold brings the relevant part of the chair down, and the opposite applies. When designing the smart jacket, however, the minimum spacing recommended between any two parallel conductive threads (2–3 mm) became a major design and technical restriction limiting the number of touch points per inch fabric, thus the sensor's input resolution. Routing and insulating the extensions of the conductive pads also restricted the resolution and made the system bulkier. In the curtain, we took advantage of the naturally uninsulated conductive yarn to enable user interaction along the length of the fabric.

In summary, working with conductive threads requires a new design framework and guidelines for smart textile user interfaces and input techniques. Fabric characteristics, such as flexibility and movement, also influence how we design textile layouts and where we place them.

System Integration: We produced diverse technical bridges between the systems, with a focus on reliability and miniaturization. For example, we developed a LonWorks Bluetooth bridge and the possibility to connect this bridge also to one of the uprising Internet of Things platforms IzoT. In a further step, we compared different existing smart home and Internet of Things approaches for their semantic congruence. This is especially important, as seamless applicability will only be established if systems can integrate themselves automatically into peoples' habitat.

Design: From the design perspective, various evaluation parameters have been established during the project. Three levels of perception of personal smart interactive textiles were defined (proximal textiles, extended surrounding area textiles, surrounding space textiles). These levels guided the design and development of the three presented demonstrators (see Sect. 4.1 and Fig. 8). Accordingly, application scenarios were designed and visualized. For each demonstrator, the optimal position(s) for the textile interface was identified (see Fig. 8).

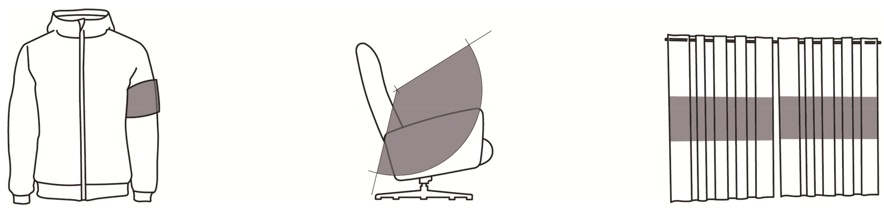


Fig. 8. Considered positions of the textile interfaces: proximal textiles (left), textiles in the extended surrounding area (middle), textiles in the surrounding space (right).

For all three demonstrators, the operating elements must be positioned ergonomically to ensure comfortable use while preventing unintentional activation. In cooperation with the research partners, we developed an optimal user-centered positioning of the interactive textile elements.

Concerning the smart jacket, it was most important that it could be operated eyes-free and while wearing gloves. Therefore, we investigated different sizes and positions of the textile interface and developed patterns and models of embroidered graphics that support the user haptically to be able to grab the handling area.

The textile interface of the armchair was integrated on the side to be operable blindly. We evaluated several designs to convey to the user how to control the different parts of the chair (footrest and back) without visual inspection (see Fig. 2). Prototypic users enjoyed the clear affordance and the direct mappings [37] between the folds and the movable parts of the armchair. We aimed for a comfortable operational experience by using a minimalistic design.

Relating to the curtain, it was our goal to insert the conductible yarn as a visual signifier and a design element: refined wavy lines, vertically processed, winging from left to right. Interaction with the curtain is realized by swiping both hands over the curtain's fabric to open or close it (see Fig. 3). The design needs to be subtle, as a decorative effect, in order to integrate well into the living. Until now, our goal has not been reached due to manufacturing problems. From the points of production technique and industrial realization, embroidery will be too extensive for large-scale production. By using current looms only dignified patterns can be reached and a conversion into large-area graphics will be limited. Therefore, the conductive paths must be weaved into the fabric and design elements transferred, e.g., via print, to the fabric.

Communication Science: Results were generated by studies on three different layers: first, scenario-based surveys that assessed the requirements, motives, and barriers for the acceptance of smart textile interfaces. Second, user-studies with non-functional demonstrators (i.e., interviews, focus groups, Wizard-Of-Oz experiments) that generated insights on intuitive interactions, applicable forms, and sizes for textile interfaces. Third, summative user studies with functional demonstrators that addressed the participant's evaluation of textile interfaces after a "hands-on experience".

Regarding the scenario-based approach, an Adaptive Conjoint Analysis was used to weight the most important dimensions that shape the acceptance of a textile product. The study revealed that the technical realization is the most decisive criteria for a products' success. Specifically, the prototypic users disliked visible electronics and asked for seamless integration of the required technology into the garments. Usage context, functionality, and haptics were found to be comparatively less-important [41]. In a second study, the motives, barriers, and conditions for using smart textiles were investigated [42]. The aesthetics and durability of the product were regarded as the most important criteria. The preferred locations for using smart interactive textiles in the home environment were the living room and office, whereas the bathroom or the bedroom were considered the least favored locations.

A scenario based survey with 136 participants identified the barriers and benefits for using smart interactive textiles in the home environment and derived a Smart Textile

Technology Acceptance Model that can predict over 86% in variance of the intention to use smart textiles at home [43].

Interviews and focus groups with non-functional demonstrators found that intuitive and preferred interaction styles differ with age. Using gesture elicitation method [44], subjects were asked to perform gestures to control a music player (change a song and control the volume) using a textile surface. Older people preferred interfaces with noticeable buttons, whereas younger generations imagined flat textile touchpads. Strikingly, other textile affordances, such as folding, wrinkling, or stretching were rarely used. Interestingly, textile interfaces were considered as valuable enablers for blind or visually impaired people to be able to interact with technology augmented environments.

In the evaluation of the three functional textile demonstrators the participants reported high usability of the smart curtain and the smart jacket but also a rather limited perceived usefulness. For the jacket, this might have been caused by the limited input spectrum in the current state of the development. Therefore, possible business cases should be carefully evaluated and suitable niches must be identified. In contrast, the smart armchair was found useful *and* easy to use by almost all our subjects. Furthermore, most participants preferred the textile interface over a conventional one in a randomized trial.

5 Discussion and Outlook

After nearly three years of work in project INTUITEX we concluded that an interdisciplinary consortium of textile and electronics engineers and designers is necessary to map the challenges and opportunities of smart interactive textiles. The following paragraphs discuss open research questions and the benefits of interdisciplinary cooperation.

From the perspective of textile engineering, there is still a lack of reliable technologies of conductive yarns which is needed for stitching, connecting with electronics, and using and washing these yarns. Current smart textile prototypes are specifically tailored for demonstration. Existing conductive yarn technologies can adapt for a small number of custom-made articles (scope), but producing larger quantities of interactive textiles (scale) is still difficult. Open questions include how conductive yarns can be connected to electrical components and how to integrate these components into the embroidery process. Interaction patterns may come in a variety of forms and sizes. In this case, a bridge between the production with scope and production at scale must be found (cf. [45]).

To date, the integration of novel sensors and actuators into our surroundings is mostly hand-crafted. In the near future, advancements towards the Internet of Things will provide better semantic and automatic integration of novel interfaces and devices into the home environment. In project INTUITEX, a series of new research questions emerged. From a technical perspective, two of the three presented demonstrators work very well. However, the smart jacket still has many problems, mainly due to constant fabric and body movements. Future research should focus on the integration and interconnection of textile devices in the home environment: this way, it would be possible to control typical smart home functions (such as the lighting, heating, and entertainment system) by using the textile interfaces of the armchair or curtain.

Regarding the design of textile interfaces, this project only explored flat textured surfaces. Textiles can also be manipulated into three-dimensional structures by using, e.g., 3D mashes or weaving in 3D. Thus, interactive interfaces may be realized as tangible objects with different design parameters.

Some of the presented studies investigated the suitability of smart interactive surfaces for aging users in the context of demographic change. In general, we found that adequately designed textile interaction surfaces are usable and useful independent of age and therefore, they can serve as additional and novel input devices to increase elderly's ICT participation. Still, there are open research questions and links to future research opportunities: How to design textile interfaces that can support and empower the elderly or chronically ill in their daily lives. Smart textile interfaces may potentially be used to prepare toddlers and children for the 21th century, as textiles and tangible surfaces may convey self-efficacy in digitalization [46].

From the perspective of technology acceptance research, we found that the established models are not able to capture the specific attributes of textile interfaces, nor the individual personality states and traits that are related to the acceptance of these interfaces. Therefore, further studies should identify, quantify, and weight the specific personality and system factors and their relationship to intended use and actual use of novel textile interfaces. A technology acceptance model specifically tailored to smart textiles with an increased overall predictive power might forecast and facilitate the success of textile products at the market.

The interdisciplinary cooperation in this project not only enabled the development of better products, but also facilitated a better understanding of the diverse wants and needs of the research partners from academia and industry. The project contributed to an enhanced interdisciplinary knowledge exchange and to a better understanding of the requirements, competencies, and methods of each partner. Retrospectively, we started as independent research partners, strengthened our ties as a team across the project period, and are now able to empower ourselves for a viable interdisciplinary collaboration beyond the project and the realized demonstrators.

Summarizing, the inherently interdisciplinary research methodology that included expertise from textile engineering, computer science, design, and psychology in combination with an early focus on users' requirements fostered the development of novel smart textile interaction surfaces and yielded increased usefulness, usability as well as high overall acceptance.

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