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Title:

The cross-section of a multi-disciplinary project in view of smart textile design practice

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Abstract

We describe the development path of a smart textile-design method, stemming from a collaborative multi-disciplinary project, with three university departments: chemistry, design and electrical engineering. While the project focus was not originally on textiles, the needs for flexible semiconducting materials led to experiments with a zinc oxide(ZnO) semiconductor deposited over cotton substrate, thus shifting the focus towards textiles. A series of exchanges and actions between the three disciplines raised the awareness of the need for textile-design methods regarding electric materials. Taking this as a starting point for generating new knowledge, drawing from the strengths of both textile design and engineering, an approach to develop smart textiles was developed. We conducted preliminary evaluation of this approach, called Teksig-method, in three contexts related to the smart textile design practice: exploratory and creative collaboration, smart textile design, and technical measurements. To this end, a workshop was organised, as well as conducting a series of measurements using a mechanical test-rig, and designing smart textiles with different types of electroconductive yarns. While the initial findings suggest usefulness, however more thorough examination is needed.

In this paper, we discuss the overall project, and identify the key stages in the interdisciplinary collaboration, in terms of textile design practice, while reflecting on the outcomes, which enabled paving the way for interwoven design and scientific knowledge embedded into smart textile design practice.

keywords

smart textile; process; interdisciplinary research; ZnO yarn

Introduction

Smart textiles and clothing have advanced to the point, where smart material development suitable for textile design is focusing on the fibre level, however, there is a distinct gap between the technologists and the designers (Cherenack and van Pieterson 2012; Castano and Flatau 2014; Stoppa and Chiolerio 2014). There are examples where textile design is indicated as central, but the designer's role is not always indicated in the process (Quirk et al. 2009; Martin et al. 2009; Karrer et al. 2011), let alone noticed as relevant (Chan et al. 2012), even though the research would otherwise be highly relevant in the field of smart textiles and clothing. Bandodkar et al. (2016) discuss in length about wearable chemical sensors, suggesting a need for collaborating with "humanists" to solve several of the current challenges facing the research field. However, they are unable to specify what the research field of the humanists would be. There are several examples aiming towards smart clothing and textile development, where the technology is intended for textile use, but there is no input from the textile designers (Löher et al. 2008; Chen et al. 2014; Lee et al. 2015), or they are only briefly mentioned in the acknowledgements (van Pieterson et al. 2011; Zysset et al. 2012; Mattana et al. 2013). Furthermore, there are already several examples, which have successfully utilised an interdisciplinary approach (Jost et al. 2014), however they are often textile led (Berzowska and Skorobogatiy 2010; Seager et al. 2013; Kuusk et al. 2015) or they have considerable commercial interest (Devendorf et al. 2016; Zhou et al. 2016).

When discussing the utilisation of e-textiles in computing education, Peppler (2013) suggests to combine both STEM (science, technology, engineering, and mathematics) fields and arts. As an example of the imbalance within e-textile learning, the author draws attention to an e-textile designer emphasising more on artistic expression than on technical functionality, noting: "in general, novices to e-textiles do not fully understand the energy transfer capabilities of physical objects and have difficulty distinguishing conductive from insulating materials". Furthermore, "creating e-textiles requires a firm understanding of electronics, yet even simple circuits can pose a challenge to new designers". To address this gap between design, science and technological knowledge and skills, the paper proposes eight guiding principles to a STEAM-powered approach to education, which aims to balance technical expertise with artistic vision, (and eventually provide wider consumer acceptance to electronic textiles). In a similar learning setting, Lau et al. (2009) taught first simple electricity, electrical circuit theory and programming before students made smart textile products. The design space for "creativity", which was determined by the students was "the placement of the sensors and the pattern and colour of the lights". However, in a study by Perry (2017), in which the knowledge and experiences of the creators of smart clothing were investigated, the results indicated that the focus on design is still on technology rather than apparel. Although contradictory, while the emphasis is more on technology, the missing knowledge to these type of skills and the difficulties in technical issues, remain to be a considerable problem, echoing Peppler (2013).

Despite this gap, there is an interest to understand both the development and the usage of materials suitable for smart textiles, specifically suited for textile design methods. With the textile design at the centre, the designer interacts with different scientific stakeholders, such as chemists and electrical engineers. This brings forth the need to be able to communicate, and to understand each other with issues, e.g. time scales of process (the time needed for conducting different processes), or keypoints in time (the moments that are important or relevant to

knowledge generation that provide distinct impact to the process), which vary between the disciplines. Drawing from Schön's quote: "in a good process of design, this conversation with the situation is reflective" (Schön [1983] 2013: 79), we also seek to understand what smart textile practitioners could do, how they could think and how they could function.

Textile design and its teachings are rooted from disciplines of art, craft, design, and technology (Igoe 2010), providing different professional roles that range between creative, social, industrial, commercial and associated practices (Gale and Kaur 2002). In an early defining paper, Moxey (1999) has touched upon the multi-disciplinary nature of a textile designer's role: a hybrid artist-technologist–social scientist, providing innovation, variety, and consumer satisfaction within the fragmented textile industry. Similarly, Wiberg (1996) draws attention to the "intertwining of the scientific-technological, the conceptual-transcendental and the artistic-intuitive" presence in the every-day practical work of a textile designer exemplified by the colouring of fabrics. In order to utilise these multi-faceted skills, in all stages of the design, development and production process, the textile designer collaborates and communicates with other professionals, i.e. engineers, technicians, logistics staff, marketing staff, salesmen and management (Bang 2010). However, as the use of textiles is furthermore expanding parallel to the development of textile material diversifying, academic research points to textile design encompassing an even broader range of practices and different forms of collaboration.

The Heat Harvest project discussed in this paper is a multidisciplinary collaboration between three Aalto University schools: Chemical Engineering (CHEM), Electrical Engineering (ELEC), Arts and Design (ARTS). This project is part of the Aalto Energy Efficiency Research Programme, and the three schools approach the topic of energy har- vesting from their respective perspectives, to develop materials and methods for extracting energy from ubiquitous waste heat, while look- ing for innovative concepts for new applications. Although the project is multidisciplinary, the science-led project revolves around atomic layer deposition (ALD), an advanced thin film coating method that fabricates ultrathin, highly uniform material layers by exposing the surface of material to alternate gaseous species. An important benefit of this method is the possibility of deposition on a variety of substrate shapes and sizes (Jur et al. 2011). Zinc oxide-based thin films were exploited in the project as a model thermoelectric material system (Tynell 2013). The deposition of n-type ZnO thin films and coatings using ALD is a familiar process at Aalto University (Tynell 2013) and worldwide (Tynell and Karppinen 2014). For a full thermoelectric module, p-type thin film materials would be required; search for such materials was another goal in this project for the chemistry partners.

Drawing from the definitions laid out by Aboelela et al. (2007), our project started as a multidisciplinary project, i.e. parallel research sharing similar research questions. However, it has gained interdisciplinary characteristics, where we utilise data from different sources across disciplines, and use methods from different fields to examine the same core issues. Ideally, the aim is towards a transdisciplinary process, where the different fields can utilise the methodology and eventually merge into one discipline. Therefore, to help understand the divergent role of a textile designer in today's textile practice and the reciprocal knowledge transfer from and to textile design within a multi- and inter- disciplinary material and product development setting, starting from the early workshops (Townsend and Ylirisku 2015), we present the work done towards the development of semiconducting ZnO-cotton mate- rial (Sarnes 2015; Karttunen et al.

2017), and the subsequent development of a methodology (Townsend and Mikkonen 2017) suited for the development of electronic smart materials. We emphasise, that the perspective in this paper is that of a textile designer, even though the collaboration has been with both electrical engineers and chemists.

In this paper, we discuss the project and identify the key stages, in terms of textile design practice and in the interdisciplinary collaboration, while reflecting on the sensory aspects of material, methods and human interactions. We also discuss preliminary findings from using the Teksig method in contexts related to the smart textile design practice. While the overall project has consisted of other parts, such as a development of a solar collector, we focus only on the aspects related to the textile design-based measurement methodology. With the intention on building knowledge and skills applicable for future smart textile design practice, we further expand our (Intersections conference [Townsend et al. 2017]) paper. In addition to looking at the creativity on textile (material) design process, as well as the process itself, we present in related works current smart textile design methods and toolkits. Also, we underscore the future needs together with landscape of the expected context of use of our new methodology through example cases.

Related Work

In general, textile design can be considered as referring to the "pro- cess of creating designs for knitted, woven, printed and mixed-media" (Steed and Steveson 2012), lace-making and knotted fabrics, as well as including more recently developed sub-fields of textiles, i.e. smart- and 3D printed textiles. However, the design process, or its combination of phases, and stakeholders can differ according to the context a textile is created and used within, e.g. art, craft, industry, the type of textile techniques and technologies employed, in addition to the relation of textiles to products, e.g. as "a raw material" for different products and end uses, or, a specific designed material that is either de-attached or formed as an integrated part of a product (Nilsson 2015). In fact, Nilsson suggests that "there is no right way to design with textiles", however the respective influence of process, interaction of the material and the character of the textile design needs to be acknowledged and taken into consideration. Thus, the diversity within the textile and cloth- ing field entails the need for different types of designers (Wilson 2001). The different practice of a textile designer within the textile industry was highlighted in Wilson (2001) and further summarised into a generic five- phase textile design process framework by Studd (2002). Bang (2010) proposed changes to the design process by exploring the emotional value of applied textiles through implementing user- and stakeholder-centred approaches. Another approach taking the identification of the end-user needs as a starting point, by McCann et al. (2005), guides the designers towards identifying and addressing both technical and creative aspects. The authors propose a "critical path" tool to address the gap of "common language" between a creative and systematic design process in the development of smart clothing. However, while textile design has a long tradition in creative practice, textile design has had less presence in the general discourse on design, or design research compared to many other sub-fields of design (Bye 2010).

Academic research in textile design has been governed by technical studies positioned within science and engineering knowledge frame- works (Kane et al. 2015). Increasingly, however textile designers are undertaking research into technical areas with creative intentions, utilising artistic modes of inquiry (Cassim et al. 2017; Morgan 2017; Paine et al. 2017), exploiting scientific research for artistic intentions (Mat- thews and Nimkulrat 2017), or challenging the perception of

technical and functional research in textiles to be conducted solely within the domain of scientific methodologies and engineering practice (Glazzard 2014). The boundaries of creative practice within the discipline of tex- tiles, are also being exploited as a value bought through collaborative practice (Valentine, Ballie, Bletcher, Robertson and Stevenson 2017), e.g. Walker and Piper (2017).

Multi- and interdisciplinary

Prevailing disciplinary divisions in design assumptions and expectations is suggested to decrease by gaining understanding of other collaborative practices and related knowledge transfer (Glazzard 2014: 48), e.g. within multi-, and interdisciplinary work. This in turn, can extend the content and outlook to what is textile design, and how knowledge and skills from other disciplines can be exploited in developing textile design research and practice.

Three early examples of interdisciplinary research topics, interactive olfactory textile surfaces (Tillotson 1997), digital 3D textiles (Harris 2000), and spray-on fabric (Torres 2001), cut across the fields of tex- tiles, fashion and science (Sams and Black 2013). In a research project involving the development of linseed fibre material (Härkäsalmi and Koskinen 2010), the textile designer exploited knowledge from fields, e.g. microbiology and agrotechnology. Härkäsalmi and Koskinen (2010) underscored the importance of multidisciplinary research, and how a designer-researcher can take the leading role in a material development process after obtaining the relevant fundamental scientific knowledge, and when having knowledge of all stages of the production chain in the development of novel raw materials. This has been further exemplified in the DWOC project (Aalto University et al. 2015), which has origins in multidisciplinary material development (Michud et al. 2015), suggesting contexts and uses to guide the development, and producing exemplars and providing methods to utilise new material (Itälä 2014); an approach further explored in CHEMARTS (Kääriäinen et al. 2017).

In a collaboration between textile design, optical engineering, dyeing chemistry, and colour analysis, Akiwowo et al. (2014) have developed a method utilising a laser to "engineer dye onto the fabric with high-resolution graphics". During the development, they configured the colour data through both visual and numerical means, "demonstrating the relationship between a specific vector grid, tonal density, and energy density" (Akiwowo et al. 2014: 144). Notably, the "energy density provided a common language", to achieve controlled and repeatable colours. A successive project focusing on laser modification of textiles, describes a research methodology attempting to illustrate the synthesis of scientific and creative approaches (Morgan et al. 2014). Partly implemented with the same team, the work falls within textile design, textile chemistry and textile engineering. The methodology describes four phases, with iterative data creation at the early phases, followed by quantitative testing and design development in the latter phases. They emphasise the importance of tacit knowledge during the knowledge generation, and describe how it combines together with scientific knowledge, drawing a clear picture on the research collaboration. They specifically mention that the "reciprocal relationship between the exploration and experimentation" was "foundational to the momentum and success" of both projects, further stating the importance of work being pulled "back into the exploration phase to maintain the design direction". Both projects demonstrate an approach in which knowledge was generated as the design practice advanced (Kane et al. 2015).

Another example of creating means for common language between design and science is presented in Glazzard (2014). In her doctoral research, Glazzard uses a designer–maker methodology, to produce auxetic, weft-knitted textiles. She demonstrated the value in the transferrable knowledge in existing knit methodologies, while providing a new methodology for consideration by science and engineering practitioners. (For example, the measurements of auxetic effect and data is represented visually and simply through graphical forms, diagrammatic forms and illustrative forms, alongside numerical data.) As an example of technology-influenced design process development, Parsons and Campbell (2004) present and analyse five digital printing projects. The paper demonstrated, how the experience and knowledge of the tech- nical constraints and possibilities influenced the design process. As the solutions to sub-problems were found, the shift in focus addressing design features gave more space over solving technical issues, thus changing the design process into a linear phase-oriented procedure.

Creativity, and developing understanding through tools and methods

Despite the approach or process, a common factor in all design activities is creativity in its different form: whether a less evident "form of a creative event", or "solution possessing some degree of creativity" (Dorst and Cross 2001). As an example, creativity has been discussed in regards to the textile and/or garment process within a framework for a system view of creative success within fashion textiles (Moxey and Studd 2000). Furthermore, Strickfaden, Stafiniak and Terzin (2015) have provided insight into understanding creativity in the design pro- cess through influence and inspiration, and how these aspects of creativity are transformed into projects. Moreover, within the domain of design and material, creativity has surfaced as "creative material development" (Thompson and Ling 2014: 207). This approach combines technical and emotional aspects of material development to allow creating products that offer new material experiences to the user, thus placing the designer into a more leading position in developing new material. This is also echoed by Karana et al. (2014), quoting: "Thus, when a decision is to be made on the materials to be used in a new design, competence is needed in predicting and defining both the experiential qualities and the performance qualities of materials". An example of such attempt can be seen in the development of a functional garment for electric stimulation, focusing on the exploitation of the electrical signalling in the knit (Li et al. 2014). The textile pattern has been designed through systematic combination of electrical engineering and garment design, specifically utilising different stitch types and materials for the intended effect.

As the field of smart textiles evolves, novel concepts utilising them are emerging, along with the possibilities to influence the users from the early education onwards. To foster such influential and creative activities, different methods and toolkits are being created, and according to Baurley (2004), "Smart functionality will also have an impact on the way products are designed and the materials developed". There are even indications from children's workshops, based on 80 participants, that early adoption of constructive methods in crafting and smart textiles may foster stronger leadership in successive development tasks for girls, altering the traditional roles (Buchholz et al. 2014). As the smart textile practitioner works in the cross-section of different disciplines, we explore how these tools attempt at supporting the creativity and prototyping.

When looking at the creative process through embodied interactions, the body, the context and the materials are at the focus (Wilde et al. 2017). Primarily, the materials and the context were explored through first-hand interactions and collaborative acting, however the props and

materials varied considerably. The technical level of the materials used in the ideation was imaginary at their simplest, using common objects through acting, while the more complex approaches involved pre-cut fabrics, functional commercial electrical devices and pre-made "carefully constructed – technology-free – wearable probes" (Wilde et al. 2017: 5165).

However, on the other end of the tool-spectrum are the toolkits, which aim to ease the development by augmenting the creative use through simplifying some aspects, usually by hiding technical complexity, of the design process. For example, MakerShoe provides hexagonal modules, which contain functional electronics, ready to be combined for different purposes on top of a shoe (Kazemitabaar et al. 2015). Whereas, Interactex provides a tablet-interface for creating the behavioural functionality, in addition to sketching the electrical layout and schematic using smart textile elements (Haladjian et al. 2016). TechSportiv attempts at motivating the child to learn by combining physical education and smart textile prototyping, using a toolkit with smart textile components (Dittert and Schelhowe 2010). There are also more specific approaches, such as FabriTouch, describing a textile touchpad, along with suggestions on how to implement them for "DIY crafting community and HCI researchers and designers" (Heller et al. 2014). However, there have even been arguments, that the scope of prototyping within the smart textiles would be so vast, that it would only be useful through the utilisation of simulations (Martin et al. 2003).

Regardless of the case, it can be seen that the smart textile practice is interdisciplinary, bordering on transdisciplinary. The proliferation of technical toolkits and the attempt to simplify difficult aspects through methods and means, either for improving creativity or implementation, indicate that the different ends of the spectrum of smart textile design practice try to draw closer to the each other. To aim at the truly transdisciplinary field of smart textile design practice, the practitioner should have broad understanding, regardless of the field of technology, be it electrical or textile.

Technical evaluation of smart textiles

The ability to co-develop with engineers and technical profession creates a need for both the collaborative aspect and communication, as well as the technical reliability of the design method, in order to improve the interdisciplinary skillset of the smart textile designer. To illustrate a typical technical evaluation of smart textiles, we explore elongation measurements, which combine the mechanical characteristics to the electrical behaviour. Elongation and breakage (SFS-EN ISO 13934-1 1999) for example, has been standardised and is common in textile development. In two different PhD theses, by Guo (2014) and Hardy (2008), and in general strain sensor development (e.g. Scilingo et al. 2003) simultaneous measurement of elongation and the resistivity of the smart textile sample is typical.

To enable interdisciplinary development and technical collaboration, the smart textile design practitioner should be able to provide new information for such evaluation cases, be able to independently con- duct such experiments and iterate based on the findings. However, the measurements tend to focus only on the resistivity, disregarding frequency-based, semiconductive or active phenomena which may be present in the textile.

It should be noted, that the frequency-based systems are at the heart of technical devices, as they typically form the basis for communication systems. As such, they are present in considerable

amount of research in smart textile and wearables context, such as for a trans- mission path (Kirstein et al. 2002), or in the selection of textile mate- rials for antennas (Salonen et al. 2004). While there has been some collaboration with design, such as for screening radio-waves (Seager et al. 2013), we feel the design practice could be better utilised. Thus, to emphasise the importance of the applicability to the interdisciplinary evaluation, the ability to visualise frequency-based phenomena is extremely important.

Background - Mapping the development path of the project

We created a map from the Heat Harvest project, and analysed it to a set of clusters. These depict the work done between 2013 and 2017 at different levels of detail, shown in Figure 1. The map describes the activities that either directly involved the design school, or had an impact to their work, and as such is not meant to be an exhaustive representation of the entire project.

The map was done to get an understanding of the interconnectedness, and to be able to analyse which steps were significant. In the map, each activity or moment of importance was visualised as a node: meetings, laboratory visits, measurement days, significant development activities (e.g. dyeing) and workshops, totalling over 50 separate points, some of which may span days or even weeks. They indicate when a key finding or an experimental outcome was gained. From each step, the most significant directions were laid out, e.g. when a meeting resulted in an access to a laboratory of a different School.

The clusters, on the other hand, show the overall stages of the work, and were based on the activities and the outcomes which are related to the same conceptual focus. By this we mean that while e.g. the ZnO yarns were created at different clusters, the reason why they were made varies between clusters. Furthermore, fundamentally different activities belong to different clusters, such as conceptual ideation belongs to "context and initial concepts", while ideating and developing new samples for the evaluation purposes belongs to "creative use". The contents of each cluster contain activities and textile-specific actions that are summarised in the Tables 1–5. Notably, the textile designer has been involved in all of these parts, apart from the very first workshop.

Project Cluster Overview

The main content of the "context and initial concepts" cluster, also seen in Table 1, was to develop novel product concepts that utilise thermoelectric components that are based on identifying different locations where energy is being wasted. This was also the initial intended contribution of the design department to the project. However, due to the outcomes of this cluster, the direction of design within the project changed towards hands-on textile material development. After this, the textile designers' research partner in ARTS changed from a software scientist to an electronics engineer.

In the cluster "sensing and sensorial expression", including details in Table 2, the work was most related to a traditional textile designers approach, although it was carried out with the electrical engineer. The work included the design of knit structures, and was textile design led. The process started with "crochet sketching" and table-machine knitting, and final samples were developed using a Stoll CMS industrial knitting machine, resulting in an SMA sleeve that was evaluated through user testing (paper under review). Laying the groundwork for the future shape change work, the evaluation was conducted in parallel with the "ALD on textile" cluster.

The work done in "ALD on textile" revolved around the chemists, as shown in Table 3, however it had considerable human interaction, regarding impact within the project. While the focus of this step was on the first ALDs on the cotton substrate, the textile designer had a concrete contribution. The yarn and textile selection was done from both the textile and the deposition perspectives, to develop a preliminary set of zinc oxide-deposited textiles and yarns. From the textile perspective, the yarn offers several benefits to other conductive yarns, being very similar to non-deposited cotton in both feel and visual outlook. Thus, the cotton-based yarns were explored in a variety of ways in the Design School. The project utilised standard resistivity measurements for the yarns, which is a standard for the chemists to verify the yarn functionality.

These measurements were followed by the design team. However, there were problems with the communication of the electronic properties, and their implications. The textile designer faced frustration, as the typical time-based measurements did not provide meaningful information in terms of textile design aspects. The results were seen electrically interesting, but when presented solely with numbers and overlaid sine waves, these were not expressive enough to see the connection between the electrical and the ZnO yarn qualities. There were hints that the behaviour of the yarn changed with the frequency; along with something else we did not yet comprehend. Thus, to utilise the yarns in smart textile development, the understanding of the signals needed to be developed. Furthermore, the textile designer indicated a need for yarns suitable for lighter garments.

The major impact within the project was in the cluster "New ZnO and knowledge", summarised to T4, which steered the deposition on textiles, having the textile design needs and suggestions as a starting point. The cluster contained several testing days. Initially the electrical tests were conducted at the designers' laboratory to verify that the findings in the "ALD on textile" were correct. Other tests were used to evaluate the frequency-related properties, as well as the DC properties. For the duration of the measurements, a lecturer and a laboratory engineer joined the team from ELEC, as well as an intern from design. These tests confirmed the findings; the test equipment gave matching results, thus allowing designer independence. There were also unexpected results, which prompted the ELEC staff to christen the samples as "magic yarn". However, during these measurements, the textile designer felt like just "sitting in and hanging around", without getting anything out of the measurements and a reference base emerged, being a major contribution to the work done in "Methodology development". At this point, there was a need to make the results comparable. Therefore, we decided to focus on the measurements which could be formalised, and to stay with the basic knit patterns.

The initial Teksig method was realised during the "methodology development" cluster, with details in Table 5. This cluster took longer than the others, taking roughly a year. It relied on findings from both "ALD on textile", and the "New ZnO and knowledge" clusters, of which the latter was the main influence. The "conflict" of engineering and design communication issues during the initial ALD yarn evaluation was addressed here, specifically attempting to solve the problem of understanding electrical signals in view of textile design. The core work of the textile designer was to create a systematic visual comparison map from the measurements, which

allowed the analysis of the samples to explain the usage and relations of the electrical features and the knit patterns. The systematic mapping, along with the sample knits, is illustrated in Figure 2. The samples were evaluated using Lissajous patterns using different frequencies, visualising the properties caused by the conductive yarns, knit patterns and semiconducting surface oxidation. The oxidation was initially perceived by the textile designer as "something wrong", as the pattern was drastically different from all other measurements. The patterns were then analysed to draw suggestions on how to develop smart textiles using Lissajous patterns, such as by showing how different textile patterns exhibit same or similar electrical behaviour.

In parallel with the evaluation, "Berlin samples" were constructed, which indicate the beginning for the on-going "creative use" cluster. The cluster itself consists of three focus areas: "shape change", "connectivity" and "teaching and education", which lead to "applied use", i.e. the practice readiness of the method. The method has also been central to the development of a patent application, which is being submitted to evaluation as of this writing. This is expected to lead to the commercialisation of the research findings in select contexts. The cluster outputs are shown in Figure 3 as a collage of the distinct images.

Smart Textile Design Practice

To demonstrate the possibilities towards the creative use, we present three different activities outlining the usability of the Teksig method for the smart textile design practitioner. The three activities are related to the situations in which the practitioner may be expected to work. The first one is the smart textile pattern design, where the practitioner is responsible for both the visual and electrical signal pattern designs. The second one is the collaborative smart textile development, where the practitioner utilises the Teksig to communicate behaviour to other designers during development. The third one is the smart textile evaluation, where the smart textile sample can be evaluated with both textile and electricalmethods with equal standing.

Smart Textile Pattern Design

The exploration of combining different conductive yarns integrated into the knit structure for seamless multi-functionality, is used as a case example, in which enables the practitioner to design with both visual and electrical signal patterns simultaneously. By selecting different materials and combining them in varied ways, broadens the use purpose possibilities.

The conductive pattern in the knit sample in Figure 4 consists of an input pattern, which is used to transmit the electrical signal into the so-called sensory knit pattern sections. The input pattern is formed of a continuous line covering the entire width, knitted with Karl Grimm High- Flex 3981 7 × 1 fach verselit Silber 14/000. The width of the sensory knit pattern is divided into five sections (A–E), and knitted accordingly with the following yarn and stitch types:

Section A: Karl Grimm High-Flex 3981 7 × 1 fach verselit Silber 14/000 and Bekaert Bekinox 50/2 Co 20% Bekinox 80%, alternating float & tuck stitches.

Section B: Karl Grimm High-Flex 3981 7 × 1 fach verselit Silber 14/000, knitted loop stitch, and Bekaert Bekinox 50/2 Co 20% Bekinox 80%, alternating float & tuck stitches.

Section C: Bekaert Bekinox 50/2 Co 20% Bekinox 80%, knitted loop stitch.

Section D: Karl Grimm High-Flex 3981 7 × 1 fach verselit Silber 14/000, knitted loop stitch. Section E: Karl Grimm High-Flex 3981 7 × 1 fach verselit Silber 14/000, alternating float & tuck stitches. The sample was knitted with a Stoll CMS ADF 32 W. Notably, sections A and B are knitted with a different spool of yarn than with sections D and E. The measurements were set up so that the signal was fed into the knit structure from the right end of the sample.

The Teksig method reveals the difference of textile patterns using various electroconductive objects on top of the textile. When com- paring the entire pattern without touch to section A, B and C when touched, it is clear that the signal behaves similarly. However, after the knit pattern changes back to the silver yarn in section D, the signal weakens. Whereas with conductive touch, the influence of the cotton– steel yarn is distinct (section C). Thus, sections A and B have acted as a signal transmission path, i.e. the signal does not degrade and is fully transmitted. Sections C and D are similar, as the D section is knit- ted with silver yarn again, displaying good conductivity and frequency properties, and therefore does not affect the signal; the signal is transmitted forward, only modified by section C. Section E, on the other hand, knitted into a different structure and being influenced by all prior sections, has the weakest signal.

Also, comparing between touch and conductive touch, the rotation of the Lissajous figure is opposite, thus there has been a phase change, which is due to the combination of the knit pattern, touch type and the materials at a specific frequency.

From the evaluation, we can see that sections A, B, and D are good as signal transmission paths: in this case, the knit/material combination does not alter the signal coming from earlier sections or the signal source. As such, they could be used to take the signal from the measurement device, through the knits – all the way to the sensors – and not cause issues for the sensor signal. In practice, the smart textile practitioner can design both the textile and signal qualities.

Collaborative Smart Textile Development

To demonstrate the use of the Teksig method as means for communicating electric phenomena, we show an example from the workshop held during Autumn 2017. The thorough examination of the findings, and the educational work leading to it, are beyond the scope of this paper. Prior to the workshop, the method was used at the wearable technology and smart textile education at the Aalto University, held during the Summer 2017. The feedback from this work was taken to the Arcintex workshop, which was held in October 2017. The example is from the second day of the three-day workshop, where the participants discuss the cause of the signal change. Prior to this, the participants were given a general overview in the form of a presentation during the first day.

The setting is shown in Figure 5, with participant A on the left, participant B in the middle, and the workshop organiser W on the right. The participant A was playing with the knit textile, which has patterns made with electroconductive yarn Shieldex 117/17 dtex 2-ply. The participant A was pressing the knit pattern under the measurement, with another conductive knit, which was otherwise not connected. This caused short circuits according to how participant A pressed the textile, and due to the high resistivity and random semiconductive properties of the conductive yarn used, the signal moved through the fabric in different ways. Pressing the conductive part created a good connection which resulted in a change of the visual Lissajous pattern, from flat thin shape to a large tilted shape, while the semiconductive phenomena trans- formed the signal to an s-shaped Lissajous figure. The semiconductive shape is not always present, and can result in

the transformation of the large tilted shape. When the s-figure became visible, it led to the following exchange, which was transcripted from a video captured with a close camera.

Simultaneously B: "wow", W: "amazing" (all looking at the oscilloscope screen)

B: "what does that mean?" (looking at the screen) A: "it's like, it's just like ..."

B: "(interrupts A) it goes like, you see it goes like, woop" (showing curve with hand)

A: "well this is just like, me that... (while pressing textile, looking at the screen)"

B: "no not that one, but do here (pointing at textile), there's curve here (pointing at oscilloscope screen)"

W: "it's showing some semiconduc ... it's semiconductive"

A: "this curve here (doing a wave motion with hand)"

From the exchange it can be seen, that B was able to distinguish the hand-press from an unknown signal on the screen. Furthermore, B was able to point to A, a spot from where to press, to make the unknown signal visible again. This resulted in the re-emergence of the visual signal pattern, which W confirmed to be a result of a semiconductive property. While A did not initially react to the "curve" B mentioned, but rather assumed it to be about hand-pressing the textile, A expressed understanding the difference by mimicking the semiconductive signal pattern by hand.

The participants were thus able to correlate signal on the oscilloscope to the smart textile use, being able to discuss the phenomena and visualise them using hands. Additionally, they were also able to point out the textile usage, which they suspected were responsible for the signals. Thus, the exchange suggests that the participants were able to discuss the phenomena in their respective levels of understandings using the Teksig method.

Smart Textile Evaluation

To substantiate the usefulness for technical evaluation, the smart textile practitioner should be able to conduct and understand the technical measurements. To demonstrate this, the "Berlinsamples" were used to evaluate the correlation of the elongation and the electrical signal. Even though the full examination is beyond the scope of this paper, we present how one textile sample degrades through successive elongation peaks. Thus, we focus on the repetitive strain, which is useful when testing and comparing the properties of visually and structurally different knits. In Figure 6, a plain knit sample consisting of Bekaert Bekinox 50/2 Co 20% Bekinox 80%, and two separate courses knitted into the top and bottom part of the sample with Karl Grimm High-Flex 3981.7×1 fach verselit Silber 14/000, is being tested.

The Karl-Grimm silver yarn is tested to see how it degrades due to over-stress. The test was conducted using Shimpo FGV-100E-L motor and FGV-100XY force gauge. The test repeatedly pulls the textile from the "zero" length (textile at 0 N) to the target length, which initially equates to roughly 4.9 N (~0.5 kg) pull force.

From the figure it can be seen, that the electrical signal path degrades over successive peaks. Even though not shown in the figure, the mechanical strength had also degraded by roughly 5% between the first and the last measurement. To compare with the typical resistive measurements (Scilingo et al. 2003; Hardy 2008; Guo 2014), it can be seen that there are properties which suggests also non-resistive changes: the effect of resistance would be visualised by only the vertical size scaling, whereas the change in the surface area, i.e. the shape change from oval-toline-to-oval, clearly suggests that the degradation also affects the inductive and capacitive properties. This implies, that the signal change is not only resistive, but also dependent on the frequency.

The possibility to include yarn combinations and knits to attain acceptable qualities in visual aesthetics and tactility can thus be combined with broader understanding of electrical signalling and tensile strength. The visual representation of the electric signal provides a goal for the practitioners to use their creativity, to explore different mate- rial and structural combinations, and validate them independently. The Teksig method would thus support the smart textile practitioner in evaluating the textiles through wider perspective, including aesthetic, tac- tile, mechanical and electrical qualities.

Discussions

By analysing the five contents of each cluster (content, activities, textile-specific actions, outcomes and collaboration) with the project as a whole, the project outcome resulted in the development of a sensorial material, enabled through human interaction in the process, culminating in a methodology. In discussions, we discuss the three main identified themes: (1) sensorial aspects of the material, (2) human interaction between research disciplines, and (3) evolution towards the smart textile design practice through the related work, and through reflective practice (Schön [1983] 2013) discuss the faced designer challenge.

Initially, the role of a textile designer in the project, was to create a mock-up, exemplar, or demonstrator exploiting the technology and mate- rial developed during the project, which enhances and supports scientific research. To create an exemplar, context in which the exemplar is expected to function needed to be first established, from which conceptual design ideas were created. However, after this phase the textile designer was confronted with a dilemma: how to design, and make exemplars, or demonstrators with technology and material which was still under early development, especially when there is limited understanding of the material's technical properties and of the material's design characteristics?

Sensory aspects of the material

At the beginning of the project, the ZnO material was not intended for sensorial development, but instead for energy harvesting from heat differences. The decision to deposit ZnO on a textile substrate was made after the workshops, which consequently broadened the intended use of the ZnO material and influenced future decisions. The ZnO yarn brought in new properties, which initially were missed; it has sensorial properties useable in textile design, feeling and looking like basic cot- ton yarn, but is also useable as a sensor.

The unforeseen change in research focus from energy harvesting to sensorial material, can be seen as an act of "reflection-in-action" (Schön [1983] 2013); a conscious response to an unexpected out- come, which was addressed in action. Also, the change in actions intended to answer the need to understand the novel yarn's properties, to be able to utilise them (Karana et al. 2014: Introduction). However, to utilise such yarn requires also knowledge of fundamental, but complex and hierarchical system of fibre, yarn, and fabric construction and finishing process that interrelate towards the sensory expression of tex- tiles (Behery 2005), and understanding to how each of these "layers" influence the overall perception and experience when constructed into a

product. Such like knowledge is built on both a textile designer's tacit knowledge (Igoe 2010), and experiential and implicit knowledge (Bang 2009). The interest towards exploring the material's sensorial properties, therefore, is not an unexpected action in the sense that sensory aspects of materiality is central in textile design. Furthermore, the textile designer's sensibility of material directed the selection of the next substrate fibres for ALD. Accordingly, new ZnO was deposited on silk and undyed thinner cotton; to explore textile design related aspects and sensorial (touch) qualities, such as dyeing and weight.

In addition to the direct exploration of ZnO material, thermal experience was explored with a SMA-knitted sleeve, to anticipate on-skin use experience of heat-related wearables.

Alongside the directly perceivable material sensorial qualities, ZnO yarns, as conductive yarns in general, have an indirect sensorial dimension; the transmission of electro-conductive signals enables e.g. changing the appearance, or feel of a smart textile, which in turn pro-vides alternating sensory expressions. Drawing from this notion, we can reflect on one of the guiding principles of the STEAM approach suggested by Peppler (2013): "Purposefully contrast multiple media, tools, and materials". As such, the Teksig method allows designing with contrasting sensorial attributes of a same material; with both the tangible attributes of conductive yarn (textile patterns as material), as with the intangible aspects (signals as material). Thus, the Teksig method transforms electro-conductive behaviour from non-perceivable to a visual pattern (the Lissajous figure), while correlating "the signal pattern" with the textile pattern, and then utilising both patterns as a design tool. Also, this creates a common language between the electrical engineer and designer.

Overall, we can summarise that considering different sensorial aspects during the development of new material applicable for smart textile design, and exploiting these aspects with the Teksig method offers a possibility in bridging together the technologists and the designers, a research gap established in the beginning of the paper.

Human interaction between research disciplines

The colour-coded clusters in Figure 7, indicate also the role, or collaboration between the three disciplines of the project, while the arrows depict the core knowledge transfer between the clusters. During the Context and Initial concepts & New ZnO and knowledge clusters, the collaboration between all three disciplines were the most active. How- ever, in Context and initial concepts cluster, the activities were ARTS led, bringing the science researchers to work outside their primary fields, which resulted in most ideas not being directly applicable in the project. Contrarily, during the New ZnO and knowledge cluster, all three disciplines bought their core expertise together to either generate new knowledge, or to provide supportive skills and expertise to the work of the design team. The productive collaboration was vital, as the out- come provided a foundation for the development of the methodology. In terms of smart textile design, the methodology development cluster formed continuing ongoing paths, but more importantly, sprouted new research directions.

Initially, the workshops brought teams together for ideation, how- ever the successive visits to the labs, and efforts to visualise the out- come of the chemical process prompted an atmosphere of openness towards new material explorations. One such point was the UV-fluorescent yarn. Regarding the development of the method, for the textile designer being able to express

frustration and discomfort was para- mount. This was a clear indicator that current methods were not suit able, enabling the push towards expanding creative possibilities, as discussed by Parsons and Campbell (2004). On the other hand, for the electrical engineer, being able to listen and respond to the frustration was equally important, thus drawing from productive friction (Hagel and Brown 2005). The openness that the chemists exhibited was seen as a considerable support, as they provided options with which to develop the textile-suitable ZnO materials, but also suggested and provided ZnO:Al yarns as a reference. Similarly, the support from the School of Electrical Engineering indicated trust in the scientific work done by the design school, but also helped verify the findings. This was in particular with the measurement of the "magic yarn". As most of this work was not at the core of the overall research project, to have time, space and open-minded people to explore the novelty was fundamental. It was seen more important to identify new paths and directions for the future.

Evolution towards the smart textile design practice

After the initial explorations using the Teksig method, we have found the method as a versatile tool for different purposes. In the Arcintex workshop, focusing on collaborative smart textile development, the method helped the participants gain new understanding on the "smart" textile behaviour, visualising the electrical signal changes based on the immediate use. For smart textile evaluation, i.e. used for technical measurements to visualise the effects of mechanical degradation on electric signals, it provided clear indication of the change in the electrical parameters beyond only resistivity. Whereas in smart textile pat- tern design, a knit designed with different knit types and materials, the method showed how the structure, material and the frequency affect the signal through the combination of touch quality and textile proper- ties, broadening the scope of a sensorial textile to include signal-based phenomena. We believe this expands the role of the textile designer towards the smart textile design practice.

Textile designer's role

During the process, the textile designer's role gradually changed, and has been evolving through the use of Teksig method after the project ended. While the role of the textile designer was initially to create exemplars based on the technology being developed, it had ranged through electrical engineering and scientific process, to a smart mate- rial developer. As there was difficulty in utilising the electrical proper- ties for textile-based sensor design, a new method for communicating findings and for designing was needed. This was addressed through systematic knit development and successive measurements.

Regarding the ZnO electrical properties, the engineer initially had a "hunch" based on experience, but the textile designer was not able to fit the findings to the existing knowledge base. However, during the process of a new methodology development, the method enabled "unlocking tacit and implicit knowledge" (Peralta and Moultrie 2010) of an electrical engineer into a language applicable for a designer. Echoing the importance of designer–researcher knowledge (Härkäsalmi and Koskinen 2010), this redirected the overall process away from the exemplars.

Creativity

Referring to when ALD was introduced to the textile designer led to a "what if" moment (Schön [1983] 2013: 145), resulting in a question if the textile substrate could be used instead of silicone for ALD. This spurred the development of the ZnO cotton, and the reference knits. The designer's efforts for creating the knit sample sets, followed by the systematic mapping of the knit sample

signal data, enabled the method development using a large data-set. This is very similar to the representation of "energy density" (Akiwowo et al. 2014: 144) used as a "common language", to achieve controlled and repeatable colours in their project (Kane et al. 2015).

The emergent findings, i.e. the semiconducting properties due to surface oxidation, were first seen by the textile designer; having already knowledge about how the visual signal should look, being able to recognise the anomaly was initially through disbelief, and a new experience. By the end of the project, the textile designer was able to use the method and notice novel properties in textile interaction, prompting the direction towards "connectivity". This mirrors the fundamental nature of prototyping and understanding of the new material, as mentioned by Thompson and Ling (2014: 203, 204), as well as the ability to focus on the creativity and not the method, mentioned by Parsons and Camp- bell (2004).

The toolkits, such as Interactex or MakerShoe, work for prototypical ideation, however they do not answer to the unknown technical properties. They present solved technical problems in an easy to use package. Similarly, methods such as the embodied workshops (Wilde et al. 2017) can be used for identifying uses or understanding situations, however they do not help with the material's electrical unknowns. On the other hand, Teksig method could augment all of these. Being very dynamic, it could provide new insights by visualising the material behaviour during embodied acting, and being signal based, it could be integrated to the functional prototyping toolkits to add the textile material properties as one functional element. Thus, it would provide an opening to play around with either the technical properties, aesthetics and sensorial qualities, or both. What about the end-user needs mentioned by McCann et al. (2005)? If we take the future textile designers as the end users, then there has been an attempt to fulfil their needs, as well as attempting to bridge the gap between the technologists and the designers. With regards to the ZnO yarn-based products, the textile designer is no longer faced with the same dilemma of limited understanding of the material's technical properties and of the material's design characteristics, and therefore the work is ongoing.

Concluding remarks

We have described the development path, discussed the directions and the rationale behind them. While we did not follow a predetermined path, instead the findings and reactions to unclear methods led towards an unexpected goal, away from the rigid "stick-to-the-plan" research: the project started as a multidisciplinary project, with the "detour" pushing it to the interdisciplinary domain (Aboelela et al. 2007), paving the way for the transdisciplinary field of smart textiles.

We can summarise this designers path in the Figure 8., focusing on the methodology. After the initial activities, and, textile and yarn selections, the role of the designer became passive at the face of electrical measurements of the initial ZnO samples. Prompting a change, the selection of the new substrates and subsequent testing led to the development of the reference knits. The systematic measurements with the reference knits enabled a verified method, and allowed a new look at the original ZnO samples. After this point, the method allowed examination at relative independence. This was followed with a creative use, where the focus was with the material development, instead of the method use. During this creative use phase, the Teksig-method has been explored in different contexts. We also note, that this is very similar to the process,

described by Kane et al. (2015). In this light, our overall process demonstrates the accumulated knowledge, contributing to smart textile practice. Regardless, it is our opinion, that if everyone had stayed rigidly on their independent, albeit multidisciplinary paths, the majority of the contributions would have been missed.

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Figure 1. The Heat Harvest-project map and cluster constituents.

Table 1. Context and Initial concepts

Table 2. Sensing and Sensorial Expression

Table 3. ALD on textile

Table 4. New ZnO and knowledge

Table 5. New Methodology development

Figure 2. Sample-knits with the systematic visual mapping

Figure 3. Collage of pics from the different clusters. Source: authors.

Figure 4. A Smart Textile knit with section-specific behaviour.

Figure 5. Exploring with conductive patterns on a textile.

Figure 6. The measurement setup and successive signals of the knit-sample, taken at peak-elongation

(captured from video, starting from top-left, in rows).

Figure 7. Clusters and the collaboration.

Figure 8. The textile designer path



Context and initial concepts Table 1	
Main overall content	Developing novel product concepts utilising thermo- electric components that are based on identifying different locations where energy is being wasted.
Activities	Two MA-level courses + workshop, Two multidisciplinary workshops: Engaging technically oriented researchers into the consideration of material sensing and engagement, as means for creating 'an experiential context' for the subsequent development in the project. (Townsend & Ylirisku 2015)
Textile design(er) input, or role	Creating exemplars, and introducing textiles and textile-materials in a broader sense to the overall research teams and opening up potential areas of innovation.
Outcome(s)	The selection of textile as a substrate for the ALD, Tthe inclusion of chemistry MSc thesis worker focus- ing specifically on cotton substrate.
Collaboration	ARTS-led (software scientist + textile designer) + CHEM + ELEC

Sensing and sensorial expression Table 2		
Main overall content	Focus on the effects of heat, and how a person would perceive the aspects of heat and tactile stimuli in on- skin applications.	
Activities	A preliminary study of a wearable SMA-actuated sleeve (surface with shape change properties), originated from the workshop ideation.	
Textile design(er) input, or role	The design and implementation of SMA embedded knit prototypes.	
Outcome(s)	The experiments suggest that the application context, method of textile integration and the active and static properties of the textile are all relevant for experiential smart textile design.	
Collaboration	ARTS (Textile designer + electric engineer)	

ALD on textile	Table 3
Main overall content	Developing atomic layer deposition (ALD) of zinc oxide (ZnO) on cotton, to create an n-type semicon- ductor on a flexible substrate, suitable for energy harvesting using temperature differences.
Activities	The main body of work revolved around the MSc-thesis (Sarnes 2015), and published in a scientific journal (Karttunen et al. 2017). Also, the chemists created an UV-fluorescent coating for a cotton yarn to evaluate the suitability for ALD (Giedraityte, Sundberg & Karppinen 2015).
Textile design(er) input, or role	Selecting and supplying sets of cotton yarns and fabric for the chemists, suitable for the temperatures of the ALD-reactor, Augmenting the ALD-reactor usage by creating a sample-holder, suitable for depositing greater amounts of yarn, Evaluating ZnO yarn for electronic properties, as well as degradation due to e.g. moisture together with an electric engineer.
Outcome(s)	Led to considerable changes in the ALD parameters due to cotton substrates differing from the standard glass- and silicon-substrates, Resulted in sets of ZnO-deposited yarns and textiles, that offers several benefits to other conductive yarns, being very similar to non-deposited cotton in both feel and visual outlook, The measurements of the yarns raised initial aware- ness of the need for textile-design methods regarding electric materials.
Collaboration	CHEM-led + ARTS

New ZnO and knowledge Table 4	
Main overall content	Building onto previous work for further understanding of ZnO-yarn properties, as well as providing material for comparison and reference to the other ZnO-yarns.
Activities	Producing additional thinner ZnO-yarns (cotton and silk) for future textile design implementation + alumini- um-doped deposited (ZnO:AI) yarns (Al-doping should increase the conductivity of the ZnO layer), Conducting further testing of yarns for e.g. electronic properties at the ARTS lab. Verifying the reliability and repeatability of the results at the School of Electrical Engineering, in an electrically isolated room.
Textile design(er) input, or role	Exhaust dyeing both cotton and silk ZnO-yarn with reactive dye, as well as by pad-patch dyeing, followed with yarn testing, Participating in yarn measurement activities, Confronting the frustration of yarn testing, as the typical time-based measurements did not provide meaningful information in terms of textile design aspects.
Outcome(s)	A suggestion for visual measurements and a knit reference base emerged.
Collaboration	ARTS+CHEM+ELEC

New Methodology development Table 5		
Main overall content	The initial developing of the method for evaluating conductive textiles, to find a textile-friendly method for evaluating ZnO-samples	
Activities	A Stoll CMS-knitting machine was used to create several pattern-wise identical textile samples with different conductive yarns as a reference base for ZnO-yarns, Measuring the effects of the textile design at the knit- pattern level, Creating a systematic visual comparison map from the measurements to enable analysing the samples to explain the usage and relations of the electrical features and the knit patterns.	
Textile design(er) input, or role	The initiative to the methodology originated from the needs of textile design. The electrical engineer suggested different approaches to the measurements, as well as the oscilloscope use. However, the textile designer conducted over 3400 measurements independently, and began creating common language and meaning between design and electric engineering.	
Outcome(s)	An approach leading to the Teksig-method, which al- lows the textile designer to evaluate the effects of the changing frequency and to develop functional textile samples independently, while simplifying the usage of the oscilloscope. (Townsend & Mikkonen 2017).	
Collaboration	ARTS (Textile designer + electric engineer)	



3A











