THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

Conductive Fabrics for Textile Electronic Interconnections and Capacitive Sensing

A Smart Textiles Perspective

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ABSTRACT

Smart textiles offer ways to integrate sensing and actuating abilities into textile structures found in garments, furniture and other applications such as filters, reinforcements, disposable products and others. A large part of the research being done on smart textiles concerns the possibilities for monitoring human health and wellbeing. In recent years, the research community has shown an increasing interest in measuring pressure using smart textiles. Observations in previous work on electrically conductive fabrics had shown that the conductivity in these fabrics was not always isotropic and the assumption was that the contact resistance between the conductive elements (often yarns) was the source of this anisotropy.

The work done in connection to this thesis investigates two questions regarding smart textiles: first electrical interconnections and second electrical sensing. An algorithm and a device for measuring the contact resistance in woven samples were developed. Results from that work showed that the contact resistance of woven samples can be measured and that in the case of metallized yarns the contact resistance does not pose a problem for interconnection. For the sensing part two explanatory models for the capacitance of a functionalized spacer-fabric under compression were developed and tested on measured data. The results indicate that both models provide reasonable agreement with the data up to ca 50% compression.

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Αργυρώ, τι να σου πω; Ξέρω οτι έχεις υποστεί, ξέρω οτι δεν ήμουνα εκεί που έπρεπε, και δεν ήμουνα όταν έπρεπε. Εσύ μου έδωσες τα θαυμάσια, τα πανέξυπνα, τα πανέμορφα παιδια μας, και Εσύ τα έφερες εκεί που έιναι. θέλω να ξέρεις οτι σ’ευχαριστω για αυτά τα αγγελούδια και την δουλιά που έκανες!

List of Appended Papers

The following papers are enclosed at the end of the thesis report:

[Paper I] A novel technique for direct measurements of contact resistance between interlaced conductive yarns in a plain weave

Emanuel Gunnarsson, Magnus Karlsteen, Lena Berglin, Jonas Stray, Textile Research Journal, vol 85, issue 5, pp 499-511 first published online September 112014, Issue published March 1, 2015

[Paper II] Characterizing Spacer Fabrics for Capacitive Sensing - Theoretical and Experimental Model Evaluation

Emanuel Gunnarsson and Fernando Seoane, *in manuscript.*

Contribution to the appended papers

In [paper I] I took part in the sample preparation, the calculations and the design of the measurement apparatus and programming of the software. I did the measurements and was responsible for writing the paper.

In [paper II] I did the measurements, the calculations and took part in the programming for the validation of the models. I was also responsible for writing the paper.

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CHAPTER 1

Thesis Introduction

1.1 Introduction

The so called smart textiles are distinguished by the fact that they are somehow functionalized and able to either sense or sense and respond to various phenomena in their surroundings. This thesis deals with two questions about the behaviour of functionalized fabrics regarding electrical functionalization: electrical interconnection and electrical sensing; The work can be said to be problem based and centred on the particular issues connoted with a special implementation, in this case the problem was to see if it is doable to produce a woven multi-layered textile capacitive pressure sensor.

Often smart textiles contain or are functionalized by some electro-conductive materials integrated into the textile structure and the interfacing with some sort of control unit, be it a regulating circuit or a micro-processor. It is very common to find that the electrically conducting material is often in the form of conductive yarns interlaced into the fabric or in the form of a coated or printed surface of conductive paste. It is not very common to use metal wires as such (i.e. one conductor wires) as conduction paths and/or sensing areas, instead textile yarns and/or fabrics containing a certain amount of either metal or conductive polymers are used. It is not trivial to say that these fabrics can be regarded as solid, homogeneous and isotropic conductors and hence a question arises: How well does an assembly of interlaced conductive yarns mimic or resemble a piece of metal? One of the differences between a metal and such an assembly is the presence of contact resistances between the conductive elements, so a more specific question is: How does the contact resistance between interlaced conductive yarns influence the electrostatic behaviour of an assembly of such yarns?

Given that the heterogeneity in conductivity in this kind of textiles is related to the flexibility of them (*i.e. their non-rigid nature and their tendency to change the contacting conditions between yarns*) then it would also probably display some changes in electric behaviour when the mechanical conditions are altered, and having in mind the overall problem of a textile capacitive pressure sensor an interesting question is: How does the deformation of a fabric under compression relate to the compressive force? Strange as it may seem there is no commonly accepted theory on this latter question even if textile scientists have been working on it for more than 80 years. Following that question is then the question that connects the two latter ones: how does the deformation of an electrically conductive fabric influence the electrical behaviour of it? This last question is so broad in its scope that it alone could be the subject for a number of theses and is only superficially touched upon here.

1.1 Research questions

In this thesis two research questions are investigated:

1. How does the contact resistance between interlaced conductive yarns influence the electro static behaviour of an electrically conductive fabric?
2. Is there a general relationship between the deformation of a functionalized spacer-fabric under compression and the change in capacitance?

1.2 Structure of the thesis

This thesis is organized as follows: first there is an introduction section on what textiles are and how they are produced, more specific subsections describe what is meant by a smart textile and what electrical problems one might expect from such textiles. The following section briefly describes the origin of contact resistance in textiles, how to measure it and what can be concluded from such measurements. The thesis report continues with a section presenting the strategies propose about modelling the change in capacitance of a spacer fabric during compression followed by a conclusions section made from the discussion of the obtained results from the theoretical and experiments work presented in the appended papers. The thesis ends with a discussion on possible future routes.

CHAPTER 2

Textiles

2.1 Textiles

Throughout history, mankind has used textiles then in three major kinds of ways: a way to protect their bodies from the environment; to decorate themselves to please their aesthetic sense; to use as a technical aid. So the term "*technical textiles*" refers to textiles not used for aesthetic or decorative pleasing but rather for their performance, *e.g.* protective clothing, ropes, tents, reinforcement of laminated products, sun protection curtains for greenhouses, upholding gravel but at the same time permeable to water so as to make artificial landscaping possible (roads, walls et c.)[1]. These technical textiles are not always produced of fibres traditionally used in textile production: they can be made of steel, copper, swelling cellulose and other exotic materials[1].

2.1.1 Textile Fibres

Traditional fibres used for making textiles include both animal hair and fibres from grown crops. Well known examples might be wool from sheep or alpaca; flax or cotton[2]. But textiles can be made of many other types of fibres as well. From ancient times onwards humans have refined and invented new fibres to produce textiles[3]. Today we are surrounded by both artificial (also called man-made) and natural fibres. The artificial fibres are often produced of petroleum but also of regenerated cellulose[4].

What is common to all fibres used for textile production is that they are much more extended in one dimension than in the others and that they produce yarns and later fabrics that are drape-able to some extent[2, 4]. The first use of textiles was for sheltering (clothes or roofs) or for carrying items[3]. That kind of utilization of the fabric demands the drape-able aspect of it in order not to diminish the flexibility of movement of the wearer.

2.2 Yarns

In order to talk about textile fabrics one needs to define it somehow, one possible definition could be "*a system of interlaced fibres*". This is a quite broad definition: it does not restrict us to any particular type of fibres, nor does it make any constriction as to how the interlacing is performed. Our intuitive notion of a textile suggests that it consists of interlaced "*yarns*", something distinguished from fibres then. A yarn is composed of fibres that are held together somehow, there are three main types of yarns: staple fibre yarns; monofilament yarns; multifilament yarns.

A staple fibre yarns is constructed of staple fibres that are spun together. The staple fibres are often between 10 to 500 mm long. Common examples are cotton, wool, acryl, flax. The spinning can be done in a number of fashions: ring spinning; jet spinning; et c. The fibres are first made parallel in what is known as carding, the carding results in slivers of the fibres. The slivers are drawn out and given a slight twist, in this stage the assembly is called a roving, the roving is fed in to the spinning equipment and the yarn is spun up on a cone or bobbin. The spinning process makes the yarn display mechanical properties that can be quite different from the fibre ones.

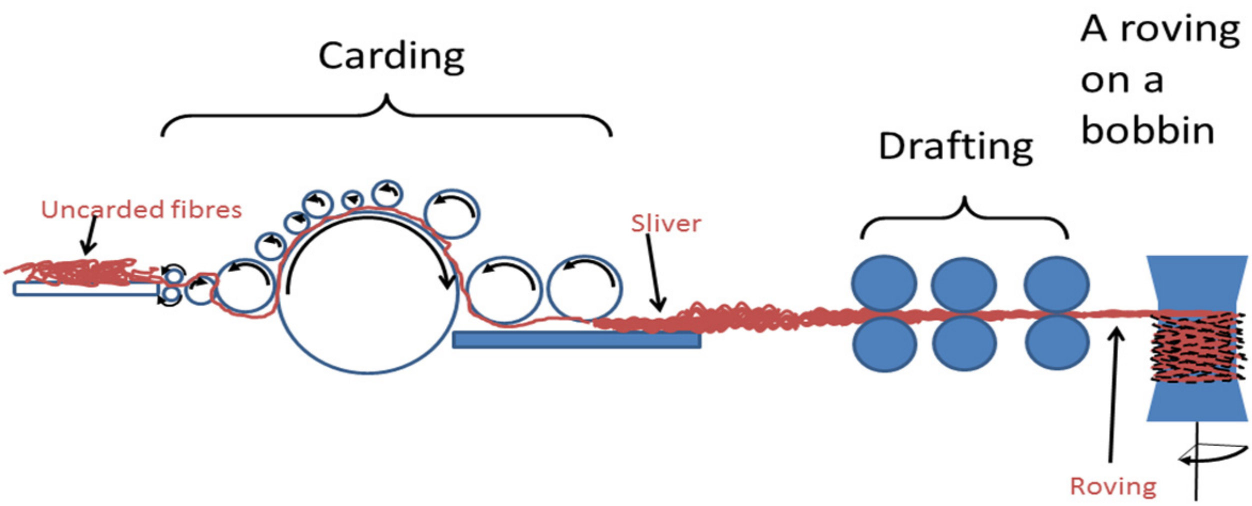


Figure 1: A schematic picture of the carding and drafting to form a roving.

The filament yarns, both monofilament and multifilament, are almost always (silk is an exception) man-made and as opposed to the staple fibre yarns the fibres in the filament yarns are as long as the yarn itself. Man-made filaments are formed by extrusion of a polymer melt or solution and at a later stage both stretched and spun. Also in the case of the filament yarns, the mechanical properties can vary a lot depending on the how the filaments are made, as an example consider dyneema™, which is the same material as in an ordinary plastic soda bottle (polyethylene)! The dyneema™ however has a tensile strength fifteen times that of steel and a rope of dyneema™ with a given thickness is much more flexible than a steel wire of the same thickness.

There are a number of parameters that affect the mechanical properties of the yarns, of course material plays a crucial role, but besides that the amount of material per unit length will also to a high extent determine the mechanical behaviour of the yarn. When it comes to staple fibre yarns it is not an easy task to determine the diameter of the yarns, in fact there is no well-defined diameter, due to the manufacturing process. Since the amount of yarn fed in to the spinning device is always to some degree varying, the diameter is bound to vary along the length of the yarn. The ends of the fibres do not come at exactly the same intervals all the time, and this is the reason for the unevenness of the feeding. This unevenness makes it impossible to define a diameter of the yarn so the textile community has agreed on using linear mass density, λ to classify yarns. There are a number of different units being used; one that is closely related to the SI unit system is the *tex*. A *tex* is the mass in grams of 1km of the material[4]. From this measure, together with the density of the material, ρ, one can obtain an effective diameter of the yarn. Assuming the yarn has a circular effective area we have

$$m = A_{eff}\, L\, \rho = \lambda_{tex}\, 1000\, L \Rightarrow A_{eff} = \frac{\lambda_{tex} 1000}{\rho} = \pi\, {d_{eff}^2}/{4} \Rightarrow$$

$$d_{eff} = \sqrt{\frac{4\, \lambda_{tex}\, 1000}{\rho\, \pi}}\ [m]$$

Another parameter is the twist, n, of the yarn; the twist is a measure of how many turns around the yarn axis a fibre makes across a unit length (*e.g. [1/m], [1/cm] or [1/yard]*). The measure is often concerned with the surface fibres of the yarns. Now using both the linear density and the twist one can put up a new measure called the twist factor which is defined as $\alpha = n \cdot \sqrt{\lambda_{tex}}$. This measure has the dimension of number times the square root of mass per length. Given that all other parameters are kept constant, two yarns with the same twist, i.e.$n_1 = n_2$, but with different linear densities (and thus different twist factors) will not have the same porosity and feel, or hand; on the contrary then, two yarn with the same twist factor but different twist, i.e. $\alpha_1 = \alpha_2$ and $n_1 \neq n_2$, will have the same porosity and feel[5].

Yarns are spun with two different directions of the twist, z-twist and s-twist. The axis of the fibre goes roughly as the middle part (the diagonal) of the letter relative to the yarn axis. The reason for having two directions of the twist it that the readymade yarn will have different properties depending on the twist. Often yarns do not consist only of one single strand of twisted fibres, but rather two or three (or even more), these stands are known as plies (singular ply). Taking then two z-twisted yarns and twisting them together in a s-twist will result in the fibres lying more parallel to the yarn axis and thus producing a stronger yarn since the strength of the yarn in this case will be more influenced by the fibre strength. One can also have two one-ply z-spun yarns spun together with a z-twist again; such a yarn will have the fibres lying almost normal to the yarn axis and will have a severe tendency to curl up. The benefit of such a yarn is that it will be transparent, because of the reduction in diameter the high twist induces. Fabrics woven from this kind of yarns can be used as transparent curtains or veils (hence the name voile, which is French for veil).

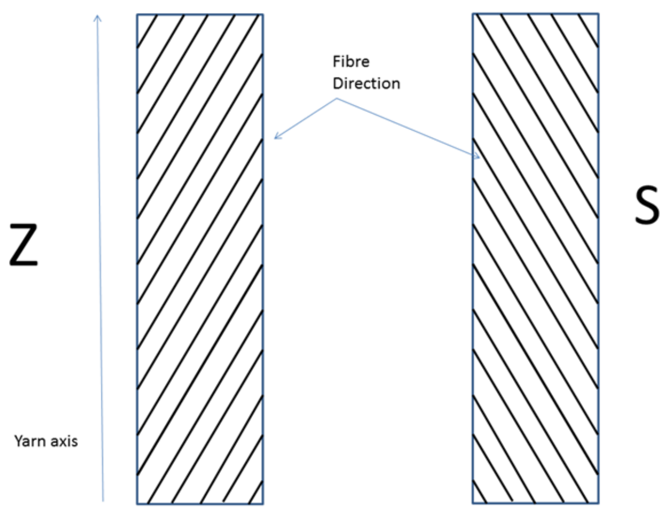


Figure 2: Z-twist and S-twist

2.3 Textile Structures

So once we have either the fibres or the yarns made of the fibres we can start making textile structures. Just as there are three main types of yarns there are three main types of textile structures: non-woven; knitted and woven fabrics. They are produced in different fashions and also give very different end products.

2.3.1 Non-woven Textiles

Non-woven fabrics are made by interlocking fibres with the help of needle punching or other techniques, the fabric can later be fixated by the use of heat, resins or other agents. These textile structures are often found in waddings, filters, sound absorbers and disposable products. Depending on the manufacturing technique the fabrics can be very isotropic or anisotropic. For instance, a staple fibre non-woven fabric made with "wet-laying" will have its' fibres randomly oriented, making it as strong across the width as along the length, while if the fabric was made with "dry-laying" the fibres would be much more parallel with the length of the fabric, making it weaker across the width than along the length[4]. Figure 3 displays a schematic view of two non-woven structures.

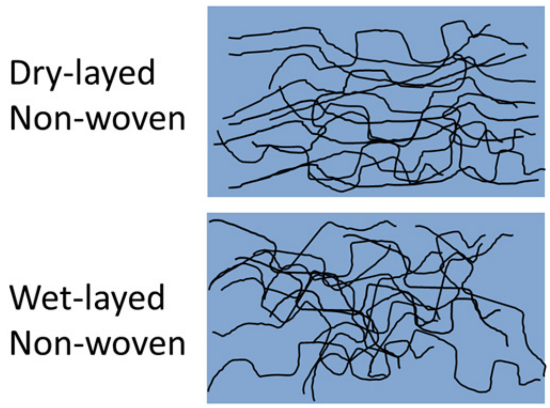


Figure 3: Schematic view of two non-woven structures. The Dry-layed version has its fibres more oriented along the length of the fabric as opposed to the wet-layed.

2.3.2 Woven Textiles

Woven fabrics consist of two yarn systems, most often in a right angle to each other, which are periodically interlaced by letting one of the yarn systems going underneath and over the other system according to some pattern. The yarn systems are called warp and weft. The simplest type of the woven fabrics is the plain weave: every other warp yarn is lifted up and a weft yarn is put in between the lifted and lowered warp yarns, the warp yarns are switched so that the previously lifted ones are lowered and the previously lowered ones are lifted, the next weft yarn is put in and so the process starts over again. Woven fabrics can display different mechanical characteristics in different directions w.r.t. the yarn systems, that is, they are sometimes anisotropic. The anisotropy of the fabric can be adjusted by using different yarn densities in the systems or by using different kinds of yarns in warp and weft. Also the binding will play a role in determining the strength and flexibility along the different directions of the fabric[6]. The three basic binding types of a woven fabric are: plain weave, twill and satin. The plain weave was described above, in making a twill, not every other, but every third warp yarn is lifted, a weft yarn is put in and the lifted yarn is lowered and the warp yarn next to the previously lifted one is now lifted, a new weft yarn is put in and the next warp yarn is lifted, this ends the report. This binding produces characteristic diagonal lines over the fabric surface, as seen on denim jeans.

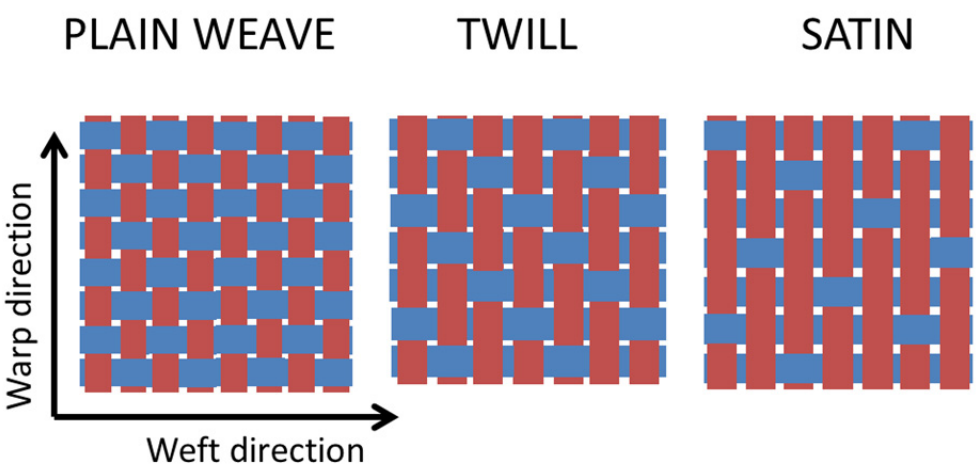


Figure 4: Three of the basic weaving patterns: plain weave, twill and satin. The twill displays its' characteristic diagonal striping.

2.3.3 Knitted Textiles

Knitted fabrics often display a higher degree of flexibility than does the woven ones. The characteristic of knitted fabrics is that instead of two yarn systems there is only one and it makes stiches that bind into one another. Think of it this way: if you have a woven fabric and you manage to start pulling one yarn out of the fabric, then once you come to the end, nothing more happens. If you manage to pull out the yarn of a knitted fabric, then once you come to the end of the fabric, the yarn will turn around and start reaping up the next row until there is no more fabric. There are many ways to vary a knitted structure. A schematic view of a plain knitted fabric can be seen in Figure 5, where the middle course is coloured differently in order to make the binding pattern clearer.

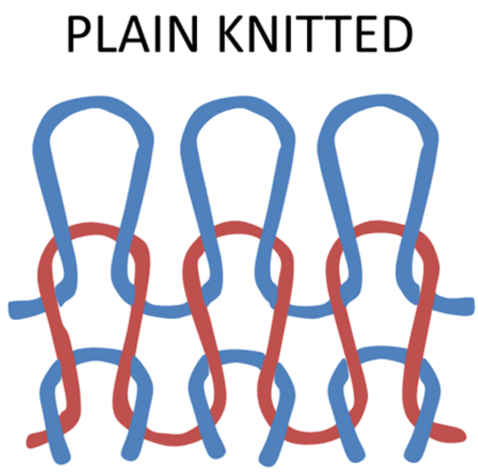


Figure 5: Schematic view of a plain knitted fabric. The middle course is coloured red in order to make the binding clearer.

2.3.4 The influence of the fibre, yarn and textile structure characteristics on the physical properties of the textile fabric

The different levels of the material described above: the fibre; the yarn; the fabric, all add something to the physical properties of the end textile product. To distinguish between them one would have to make up a scheme like this: spin yarns of different fibres with the same twist (both direction and twist number) and make your tests; this will say something about the fibre properties. Do measurements on individual fibres of some material and then make yarn of that kind of fibres and do the same tests, this will say something about how the yarn characteristics change the properties. Make different kinds of textile structures of the same kind of yarn and make your measurements, this will say something about how the binding of the yarns affect the physical properties.

As can be imagined the above scheme will present countless possibilities of variations and this is also what we know from everyday life: textiles come in so many forms with so varying properties that one is overwhelmed with it. Even if we only used white yarns and allowed to vary the fibre material, the yarn construction and the binding we could have a material variety that would suffice for research for a long time.

The fineness of the fibres play a crucial role in the production of yarns, the finer the fibres the easier it is to make an even yarn of a given linear density. Also the finer the fibre, the finer the yarn producible from it can become. The spinning limit is the limit of the amount of fibres per cross section when the fibres can no longer be twisted to hold together a yarn is reached earlier with a coarse yarn than with a finer one [7].
The stiffness of the fibre is strongly affected by its fineness. The flexural rigidity is proportional to the second moment of area, and for a more or less circular cross section the second moment of area is proportional to the fourth power of the diameter[8] which then means that a finer fibre of some material will be essentially less stiff than would a coarser one.

The length of the fibres is also an important factor; often spinning equipment is labelled with the shortest possible length spin able on it. A longer fibre will more easily produce a more even yarn and also a stronger one. Both fineness and length are more uneven and unknown for the natural fibres (wool, cotton, flax et c.) as opposed to man-made fibres where the nozzle size, extrusion rate, stretch and all other production factors are well controlled[4]. In the man-made fibres then, the fineness is more narrowly distributed and the fibre length is very well known since the length is determined by cutting the fibres in a desired length.

As mentioned earlier the linear density is a fundamental property of a yarn, because of the impossibility of making a meaningful measurement of its diameter. Not only is the diameter changing along the yarn due to both twist and fibre length, but also will the diameter of the yarn deform tremendously if squeezed between some measuring clamps, this means that in order to make measurements of yarn diameters the community would have to agree on a certain pressure at which the measurement was supposed to be done. Otherwise one could try to use some optical method, like microscopy or scattering techniques, but then comes the problem of defining where to start counting the rim of the yarn; this is not unambiguous since most staple fibre yarns have fibres protruding the ‘’main body’’ of the yarn. All these uncertainty factors make it clear to see that the linear density is to be preferred as a measure of fineness of the yarn. The linear density can easily be measured with a very high accuracy: the longer the amount of yarn that is used, the more precise will the measure be.

The twist of a yarn has effect not only on the strength of the yarn but also on the level of pilling and abrasion of the fabric made from the yarn. The higher the twist the ore the fabric will resist both pilling and abrasion. Also when it comes to plied – also called folded – yarns (2-ply, 3-ply et c.), the variation of the twist of the unfolded yarns with each other will have a huge impact on the behaviour of the folded yarn.

CHAPTER 3

Smart Textiles

3.1 Introduction to Smart Textiles

Smart textiles is a notion that started showing up in scientific literature around the turn of the century. At this time much focus was put on how to integrate electronics into garments. Still today there is quite a lot of effort put down into making garments that sense and reacts on human or other environmental input, but there has also emerged an interest in integrating "smartness" in technical textiles, both traditional and novel ones. In "Smart fibres, fabrics and clothing"[9] Tao makes the distinction between three classes of smart structures:

- passive smart that can sense their surroundings,
- active smart textiles that can sense and respond to their surrounding and
- very smart textiles that can sense, respond and adapt according to environmental changes[9].

The driving forces for these research efforts had its' sources partly in military needs (US Navy financed for instance the Georgia Tech Motherboard)[10-12] and in Europe, as an enabling technology to foster a paradigm shift in healthcare first as well as a possible way to revitalize the textile industry [13].

Already in the mid 50' Edward Thorp and Claude Shannon designed a wearable computer[14] and the concept of "wearable technology" is a clear predecessor of smart textiles. The wearable technology was/is mostly concerned with the integration of electronic devices or gadgets in clothing via pockets and special channels for cabling, *i.e. the integration of the functionality is not made in the fabric itself.*

In contrast to this wearable technology, smart textile projects that were described and reported during the first years of the 21 century (and even earlier [15]) displayed a focus on integrating electrical circuitry and sensing functions directly in the fabric [16, 17]. The means for doing this were often electrically conductive yarns acting as wires and the circuitry often small modular PCBs placed at appropriate locations. Problems that people concentrated on at the time were the interface between rigid electronic components and the drape able and flexible fabric. Different approaches have been tried out: conductive adhesives; point-welding; embroidery; snap-buttons et c, all of these has their own pros and cons and the problems still remains unsolved in the sense that no universal "best practice" is agreed upon. From 2004 and onwards, some groups started reporting on progress in fabricating semiconducting devices using textile production methods, *e.g. a woven transistor* where the transistor is actually integrated in the yarn and the base is connected via an interlacing yarn in the other direction [18-20].

3.2 Sensing with Smart Textiles

The smartness in all the three classes above has as a common denominator the ability to sense and many papers deal with different sensor implementations. There is a vast number of articles reporting on the development of different kinds of electrodes and other sensors aimed to measure physiological phenomena (ECG[21-23], heart rate[24], EEG[25], breathing patterns[26], EMG[27].) made of a textile material.

It is not only electrical circuitry that interest the research community; other types of sensing and actuating functions could also be integrated into textiles, such as thermo-chromic or UV-sensitive pigments, shape-memory and shape-shifting structures and shear-thinning or shear-thickening materials. These latter examples both sense and react to the changes in the environment without the need for electrical circuits.

From here on when the term smart textile is used I will mean by that an electrically conductive textile structure, unless another specific meaning is given.

3.3 Electrical Issues with Smart Textiles

There are a number of challenges that remain unsatisfactory solved when it comes to electrically conductive fabrics. These issues might be partially behind the reasons impeding the proliferation of smart textile products worldwide; after more than 15 years of existence the so expected major commercial breakthrough remains unseen. Some of such issues are the following:

- Interface between soft, flexible and drape able textiles and electronic components (often hitherto stiff, rigid and needing soldering)
- Wash-ability, electrical components with exposed metal connectors often do not go well with water and detergents
- Flexibility of the circuitry, are the electrical conduction-paths and sensing and actuating part able to perform when the fabric is deformed?
    - Do the contact resistances in a woven conductor influence the electric behaviour of the conductor?
    - Does the deformed geometry influence the response to fields of actuating or sensing parts?

Some of those challenges influence specifically to manufacturability, others to functionalization and others to user acceptance [28] and long-term usage. The main focus of this work targets mainly the functionalization per se.

3.4 Contact Resistance

The use of yarns as electrical conductors, interconnection tracks, may or may not pose a problem depending on the intended application. There are many different kinds of conductive yarns, some are plastic mono- or multi-filament yarns with metal coatings, other are staple fibre yarns with a certain amount of metal fibres spun in to them, yet others use conductive polymers instead of metal to achieve conduction.

The conductive property of the yarns is often stated as the linear resistivity, ρ_l of the yarn. The linear resistivity is simply the resistance of a certain length of the yarn expressed in units of Ω/m. This value will differ a lot depending on the type of yarn. A silver coated multifilament yarn can have $\rho_l = 100 \pm 10\ \Omega/m$ [29] , yarns using conductive polymers can have $\rho_l \approx 1 - 10\ k\Omega\ /m$ [30, 31].

One thing that could pose a problem is that a woven, knitted or non-woven fabric made of conducting yarns cannot always be considered as a solid homogeneous conductor. Independently of how good or poor conductivity two bodies have, every time two such bodies are brought in contact with each other a contact impedance between them will arise. Woven or knitted fabrics consist of interlaced yarns. If the surfaces of the yarns are conductive, then at each crossing point between two of the yarns there will be an electrical contact with an associated contact resistance. Having said that, the existence of these contact resistances could also be utilised to form sensors [32].

Much theory and experimental measurements on contact resistance was provided by Ragnar Holm, in his book “Electrical Contacts, Theory and application” he lays forward the theory that the contact resistance is build up by two main contributions: the constriction resistance and the “pollution” resistance[33]. The constriction resistance comes about because on a micro-level the surfaces of the yarns (even in the case of newly made monofilament yarns) are not smooth and so the real area of contact between the yarns is much smaller than one would think at first sight. This finite and miniscule contacting area implies that the current running from one yarn to the other is constricted and this is seen as a finite resistance on a macroscopic level. The “pollution” resistance has its origin in the presence of alien films on the surface of the yarns, some films will be insulating but if they are thin enough there is a chance of electrons tunnelling through[33]. Later Mikrajuddin et al. could show that the Holm expression for the contact resistance is given in the limit of the spot being much larger than the wavelength of the conduction electron starting with the Sharvin expression for the contact resistance, which deals with contacts that are smaller or on the same scale as the electron wavelength and thus quantum mechanical [34].

To illustrate the roughness of the yarns used in [Paper I] two AFM pictures of such yarns can be seen in Figure 6, the left pane shows a filament taken from a yarn directly from the bobbin, and the right pane shows a filament from a yarn pulled out of the fabric that the samples were made from.

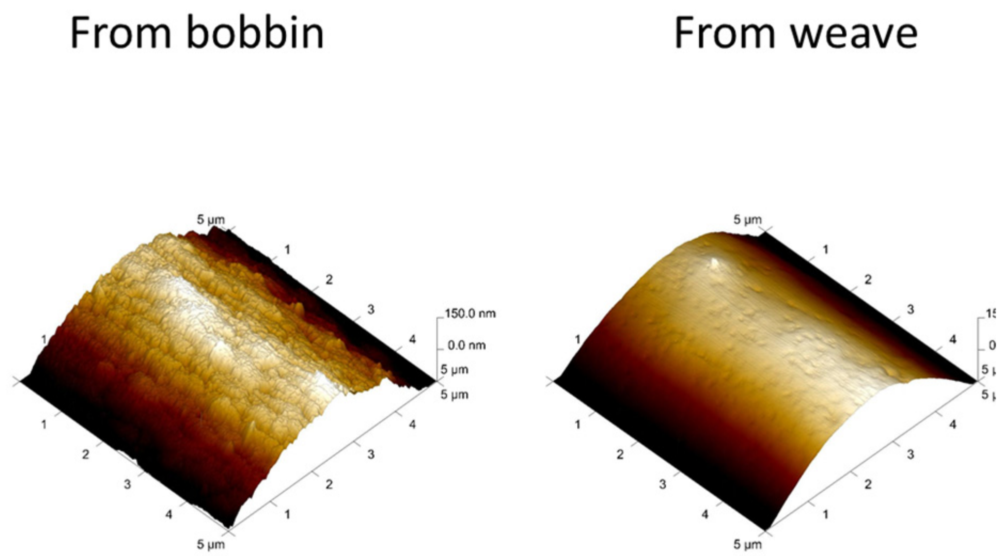


Figure 6: Reconstruction of the surfaces from AFM of two filaments of Statex Shieldex yarn. As can be seen the surface of the filament taken directly from the bobbin is much rougher than the surface of the filament taken from the woven sample.

As can be seen in Figure 6, the surface of the yarn that has not gone through the weaving process is much rougher than that of the yarn from the fabric. I speculate that part of the explanation to this is that when the yarn is subjected to the forces of the weaving process it is both stretched along its axis and to some extent there might be abrasion as well. If the textile manufacturing process is altering the surface in this way then measuring the contact resistance of two crossed yarns in free will not give the same results as measuring it while situated in a fabric since the shape, size and number of contacts will most certainly differ between these cases [35]. To be able to determine whether or not these contacts can be neglected or not one would like to measure them.

3.4.1 Measuring Contact Resistance in Conductive Fabrics

Some theoretical analysis on this has been done, combined with some simulation work and experiments [36-39]. The theoretical work cited make the assumptions that all yarn resistances between the contact points are alike, and that also the contact resistances are alike. It is of course reasonable to assume that the values of the members of either kind will be of the same order of magnitude but there is nothing that says that they should all have the same numerical value. In order to investigate this, in [Paper I] we describe a measuring device that was constructed and an algorithm for determining the contact resistances and the yarn resistances was written.

The measurement procedure presented in [Paper I] was used on plain woven fabric with silver-coated yarns as the conductive part. The geometry of a unit cell of plain weave can be seen in Figure 7A. The fabric consists of four yarns: two in the warp direction and two in the weft direction. The fabric can then be modelled as a resistive network with the topology seen in Figure 7B.

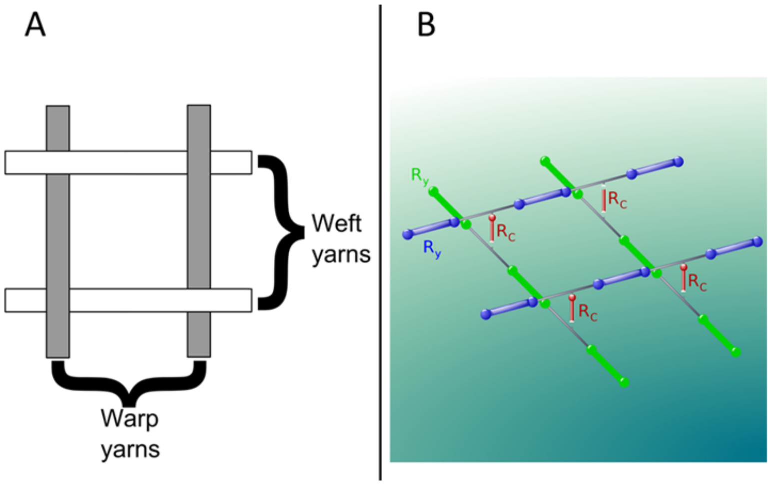


Figure 7: A) schematic picture of a unit cell of a plain weave. B) The electrical model of a unit cell of a plain weave. The blue and green resistors are the three resistances compricing the yarns and the red ones are the contact resistances between the yarns.

The equivalent circuit, which can be seen schematically in Figure 8, has 16 resistive elements.

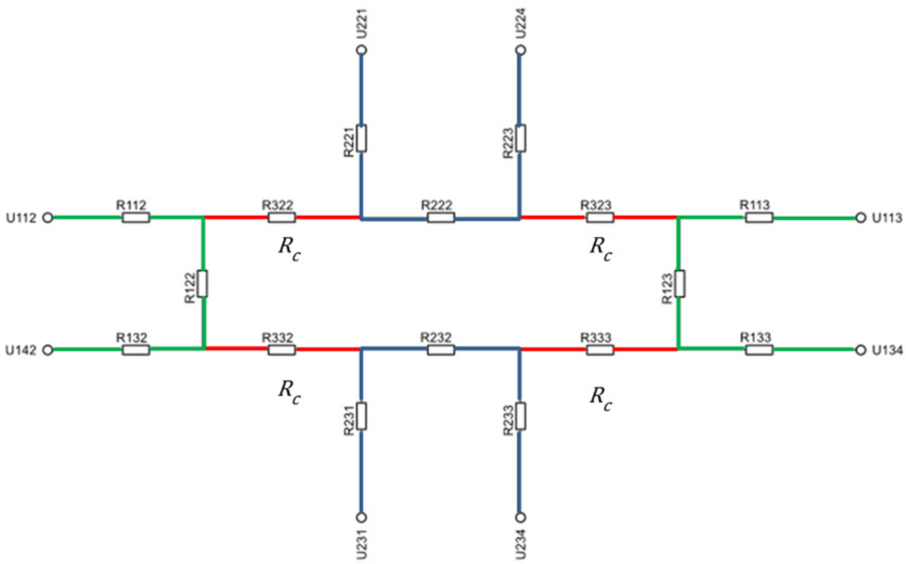


Figure 8: The equivalent circuit for the model in Figure 7 is shown. The colours of the paths correspond to the colours of the resistors in Figure 7B.

Each yarn consists of three series resistors and in addition there are four contact resistances. Each end of the middle resistor of each yarn connects to a boundary resistor of the same yarn and to a contact resistor. This unit cell is the largest symmetric cell for which an analytical expression for the contact resistances can be expressed in terms of the injected currents and the outer node voltages (a cell consisting of 2x3 yarns can also be drawn in a planar way but as soon as there are 3x3 yarns or more, the network is no longer planar).

A device, displayed in Figure 9 was constructed to measure on such a unit cell.

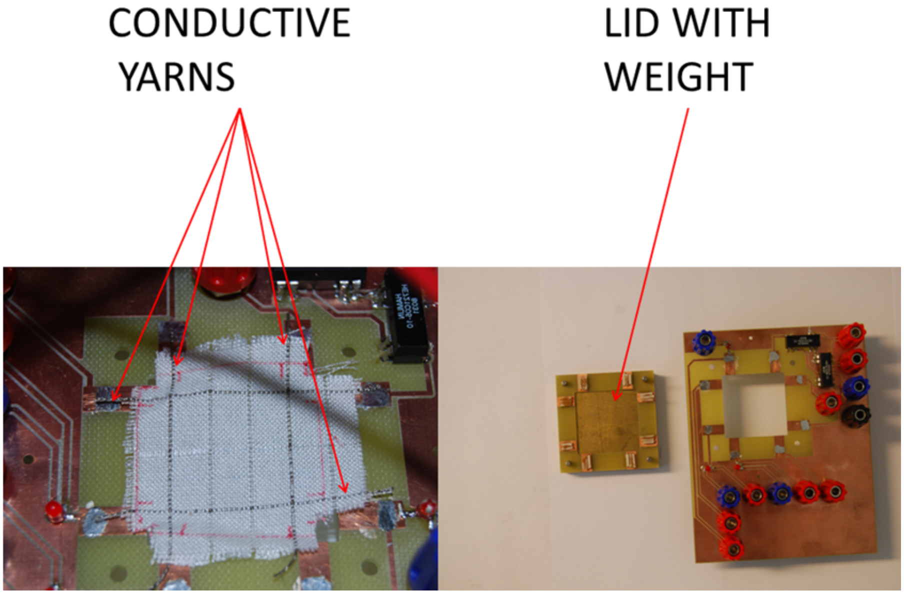


Figure 9: the device for measuring contact resistances. The left photograph depicts a sample being mounted. The right photograph also includes a lid that was used for keeping the sample in place, and to maintain electrical contact between the yarns and the rest of the circuit.

The expressions for the resistances are on the form

$$R = \frac{\Delta U_i' \cdot \Delta U_j'' - \Delta U_j' \cdot \Delta U_i''}{\Delta U_i' \cdot I'' - \Delta U_i'' \cdot I'} \ [\Omega] \quad (1)$$

Where the subscript indices indicate over which nodes the voltage is measured and the primes indicate which of the consecutive measurements (prime: the first measurement, biss: the second measurement). Once two of the resistors in the network are known their value can be used to determining the current in each branch of the loop. The knowledge of the branch currents allows us to compute three of the contact resistances as the voltage drop across them divided by the current through them. To extract the values of all four contact resistances and all four yarn resistances four measurements are needed with different boundary conditions for each measurement. The details of the derivation of the expressions for the resistances can be found in Appendix A.

3.5 Textile Capacitive Pressure Sensing

An instance of a smart textile application could be a textile capacitive pressure sensor integrated in a garment or furniture. Such sensors have been reported elsewhere [40-43]. The textile capacitive pressure sensors reported in the cited papers all build on the parallel plate capacitor geometry. With this geometry the capacitance is determined by three numbers: the overlapping plate area, the distance between the plates and the relative permittivity of the volume between the plates.

The ideal parallel plate capacitor consist of two planes (infinitely thin) parallel to each other separated by a distance y, and each with an area, A so large that $A \gg y$ and the volume between them filled with a medium of constant relative permittivity of ε_r. The expression for such the capacitance of such an ideal capacitor is

$$C = \frac{Q}{U} = \frac{A\varepsilon_0\varepsilon_r}{y}\ [F] \tag{2}$$

Where $A, \varepsilon_0, \varepsilon_r$ and y are the area of the plates, the permittivity of free space, the relative permittivity of the dielectric layer and the distance between the plates respectively. To make a sensor of a parallel plate capacitor one thus have basically three choices of what to vary: the area, the permittivity or the distance between the plates.

A capacitive pressure sensor could in principle build on the variation of all three of these dimensions, but it seems unnecessary cumbersome to manufacture a device that changes its area or dielectric constant when exposed to a variation of pressure. On the contrary then, it seems plausible to rely on the change in distance between the plates as a pressure is exerted on them. The change of distance between plates is the most common option that I have found in the literature. The exception is a paper by Merritt et al. that presents a pressure sensor for breathing monitoring, and the sensor described there relies on the change in overlapping area [44].

Capacitive pressure sensors that rely on the change of distance between the plates are also common as "ordinary" pressure sensors. They are usually formed by a cavity filled with some homogeneous medium with a well-defined relative permittivity that does not change significantly with temperature, pressure or other ambient parameters. The cavity has two of its walls acting as the plates. One of the plates is made of an elastic material, which bulges as a pressure is exerted on it.

When it comes to a textile capacitive pressure sensor one is faced with the design issues stated earlier: the wish to keep the textile qualities and at the same time the wish to build a reliable sensor. These two ideals are most often in conflict with each other to some extent. Textile structures tend to be non-homogeneous, anisotropic and vitiated with a lot of imperfections. The plates are made of electrically conductive yarns or coatings, neither of these choices form a pair of perfectly parallel and infinitely thin planes. If one wants to make a sensor with a relatively small area the aspect ratio between this area and the distance between the plates will not be very large either. The volume between the plates is defined by the rims of the interlaced yarns. This volume is there for heterogeneous in nature. Part of it will be occupied by air and part of it by the yarn material. In addition to these major constituents there will in most cases also be some moisture and contaminations present.

When designing any sensor the intended use, the application, is of paramount importance. If the sensor is intended to act as a switch then perhaps certain non-idealities in the sensor geometry, behaviour or structure can be dealt with by setting a high enough threshold for the switching point so that all deviations from the ideal behaviour becomes unimportant, but if the sensor is intended to record different levels of pressure, then one needs to take these imperfections in to consideration. The remaining of this chapter presents the situation that an engineer is faced with when intending to design a textile capacitive pressure sensor. Of course one needs to consider the function of the sensor.

3.5.1 Modelling

The work done in relation to this thesis deals with the question of how the dielectric layer changes when compressed. Even without compression the permittivity of a heterogeneous dielectric is not a trivial task to quantify. The main strategies seem to be either using some sort of mixing rule or to discretise the volume into cells with some equivalent impedance.

Models aim at capturing certain aspects of the original entity they substitute. When working with modelling, there are two different kind of models: descriptive and explanatory [45]. Descriptive models focuses on capturing the response of an entity given a certain stimuli without necessarily being concerned with a detailed anatomy of structures resembling that of the original and the model relies on large sets of measurements (this kind of model is also called “black-box”), while explanatory models on the other hand builds on an “as-correct-as-possible” incorporation of the structures of the entity investigated ("white/glass-box"). The descriptive models then have only predictive power when the initial conditions at hand are equal or very similar to initial conditions that existed for already measured situations. The explanatory model, if valid, can predict also the outcome of situations not measured before. In practice most models will be a combination of explanatory and descriptive; a completely explanatory model would have to be as detailed as the original entity it tries to model so approximations are most often done to some extent. In the remainder of this section we present the additional two models used in Paper 2, the first one is Equation (2).

3.5.2 Mixing Rule and Effective Permittivity Model

The mixing route goes back to Maxwell and Bruggemann. Considering a biphasic mixture as the dielectric, with this approach the heterogeneous dielectric is approximated by inclusions of permittivity ε_i (i for inclusion) and concentration f immersed in a background matrix of permittivity ε_h (h for host) and concentration $(1-f)$. Depending on the shape and concentration of the inclusions, different expressions for the effective permittivity will hold. Some of these expressions for different shapes and concentrations are presented by Giordano in [46]. The Maxwell mixing rule does only apply for dilute mixtures ($f \leq 0.1$) and for spherical inclusions. If the inclusions are shaped as parallel elliptic cylinders Giordano states the following expressions for the permittivities in the x, y and z directions (e being the eccentricity of the cylinders):

$$\begin{cases} 1-f = \dfrac{\varepsilon_i - \varepsilon_x}{\varepsilon_i - \varepsilon_h}\left(\dfrac{\varepsilon_h}{\varepsilon_x}\right)^{\frac{e}{e+1}} \\ 1-f = \dfrac{\varepsilon_i - \varepsilon_y}{\varepsilon_i - \varepsilon_h}\left(\dfrac{\varepsilon_h}{\varepsilon_y}\right)^{\frac{e}{e+1}} \\ \varepsilon_z = f\varepsilon_i + (1-f)\varepsilon_h \end{cases} \tag{3}$$

If the eccentricity is 1 (i.e. circular cylinders) and the electric field is applied in the z direction then the effective permittivity would be given by the last expression. This expression was used in [Paper II]. This is essentially the case before the compression of the fabric; the spacer yarns are oriented with their axes from one "plate" to the other at an angle. At high compression this is not the case, the spacer yarns will be deformed. Figure 10 shows a unit cell of the fabric in the x-y plane. The coloured lines are the four spacer yarn in the cell. The lower picture in Figure 11 shows the z-y plane and how the spacer yarns are deformed during compression.

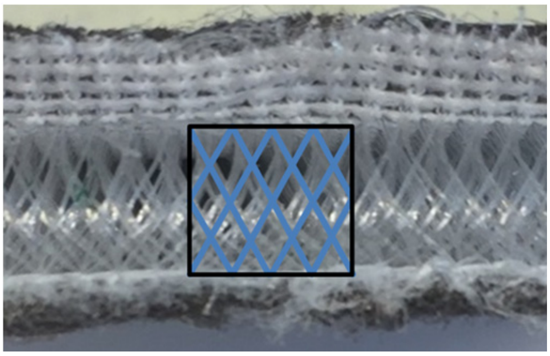


Figure 10: Photography of one of the samples used in [Paper II]. The Black rectangle indicates the y-z view of a unit cell in the y-z-plane. The blue lines are the approximations of the spacer yarns.

The expression for the capacitance of a unit cell under the assumption of a changing effective permittivity according to Equation (3) and the addition of the fabrics outer layers is

$$C_{mod2} = \frac{A\varepsilon_0\varepsilon_r\left(1+f(1-\varepsilon_r)\right)}{2\,d\,\left(1+f(1-\varepsilon_r)\right)+\varepsilon_r y} + C_o\ [F] \tag{4}$$

3.5.3 Lumped Element Model

In the lumped element approach we assume the whole capacitor can be described as a combination of parallel plate capacitors of homogeneous dielectric constants. The area of a unit cell is divided into three parts: one that is partially filled with the material of the spacer yarns, one that is totally filled and one that is totally filled with air. Also in this model the outer layers of the spacer fabric will add to the total capacitance.

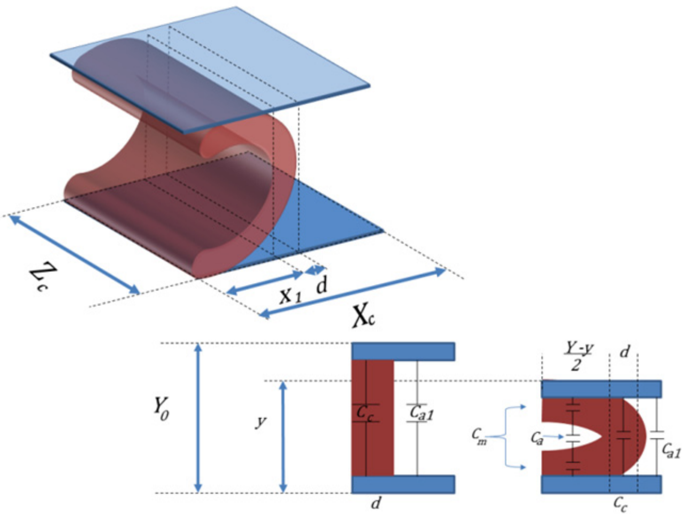


Figure 11: The lumped element model of a unit cell of the capacitor. There are three partial capacitances in parallel contributing to the total capacitance. In the rightmost lower part the partial capacitaces are drawn ontop of the geometrical model.

The expression for the capacitance in that case is

$$C_{mod3} = N \frac{\varepsilon_0 \varepsilon_r \left(8d^3(\varepsilon_r - 1)^2 - 2d^2(\varepsilon_r - 1)(3\varepsilon_r - 2)y + \varepsilon_r X_c y^2 + d(\varepsilon_r - 1)y\left((\varepsilon_r - 1)y + Y_0 - 4X_c\right)\right) Z_c}{y(-4d(\varepsilon_{r-1}) + \varepsilon_r y)(-2d(\varepsilon_r - 1) + \varepsilon_r y)} + C_o \ [F] \tag{5}$$

Where X_c, Y_0, Z_c and d are the length of the unit cell, the uncompressed height of the capacitor, the width of the unit cell and the diameter of the yarn respectively.

CHAPTER 4

Discussion and Conclusions

4.1 Contact Resistance Measurements

Preliminary measurements on the yarns used in [Paper I] showed that the yarn-resistances at hand would be in the range of $2\,\Omega \leq R_y \leq 3.5\,\Omega$ and the contact resistances in the range of $0.1\,\Omega \leq R_y \leq 0.5\,\Omega$. For this reason a network with of ordinary through-hole film resistors with values in the same ranges was made by soldering. The measurements on that network showed that the new method provided readings that deviated less than 2% from four-wire measurements of the individual resistors with one exception: one of the contact resistances which had a deviation of almost 5%. This indicates that the method is useful for measuring the contact resistances in a woven structure.

Comparing the four-wire, individual measurements and the new method, the standard deviations for the resistors mimicking the contact resistances increased approximately 6 times more than the standard deviations for the resistors mimicking the yarn-resistances. This is probably due to the low nominal values.

In the analysis of the measurements on the woven samples, one observation made was that the variance of the contact resistances was about one order of magnitude larger than the variance of the yarn resistances. This indicates that the contact resistances changed during handling while at the same time the yarn resistances did not change. The reason for this is that the contacts are very sensitive to changes in the environment.

The values obtained from the measurements on the woven samples also suggest that in the case of silver-plated multifilament yarns the contact resistance between the yarns will not contribute noticeably to the overall resistance of the fabric. The values suggest that for the yarns used there the contact resistance was in the range of $R_c \approx 0.4\ \Omega$ and the linear resistivity of the yarns is both according to the manufacturer and to the measurements reported in the article around

$$\rho_l = 110\,{}^{\Omega}\!/_{m}$$

So if a fabric was made with 20 yarns / cm and every other yarn was of this conductive type the yarn resistance would be $R_y = 0.11\ \Omega$. Looking at what this would mean if both ends of, say one of the warp yarns were connected to a voltage source and the ends of the other warp yarn connected to ground. The resistance for the whole cell in this case would be given by

$$R_{tot} = \frac{3}{2}R_y + R_c$$

Inserting the numbers above gives $R_{tot} \approx 0.57\ \Omega$. Suppose now that one uses a model where one neglects the contact resistances (*i.e.* $R_c \to 0$), then the resistance for the same boundary conditions would give $R_{tot} = 0.17\ \Omega$. Next we have to realize that when attaching electrodes to such a fabric, there will be parallel connections to hundreds of unit cells resulting in very small overall impedance. So in this case the contact impedance does not seem to pose any problem.

4.2 Textile Capacitive Pressure Sensor

The modelling of the capacitance for the samples used in [Paper II] showed that all three equations gave fittings that had deviations from the measured data below $\pm 5\%$ down to 50% compression for the thicker samples. The same result also hold for the mixing rule model and the lumped element model for the thinner samples, but the ideal model deviates slightly more. So from a descriptive point of view one might even settle for the ideal model represented by expression (2), which is the simplest one. But that equation does not provide us with an aid in designing new samples. On the other hand both expressions (4) and (5) will provide us with such a tool. Looking at the final value of ε_r from the fittings to both these latter equations one can observe that the mixing rule model suggest values around $\varepsilon_r \approx 8$ while the lumped element model gives $\varepsilon_r \approx 6$. Both of these values are too high for polyester (tabulated values are $3.2 \leq \varepsilon_r \leq 4.3$). There are a couple of possible explanations to this discrepancy.

In the case of the mixing formula, the expression for the effective permittivity is valid when the inclusions are circular cylinders with their axes aligned with the electric field exciting the capacitor, as mentioned earlier this is approximately the case before the onset of the compression, but as the fabric is compressed the spacer yarns bend and after a while they will be better approximated by rods lying with their axes normal to the field.

In the case of the lumped element formula we have made the approximation that the spacer yarns can be seen as a solid "wall" bending during the compression. This is also not the case in reality, in reality there is some portion of air also within this "wall" so we might be overestimating the amount of material in the capacitor. On the other hand, the unit cell has several yarns building up this wall, and we have assumed the wall to be one yarn diameter thick, but of course the different yarns cannot occupy the same volume so in that perspective we might be underestimating the amount of material.

In any case the lumped element model gives values of ε_r that are closer to the tabulated values and it is certainly not more involved that the mixing rule model. So it seems plausible to develop it further.

4.3 Conclusions

Based in the results presented in the appended papers and its discussion, we can conclude that in fact the contact resistances of a unit cell of a plain woven fabric with conductive yarns can be accurately measured with the method proposed by the authors. Using such method, we have been able to learn that in the case of metalized yarns with relatively low resistivity, the contact resistance between the yarns does not actually influence the behaviour of the conductive fabric significantly. The performed analysis suggests that for fabrics made of yarns with poor conductivity, the contact resistance might have a significant influence on the overall resistance. If the interconnection to other parts, *e.g. sensors, textile electrodes,* is made over a large enough number of parallel cells, the equivalent contact resistance of such connection can be actually neglected.

From the results presented in [Paper II] we can conclude that all the three models used for fitting all give reasonable agreement up to ca 50% compression. We also see that the lumped element model predicts lower values of the relative permittivity as compared to the mixing rule model, and that the permittivity values obtained for both these values lie above tabulated values for the permittivity of polyester. Therefore, we can conclude that, in principle and within the discussed limitations, both models can be used to guide the design of spacer-fabrics for capacitive sensors regarding dimensions and spacer yarn density. Further research is required to investigate the specific issue of permittivity of the spacer yarn and sensing beyond compression rates above 50%.

4.3.1 Future Work

As concluded for the contact resistance part, it is suggested that in the case of metalized yarns there is no need to investigate this further from a signal integrity perspective. One could do investigations on types of yarns with larger electrical resistivity to quantify the contact resistances of fabrics made with those. This could perhaps aid in designing stretch sensors relying on the change of contact resistance with pressure.

In order to test the extend of the validity of a model for a textile capacitive pressure sensor much more controlled experiments need to be carried out. Two main factors must be addressed; one is the synchronisation of the capacitance and deformation data and the other is the actual textile manufacturing beyond just lab samples.

The manufacturing of new samples would preferably be done by a simple textile process. At the Swedish School of Textile there is a knitting lab with modern and versatile equipment and highly skilled technicians. They have produced structures that resemble the main features of the samples that have been used in one process (i.e. no lamination or cutting is needed, the knitting machine "spits out" readymade samples). Therefore utilising such capability, the type of spacer yarn could be varied as well as the density and height of these yarns.

The relative simplicity of the lumped element model is promising. It would be interesting to see, in combination with the more controlled experiment suggested above, and possible modification of it, how far it can be used. The results in [Paper II] indicate that fitting could be done to a satisfactory level down to more than 50% compression.

REFERENCES

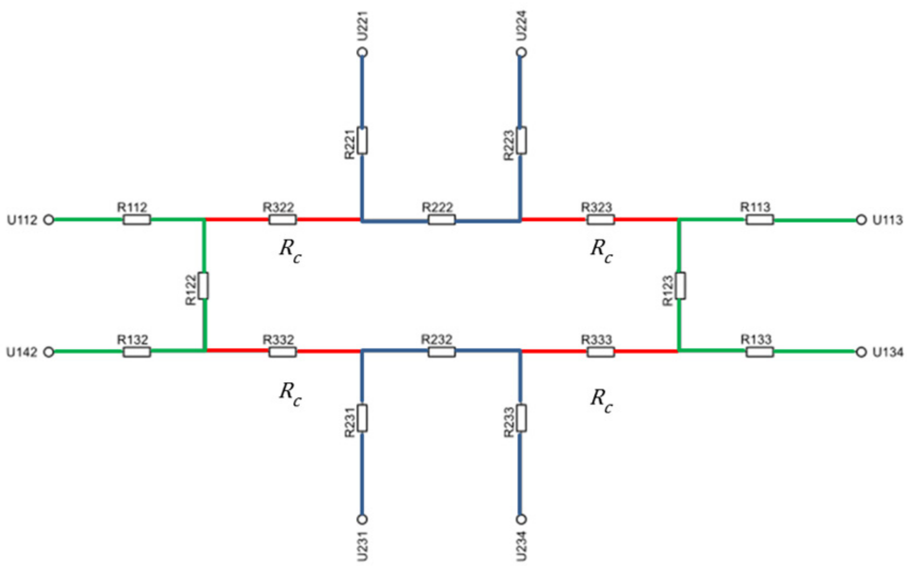
1. Byrne, C., *1 - Technical textiles market – an overview*, in *Handbook of Technical Textiles*. 2000, Woodhead Publishing. p. 1-23.
2. Hatch, K.L., *Textile Science*. 1993, Minneapolis/Saint Paul: West Publishing Company.
3. Balter, M., *Clothes Make the (Hu) Man.* Science, 2009. **325**(5946): p. 1329-1329.
4. Wynne, A., *Textiles*. The Motivate Series. 1997, London and Basingstoke: MACMILLAN EDUCATION LTD.
5. Saville, B.P., *4 - Yarn tests*, in *Physical Testing of Textiles*. 1999, Woodhead Publishing. p. 77-114.
6. Kadolph, S.J., *Textiles: Pearson New International Edition*. 2013: Pearson Education M.U.A.
7. Saville, B.P., *3 - Fibre dimensions*, in *Physical Testing of Textiles*. 1999, Woodhead Publishing. p. 44-76.
8. Gross, D., et al., *Bending of Beams*, in *Engineering Mechanics 2: Mechanics of Materials*. 2011, Springer Berlin Heidelberg: Berlin, Heidelberg. p. 97-187.
9. Tao, X., *1 - Smart technology for textiles and clothing – introduction and overview*, in *Smart Fibres, Fabrics and Clothing*. 2001, Woodhead Publishing. p. 1-6.
10. Nguyen, P.S., Jeremiah, *Electro-Optic Fabrics for the Warrior of the 21st Century - Phase II*. JAN 2010, Foster-Miller Inc. p. 156.
11. Winterhalter, C., Teverovsky, J., Wilson, P., Slade, J., Farell, B., Horowitz, W., and Tierney, E. , *Development of Electronic Textiles to Transport Data and Power in Future U.S. Military Protective Clothing Systems*. Journal of ASTM International, 2005. **2**(7): p. 1-9.
12. Lind, E.J., et al. *A sensate liner for personnel monitoring applications*. in *Digest of Papers. First International Symposium on Wearable Computers*. 1997.
13. Lymberis, A. and S. Olsson, *Intelligent Biomedical Clothing for Personal Health and Disease Management: State of the Art and Future Vision.* Telemedicine Journal and e-Health, 2003. **9**(4): p. 379-386.
14. Thorp, E.O. *The invention of the first wearable computer*. in *Digest of Papers. Second International Symposium on Wearable Computers (Cat. No.98EX215)*. 1998.
15. Inaba, M., et al. *A full-body tactile sensor suit using electrically conductive fabric and strings*. in *Intelligent Robots and Systems '96, IROS 96, Proceedings of the 1996 IEEE/RSJ International Conference on*. 1996.
16. Klemm, M., I. Locher, and G. Troster. *A novel circularly polarized textile antenna for wearable applications*. in *34th European Microwave Conference, 2004*. 2004.

17. Locher, I. and G. Troster, *Fundamental Building Blocks for Circuits on Textiles.* IEEE Transactions on Advanced Packaging, 2007. **30**(3): p. 541-550.
18. Bonderover, E. and S. Wagner, *A woven inverter circuit for e-textile applications.* IEEE Electron Device Letters, 2004. **25**(5): p. 295-297.
19. Hamedi, M., R. Forchheimer, and O. Inganäs, *Towards woven logic from organic electronic fibres.* Nature Materials, 2007. **6**(5): p. 357-62.
20. Locci, S., et al. *Woven Electronics: a new perspective for wearable technology.* in *2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. 2007.
21. Pani, D., et al., *Fully Textile, PEDOT:PSS Based Electrodes for Wearable ECG Monitoring Systems.* IEEE Transactions on Biomedical Engineering, 2016. **63**(3): p. 540-549.
22. Ishijima, M., *Cardiopulmonary monitoring by textile electrodes without subject-awareness of being monitored.* Medical and Biological Engineering and Computing, 1997. **35**(6): p. 685-690.
23. Paradiso, R., G. Loriga, and N. Taccini, *A wearable health care system based on knitted integrated sensors.* IEEE Transactions on Information Technology in Biomedicine, 2005. **9**(3): p. 337-344.
24. Seoane, F., et al., *Wearable Biomedical Measurement Systems for Assessment of Mental Stress of Combatants in Real Time.* Sensors, 2014. **14**(4).
25. Löfhede, J., F. Seoane, and M. Thordstein, *Textile Electrodes for EEG Recording — A Pilot Study.* Sensors, 2012. **12**(12): p. 16907.
26. Cuba-Gyllensten, I., et al., *Removing respiratory artefacts from transthoracic bioimpedance spectroscopy measurements.* Journal of Physics: Conference Series, 2013. **434**(1): p. 012018.
27. Linz, T., L. Gourmelon, and G. Langereis, *Contactless EMG sensors embroidered onto textile*, in *4th International Workshop on Wearable and Implantable Body Sensor Networks (BSN 2007): March 26 – 28, 2007 RWTH Aachen University, Germany*, S. Leonhardt, T. Falck, and P. Mähönen, Editors. 2007, Springer Berlin Heidelberg: Berlin, Heidelberg. p. 29-34.
28. O'Connor, K., *How Smart Is Smart? T-shirts, Wellness, and the Way People Feel about "Medical" Textiles.* TEXTILE, 2010. **8**(1): p. 50-66.
29. Statex, *Shieldex 235f34 dtex 2-ply HC.* 2009, Statex Produktions & Vertriebs GmbH.
30. Bashir, T., M. Skrifvars, and N.-K. Persson, *Synthesis of high performance, conductive PEDOT-coated polyester yarns by OCVD technique.* Polymers for Advanced Technologies, 2012. **23**(3): p. 611-617.
31. Kim, B., V. Koncar, and C. Dufour, *Polyaniline-coated PET conductive yarns: Study of electrical, mechanical, and electro-mechanical properties.* Journal of Applied Polymer Science, 2006. **101**(3): p. 1252-1256.
32. Zhang, H., et al., *Conductive knitted fabric as large-strain gauge under high temperature.* Sensors and Actuators A: Physical, 2006. **126**(1): p. 129-140.
33. Holm, R., *Introduction. A simplified summary of the theory of stationary electric contacts*, in *Electric Contacts: Theory and Application*. 1967, Springer Berlin Heidelberg: Berlin, Heidelberg. p. 1-7.
34. Mikrajuddin, A., et al., *Size-dependent electrical constriction resistance for contacts of arbitrary size: from Sharvin to Holm limits.* Materials Science in Semiconductor Processing, 1999. **2**(4): p. 321-327.
35. Holm, R., *The load bearing contact area as a function of load and elastic and plastic properties of the members*, in *Electric Contacts: Theory and Application*. 1967, Springer Berlin Heidelberg: Berlin, Heidelberg. p. 29-39.
36. Banaszczyka, J., A. Anca, and G. De Mey, *Infrared thermography of electroconductive woven textiles.* QIRT JOURNAL, 2009. **6**(2): p. 163-173.
37. Banaszczyk, J., et al. *Current Distribution Modelling in Electroconductive Textiles*. in *Mixed Design of Integrated Circuits and Systems, 2007. MIXDES '07. 14th International Conference on*. 2007.
38. Banaszczyk, J., et al. *Contact resistance investigation between stainless steel electroconductive yarns*. in *2009 MIXDES-16th International Conference Mixed Design of Integrated Circuits & Systems*.

39. Pola, T., *Advanced Materials Research: Selected, Peer Reviewed Papers from the 2011 International Conference on Advanced Material Research* Vol. 213. 2011: Trans Tech Publications, Limited.
40. Meyer, J., P. Lukowicz, and G. Troster. *Textile Pressure Sensor for Muscle Activity and Motion Detection*. in *2006 10th IEEE International Symposium on Wearable Computers*. 2006.
41. Min, S.D., Y. Yun, and H. Shin, *Simplified Structural Textile Respiration Sensor Based on Capacitive Pressure Sensing Method.* IEEE Sensors Journal, 2014. **14**(9): p. 3245-3251.
42. Sergio, M., et al. *A textile based capacitive pressure sensor*. in *Proceedings of IEEE Sensors*. 2002.
43. Hoffmann, T., B. Eilebrecht, and S. Leonhardt, *Respiratory Monitoring System on the Basis of Capacitive Textile Force Sensors.* IEEE Sensors Journal, 2011. **11**(5): p. 1112-1119.
44. Merritt, C.R., H.T. Nagle, and E. Grant, *Textile-Based Capacitive Sensors for Respiration Monitoring.* IEEE Sensors Journal, 2009. **9**(1): p. 71-78.
45. Grimnes, S. and Ø.G. Martinsen, *Chapter 9 - Data and Models*, in *Bioimpedance and Bioelectricity Basics (Third Edition)*. 2015, Academic Press: Oxford. p. 329-404.
46. Giordano, S., *Effective medium theory for dispersions of dielectric ellipsoids.* Journal of Electrostatics, 2003. **58**(1–2): p. 59-76.

APPENDIX A

Expressing the resistances of a unit cell of plain weave in measured quantities



Here we go through the procedure for the resistances $R232$ and $R232$, the procedure is similar for the rest of the resistances. We need to inject current twice in order to express the resistance in quantities known to us; upper indices will refer to these turns, e.g. $U113^1$ refers to the potential $U113$ measured for the first time and $U113^2$ refers to the potential $U113$ measured for the second time.

First inject a current I_1 at node $U112$ and let it sink at node $U134$ and measure all the remaining voltages indicated in the figure, then inject a current I_2 at node $U231$ and let it sink at node $U134$ again measure all the remaining voltages . Call the currents flowing through $R322$ i_1^1 and i_1^2 and the currents flowing though $R122$ i_2^1 and i_2^2. Applying Ohms' law between: nodes $U224$ and $U113$; nodes $U231$ and $U234$, and Kirchhoffs current law at the node connecting $R112, R122$ and $R322$ gives us

$$\begin{cases} i_1^1 = \dfrac{U224^1 - U113^1}{R323} \\ i_2^1 = \dfrac{U231^1 - U234^1}{R232} \end{cases}$$

And

$$\begin{cases} i_1^2 = \dfrac{U224^2 - U113^2}{R323} \\ i_2^2 = \dfrac{U231^2 - U234^2}{R232} \end{cases}$$

And

$$\begin{cases} I_1 = i_1^1 + i_2^1 \\ I_2 = i_1^2 + i_2^2 \end{cases}$$

Inserting the expressions for the branch currents into the expressions for the total currents leaves us with

$$\begin{cases} I_1 = \dfrac{U224^1 - U113^1}{R323} + \dfrac{U231^1 - U234^1}{R232} \\ I_2 = \dfrac{U224^2 - U113^2}{R323} + \dfrac{U231^2 - U234^2}{R232} \end{cases}$$

Solving this for $R232$ and $R323$ gives

$$\begin{cases} R232 = \dfrac{(U224^2 - U113^2)(U231^1 - U234^1) - (U231^2 - U234^2)(U224^1 - U113^1)}{(U231^1 - U234^1)I_2 - (U231^2 - U234^2)I_1} \\ R323 = \dfrac{(U224^2 - U113^2)(U231^1 - U234^1) - (U231^2 - U234^2)(U224^1 - U113^1)}{(U224^2 - U113^2)I_1 - (U224^1 - U113^1)I_2} \end{cases}$$