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E-Textiles.

Study of the interaction between devices, connection methods and substrates.

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MASTER FINAL THESIS

Abstract

It is common knowledge that textiles and textile products are available in different forms along the textile chain. However, right now, all the attention is paid to the relationship between these materials and the most recent developments in the world of electronics. When a garment is implementing electronic components, ranging from sensors to conductor paths, that are applied or integrated into the textile surface, it's commonly called an E-Textile.

Nowadays there is a continuous demand for these products because they can satisfy a great extent of needs without interfering too much with the user's life or without the obligation of modifying too much the original product in the beginning.

This study, however, focuses on analyzing the interaction and interactivity which allows electronic communication between the components present in the textiles. It is believed that there is a knowledge gap in these most recent developments.

In this paper, a literature investigation is carried out using various databases, which resulted in different contributions to the researched subjects.

Also, an overview of materials, production technologies and testing methods is given. The concepts of smart and e-textile, textile structure, conductive materials, electronic communication and connection are classified. The influencing factors on the properties of the material structure are presented and a discussion is made referring to the potentials and challenges related to e-textiles.

Finally, a brief consideration of sustainability and environmental aspects is done and, in the end, the main conclusions of the investigation are stated.

The main focus of the research lies in defining processes and material properties for improving connection techniques between the textiles and the electronic components, and also between the components themselves.

Only limited research will be conducted on simulating the behavior of these technologies. Various ideas for applications exist, starting from ones of classical nature (flexural rigid materials), to 3d printed additive manufacturing or other ones of a textile nature in the form of embroidered conductor paths. Unluckily little research has been conducted on real applications. Therefore, the challenges are only identified, and future research directions are derived.

Resumen

Los textiles y los productos textiles están disponibles en diferentes formas a lo largo de la cadena textil. Sin embargo, ahora mismo, toda la atención está puesta en la relación entre estos materiales y los desarrollos más recientes en el mundo de la electrónica. Cuando una prenda implementa componentes electrónicos, que van desde sensores, hasta recorridos de conductores, que se aplican o integran en la superficie textil, comúnmente se denomina E-Textile o “tejido electrónico”.

Hoy en día existe una continua demanda de estos productos, ya que pueden satisfacer gran parte de las necesidades sin interferir demasiado en la vida del usuario, o sin la obligación de modificar demasiado el producto original. Esta investigación, sin embargo, está enfocada en analizar la interacción e interactividad que permite la comunicación electrónica entre los componentes presentes en los textiles. Se cree que existe una brecha de conocimiento en estos desarrollos más recientes.
En este trabajo se realiza una investigación bibliográfica utilizando diversas bases de datos, lo que dio como resultado diferentes aportes sobre los temas investigados.

Además, se proporciona una descripción general de los materiales, las tecnologías de producción y los métodos de prueba. Se clasifican los conceptos de tejido inteligente y tejido electrónico, estructura textil, materiales conductores y comunicación electrónica.
Se presentan los factores que influyen en las propiedades de la estructura del material y se hace una discusión sobre el potencial y los desafíos relacionados con los tejidos electrónicos. Finalmente se hace una breve discusión sobre sostenibilidad y implicación ambiental y al final se exponen las principales conclusiones de la investigación.

El enfoque principal de la investigación radica en definir procesos y propiedades de los materiales para mejorar las técnicas de conexión entre los textiles y los componentes electrónicos, y también entre los propios componentes.

Solo se llevará a cabo una investigación limitada sobre la simulación del comportamiento de estas tecnologías. Existen varias ideas de aplicaciones, desde las de carácter clásico, hasta las más recientes y innovadoras. Desafortunadamente, se han realizado pocas investigaciones sobre aplicaciones reales. Por lo tanto, solo se identificarán los desafíos y se derivarán futuras líneas de investigación.

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PCB: Printed Circuit Board
NCA: Non-Conductive Adhesive
ICA: Isotropic Conductive Adhesive
ACA: Anisotropic Conductive Adhesive
ECA: Electrically Conductive Adhesive
IOT: Internet of Things
WBAN: Wireless Body Area Network

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1 Introduction

Since the last century, revolutionary changes have been occurring in many fields of science and technology, which had profound impacts on every aspect of our life. These advances, have affected directly the textile industry, which as we will see in the related chapter, has a history that goes back thousands of years.

In this industry, many of these advances not only include better manufacturing technologies and techniques, but are the result of the combination of textiles and these new developments in technology.

Today, we are living in a world where the impacts of technology on the traditional textiles and clothing industry, made possible the creation of smart textiles and, consequently, e-textiles.

1.1 Object of study

The object of this Master Thesis aims to provide an investigation and discussion about all the most common and reliable connection methods used for e-textiles. This research covers different materials, processes and techniques to be taken into account for the production of e-textiles. Then these are discussed to evaluate their feasibility for different applications.

All the information found is based on knowledge acquired during the course, during personal work experience and finally using researched literature studies.

1.1.1 Project Flow

At first, a brief introduction related to smart and e-textiles is made also explaining potential applications.

Later on, the four main pillars that support all of the investigation are presented in this order:

- Fibers and Textile structures
- Conductors
- Manufacturing of E-textiles
- Connection methods in E-textiles

This background analysis is followed by a discussion where a resume of the connection methods is presented and the methodology of selection of a method is considered.

Also, an overview of the properties and opportunities is done, followed by another of the issued and challenges related to the object of study.

Finally, the environmental implications and sustainability issues are discussed and the conclusions are presented.

1.2 Motivation of this investigation

The motivation behind this thesis is the need to organize onto the same investigation the majority of the information found related to the subjects explained on the object of the study.

At the moment, although the field of smart textiles has drawn considerable research and commercial interest, currently available products are very few.

This translates, in e-textiles, on a development of prototypes and products related to the connection of conductive materials that is scarce. Subsequently, joining technologies for e-textiles also appear rarely within the literature on e-textiles and very few studies involving several techniques at the same time exists.
Many researches are also just focusing on the development of textile sensors and e-textile garment platforms, rather than developing studies mentioning all the materials, processes and technologies behind e-textiles.

This investigation aims to cover all the topics related to e-textiles since they will allow the reader to grasp the basics of production: understanding the substrates, knowing the differences between conductive components, etc.

1.3 Scope

The scope of this study is the investigation of various e-textiles connection techniques and the evaluation of their feasibility.

A background of smart textile production is presented, adding common applications. An introduction to basic textile structures is made, to help users coming for non-textile background understand how they can affect the production of e-textiles.
Commonly used conductors are also presented and the interaction between textile substrates and conductive components is explained.

Then, a systematic review of the connection techniques developed in the recent ten years is made using researched literature and the feasibility of these methods is discussed. Additive manufacturing techniques such as 3D printing or conductive inkjet printing used for creating electronic paths and connection, will not be taken into account, since they are neither fixed nor detachable joining techniques.

2 Background Review

In this chapter, all the topics related to the production of e-textiles will be thoroughly described, starting from a brief explanation of smart textiles, since e-textiles are a branch of these, we will understand their characterization and potential applications.

2.1 Introduction to smart textiles

The development of smart textiles requires a multidisciplinary approach in which knowledge of circuit design, smart materials, micro-electronics, and chemistry are fundamentally integrated with a deep understanding of textile fabrication. [1]

These smart objects can be defined as textiles that can sense and react to environmental conditions or stimuli, such as those from mechanical, thermal, chemical, electrical, magnetic or other sources.
In "*Smart fibers, fabrics and clothing*" a distinction is made between three classes of smart structures:

a) passive smart textiles that can sense their surroundings.
b) active smart textiles that can sense and respond to their surroundings.
c) very smart textiles that can sense, respond and adapt according to environmental changes. [2]

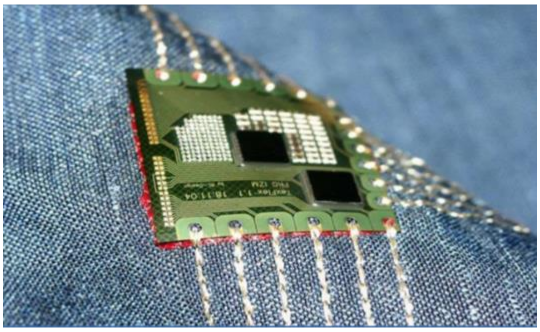


Figure 1. Nanostructure integrated onto a textile. (Source: Google)

However, smart textiles are not only based on electrical circuitry; other types of sensing and actuating materials could also be integrated into a fabric. For example, thermo-chromic or UV-sensitive pigments, shape-memory and shape-shifting structure, fabrics with microcapsules that react to humidity, etc.
These examples both sense and react to the changes in the environment without the need of an electrical circuit. That's why, if not explained beforehand, when the term E-textile is used in this study, it will mean an electrically conductive textile structure.

When referring to e-textiles, we must think of products with properties that are of value in a textile. Usually e-textiles can be characterized by function and application. More in depth, these properties related to a textile are flexibility, breathability, comfort, etc. However, such properties may be more or less important depending on the application. For example, the evaluation of the electrical behavior of the object itself must also, always be involved.

2.1.1 Potential applications of e-textiles

By integrating electronics onto textiles substrate, the textile material is able to fulfill more complex functions as we will see in this chapter. However, the most important rule to be taken into account is that the user's experience is key to the development of e-textiles. Preferably, the user shouldn't be able to notice these systems. Years ago, wearable electronics were replaced by textile-based electronics. This, made possible the development of e-textiles that wouldn't affect the feel or aspect of the final product.
Today, the advances in construction of micro and nano electronics made possible embedding electronics into the textiles and the development of new connection methods has helped the improvement of already existing e-textiles.

As we can see in Figure 2, the potential applications for this technology are various. These smart objects can be used in sectors such as security, medical and wellness, sports and fitness [1], but also communication, fashion and personal protection.

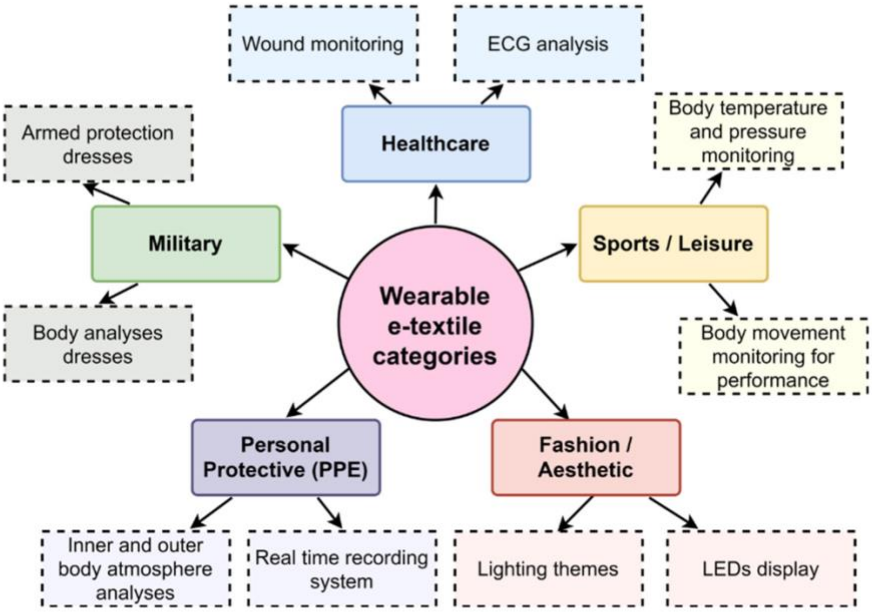


Figure 2. E-textiles wearable technology applications. (Source: Smart E-Textile Systems: A Review for Healthcare Applications).

Based on the information found during the research, the most widely uses of e-textiles are related to answer the needs of our daily life, such as in healthcare or sports, since the electronic technologies involved with the textile substrate make possible the monitoring of various aspects of the user's condition, such as body temperature, heart rate, blood pressure, or detect various activities, such as sweating, skin pH, moisture levels, etc.

At the same time, the user's quality of life will be dramatically increased because of the integration of these systems into a textile. For example, a comfortable bed sheet that reads the conditions of patients that cannot move from their bed, would be a less invasive solution and would benefit the overall situation of the user.

Other applications for e-textiles can be related to areas such as fashion, automotive and military, home interiors or work protection.

Although, developments in smart clothing technology are highly innovative and advanced, application is only in its starting phase, which suggests that their potential use is very extensive. [1].

2.2 Understanding fibers and textile structures

A brief but effective description of the textile history, and products, must be made.

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.
Personally, I believe that these technical textiles are not to be used for an aesthetic or decorative pleasing, but rather for their performance, as for E-textiles. That's also why they are not always produced of materials traditionally used in textile production.

Usually, we define "textile matter" as something normally fibrous, that properly treated in a spinning mill is transformed into thread and that, at the same time, meets conditions of flexibility, elasticity and resistance sufficient to be woven or knitted.
These yarns or fibers can be classified according to their method of obtention.
They can either be:

1. Natural. With an animal (for example coming from hair, like wool, or from silk worm cocoons) or vegetable origin (that are extracted from the fruit, like cotton, or stem, like flax, of a plant).
2. Artificial. Present in nature, but not in a fibrous form. They must be manipulated physically or chemically to be transformed into textiles.
3. Synthetic. Not to be found directly in nature, but that are made strictly starting from chemical reactions that obtain molecules in linear form (polymerization). The final product of these reactions can be transformed into fiber or yarn, like for example Rayon, Polyester, etc.

After illustrating the basics of the textile matter origin, a short description of the textile fibers spinning process will be made, as it could affect the behavior of the final functionalized smart fabrics.

All textile fiber must follow a process, according to their origin and characteristics, to be transformed into yarns, with properties suitable for working with them. A yarn is composed of fibers that are held together by a series of specific processes. There are three main types of yarns: staple fiber yarns, monofilament yarns and multifilament yarns.

A staple fiber yarns is constructed of staple fibers that are spun together. The staple fibers are often between 10 to 500 mm long. Common examples are cotton, wool, acryl, flax. The filament yarns, both monofilament and multifilament, are almost always (silk is an exception) man-made and as opposed to the staple fiber yarns the fibers in the filament yarns are as long as the yarn itself. Man-made filaments are formed by extrusion of a polymer melt or solution that, at a later stage, will be stretched and spun.

If the materials used plays a crucial role, there are other parameters that will affect the mechanical properties of the yarns, like measuring the amount of material per unit length (Tex, Dns, etc.) or measuring the twist, said in other words, how many turns around the yarn axis a fiber makes across a unit length.

Taking into account all these variables, we could begin to determine the characterization of a yarn. However, in addition their mechanical properties, which can be adjusted with regard to the intended application, fibers must be able to handle different types of mechanical stresses that can occur during both textile production or later during use. More specifically, fibers used for the production of e-textiles, must be able to maintain their functionality in different types of environments, mostly related to their exposure to ambient atmosphere and humidity which could affect electrical conductivity or their exposure to water during washing and use (sweat, rain, etc.), as well as exposure to other chemical agents (detergents). These additional requirements may affect electrical and mechanical performances, as discussed in more detail in the chapters related with conducting materials and common issues in e-textiles.

Having explained the basics of fibers and yarns, we can begin to understand, and imagine, textile structures.

There are three main types of textile structures: woven, knitted and non-woven ones, as seen in Figure 3. They are produced with different techniques and machines, and end up resulting in very different fabrics.

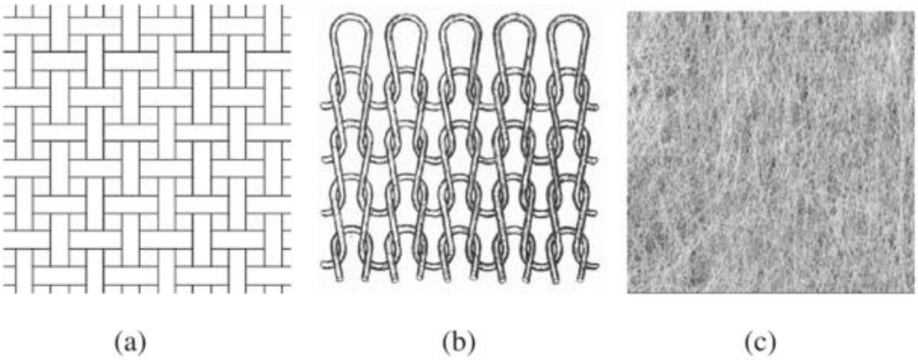


Figure 3. Detailed image of three main textile structures. (Source: Mohd Iqbal Misnon, ResearchGate)

a) 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. Woven fabrics can display different mechanical characteristics in different directions.
The anisotropy of the fabric can be adjusted by using different yarn densities in the systems, by using different kinds of yarns in warp and weft, or by changing the binding structure.
Also, included in the woven structures, we find braided fabrics made by using a special kind of weaving loom.

b) The characteristic of knitted fabrics is that instead of two yarn systems, like in the woven ones, there is only one yarn that makes stiches that bind into one another. There are many ways to vary a knitted structure, but in general we can differ between weft and warp knitted fabrics. Unlike woven and non-woven ones, knitted fabrics have a higher degree of flexibility and a fast-manufacturing process, which is why they are used mostly for clothing.

c) Non-woven fabrics are made by interlocking fibers with the help of needle punching or other techniques, the fabric can later be fixated by the use of heat, resins or other agents. Depending on the manufacturing technique and the desired final product the fabrics can be very isotropic or anisotropic.

2.2.1 Comparing woven, knitted and non-woven architectures for e-textiles

As far as we know, the two main fabric forming methods in the production of e-textiles are weaving and knitting since they present various opportunities, but also challenges.
In weaving, using warp and weft yarns it's possible to create an ordered array of conductive junctions, depending on the structure and yarn used, that is known to be stable when worked on. Using insulated materials reduces the risk of shorting, and the weaving process itself, makes it possible to use different kind of stiff yarns and fibers that wouldn't be possible to work on a knitting machine. One potential challenge related to the use of stiff materials is that the final fabric will surely lack flexibility and elasticity.

On the other side, knitted fabrics thanks to the structure of the yarns that forms the previously seen loops between each other, grants a high level of flexibility and stretchability, both uniaxial and biaxial.
This is why knitted fabrics are mostly used for creating garments since a tight fit to the skin may be needed for the systems to work correctly. The modern knitting machines can combine standard yarns together with conductive yarns to achieve pliable fabrics and even spacer conductive ones. However, there are limitation to the knitting process, since pure metal yarns or the ones with higher stiffness may require machines and processing parameters that are not cost effective.

Lastly, the great potential on non-woven, is its faster and much less labor-intensive process rather than the knit or weave fabrics one, which makes it a more environmentally friendly material to produce as well. Also, the structure of these fabrics, doesn't limit the possibility to encase conductive materials and makes it possible to create lightweight and flexible fabrics. In Project Jacquard, Google, in a partnership with Levis™ created woven garments that works like touchscreen-like input devices. In Figure 4 we can see a detail of a Bluetooth module integrated as a cufflink, to send the touch inputs to the receiver.

Figure 4. Bluetooth device attached as a cufflink (Source: textiletoday.com).

Techniques behind 'Project Jacquard' of Google and Levi's

Now that we have an idea of the basics of textile production, we must be conscious of the impact that variables such as the type of fiber, yarn and textile structure characteristics, will have on the physical properties of the final textile product.

What is important to understand is that these products find their applications in almost all of our activities, since we are surrounded with textiles in almost all our environments. The integration of multifunctional values in such common materials has become a special area of interest in recent years.
These days, a lot of focus is put on how to integrate electronics into garments, so to create garments that sense and reacts on human or other environmental inputs, but we will talk about this more thoroughly in the next chapter.

2.3 Introduction to Conductors

Most of the e-textiles available at the moment are functionalized by some electro-conductive materials integrated into one of the previously mentioned textile structures and controlled by some sort of regulating circuit or micro-processor.
These materials that conducts electricity, are commonly called conductors. They are usually not categorized as sensors or actuators because, due to their conductive properties, they are mostly useful as pathways to connect the different components of the system.
In this chapter I will try to briefly introduce the most commonly known conductive materials and how they can be implemented into various types of fabrics.

One of the key factors in choosing the right conductive material is the fact that they can display extremely wide range of conductivities and resistivities that can affect the final behavior of the designed product. As a matter of fact, for example, the use of yarns as electrical conductors may, or may not, pose a problem depending on the intended application. The conductive property of the yarns is often stated as the linear resistivity of the yarn. The linear resistivity is simply the resistance of a certain length of the yarn expressed in units of Ω/m.

As explained in the research made by A. L. Leon in "*Recent researches concerning the obtaining of functional textiles based on conductive yarns*" [3], several types of conductive yarns to be used on e-textiles can be listed:

a) Conductive polymers produced by wet or melt spinning, electrospinning, fiber-drawing or dipping and drying. Thanks to their flexibility of and their ability to be processed in solution, they are considered extremely useful for creating flexible electronic components, including conductive yarns. They can also be used as coatings for other types of yarns, in order to add conductivity to the original mechanical properties of the core material. One of the drawbacks of these materials is that their conductivity is normally much lower than that of metal and metallized yarns, however in the creation of sensor conductive polymers they can be used since these applications are not always dependent on high conductivity.

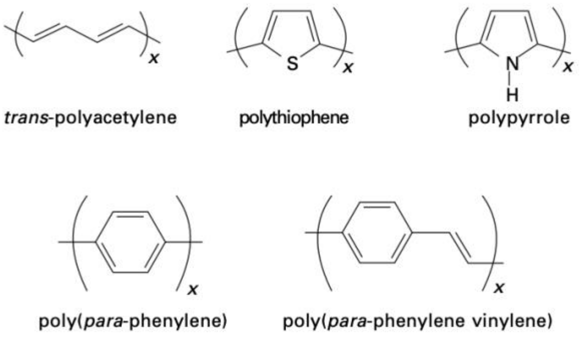


Figure 5. Repeat units of intrinsically conductive polymers. (Source: Intelligent Textile and Clothing by H.R. Mattila)

b) Metal yarns. Mostly metal monofilaments that can be blended with other fibers or directly fed to the weaving or knitting machines; Some metals are the most conductive materials to be used, like silver and copper for example, however These metallic yarns, though featuring relatively high electrical conductivities, are generally heavier and stiffer than commercial textile yarns based on the polymer materials, and can affect the overall characterization of the final product, influencing it's daily applications.

c) Metallized yarns that are produced twisting, embedding or coating to a core yarn. These are the yarns used for producing high-performance textiles and sewing threads because of their characterization that gives them exceptional strength, abrasion and perspiration resistance, good elasticity and permanent press and wash-and-wear performances. Examples of these yarns are copper-coated polyester yarns or silver-coated polyamide yarns.

d) Electrically conducting strips. Metallic strips with a minimum width of 2mm that are inserted as weft in woven structures or used as conducting lines printed on plastic strips;

e) Fibers containing conductive elements like metal or carbon particles that are introduced during the extrusion process in the polymeric matrix. This is a useful way to improve textile properties such as handle, washability and flexibility. For example, conductive carbon-filled composites have been spun into fibers using various synthetic and natural polymers, as to achieve conductivity and being able to develop textiles sensors or capacitors.

f) Carbon-based fibers. They offer a range of electrical conductivity levels depending on the precursor and processing conditions. As said in "*Conductive polymer yarns for electronic textiles*", by H. QU, these materials feature a unique one-dimensional structure and extraordinary physical properties, such as high aspect ratio, light weight, and good electrical and thermal conductivities. [4]

Although this list may seem long, conductive yarns are not the only materials that can be used as electrical conductors. Other methods for developing e-textiles include printing patterns of conductive ink onto conventional textile fabric [5] or embedding larger electronic components on a fabric using pins, embroidery or adhesives. However, we will discuss these methods on the chapter related to the connection methods in e-textiles.

2.3.1 Common doubts about using conductive materials for e-textiles

Electrically conductive fibers are thought to be lacking properties such as comfort, washability, wear resistance, and dyeability. One of the common doubts is regarding the nature of these products. Shall we consider them as solid, homogeneous conductors like a piece of metal? Or shall we treat them as new textile materials with a modified fiber structure that grants them numerous possible outcomes?

The main difference between a solid piece of metal and a conductive textile is their electric behavior.
The natural electric resistance present into the conductive elements of a fabric, will be influenced by their flexibility which changes the conditions of the yarn itself. And the mechanical deformation of these fabrics, due to normal usage, will also influence its behavior? All of these problems can only be solved by choosing the right textile structure depending on the product we want (increasing wear resistance) by using the correct connection methods (coatings and finishes to prevent shorting and electrical interferences) and new materials (improving overall appearance and conductivity).

2.4 Manufacturing of E-textiles

In this chapter, core of the whole investigation, we will review all the different methods and materials up to date that could be listed, for creating connections between parts of an e-textile circuit. As explained in "*Smart fabric sensors and e-textile technologies: A review*" by L. Castano, the three common categories of bonds for connectors and interconnects are mechanical, physical and chemical:
Mechanical connections entail the gripping or joining of components to conduction lines. Physical connections include micro welding, thermoplastic adhesion, mixed conductive polymer adhesion, joint soldering and electroplating. Examples of chemical connectivity include covalent chemical bonding, acid oxidation, hydrogen bonding, and plasma pre-treatments. [6]

There are many more ways to characterize connection methods, but the ones that we will discuss now are the most relevant to e-textile applications, since they don't involve high voltages and are mainly battery powered.

2.4.1 Interactions between textiles and electronics

Before listing the connection methods found in this investigation, it is necessary to explain the variety of approaches that are used to create e-textiles, and these are covered in depth across several existing papers. These approaches explain the extent of electronic integration between textiles and electronics, and how the functionality of the final product is affected by each and one of them.
We will only be taking into account more recent projects, since the first examples of E-textiles consist of unsophisticated objects connecting electronic elements with the textile with raw methods.

As listed in *Review on the Integration of Microelectronics for E-Textile*, there are three main types of interactions, examples of which are shown in Figure 6, which, in order from left to right, are: *textile-adapted, textile-integrated and textile-based.* [7]

Figure 6. Level of electronic Integration. (Source: [7])

On the same paper, a detailed review of each one of these types of interactions is made. Summarizing, they can be defined as it follows:

a) Textile-adapted textile products are the ones where textile and electronics are produced separately and later joined together to integrate an electronic function. (e.g. A jacket with a pocket specially made for inserting a Gps tracker module).

b) Textile-integrated solutions where there is an interconnection between the electronic and the substrate. Unlike the previously seen example, this kind of interaction is made at textile-level using common techniques such as sewing or soldering and makes it possible to achieve and higher level of flexibility and accessibility. (e.g. The previously seen Lilypad electronic module sewn onto a textile).

c) Textile-based interactions where the most important part of the system is given by the structure of the textile itself. In this group we find the so called “textiles as sensors” for example, as the conductive components can be embedded into the substrate in the form of a yarn, printed pattern, etc. (e.g. UPC Professor Ignacio Gil's antennas, embroidered onto various textile substates). This approach is the most sought one since, it replaces traditional electronic circuitry with textile alternatives giving added value to the product and a high level of overall quality.

2.5 Connection techniques in E-textiles

Explained the main types of interactions, all the different connection methods that are exhaustively described in various literature researches will be analyzed. These investigations demonstrate different connection approaches between the rigid electronic components and soft textiles.

The principle governing the whole procedure is explained ideally in “*Review on the Integration of Microelectronics for E-Textile”,* where the authors explain that in order to interconnect different electronics components such as conductive yarns, sensors, batteries, and processing circuits, the conductive tracks have to embed directly into/onto the textile. The most basic function of the chip-level interconnections is to provide electrical paths to and from the substrate for power and signal distribution. The integration of electronics into/onto the textiles requires two straight-forward connection steps. The first one is the mechanical connection to a textile material, while the second step is the electrical connection integrated on the conductive structures. Both connections must be functional and reliable. [7]

Explained this principle, two main families of connectors used when producing e-textiles can be disclosed:

a) Fixed connections used for attaching an electronic component on a substrate, using methods such as gluing, stitching or soldering.

b) Detachable connections such as USB or snap fasteners that count as electromechanical components, used predominantly for attaching power sources, antennas or sensors.

The first type is defined fixed as it is not easily detached and consequently reattached, however it is not impossible to do so. An adhesive can be removed or a stitch can be undone, but it will be a process that will take longer compared to the other detachable connections.

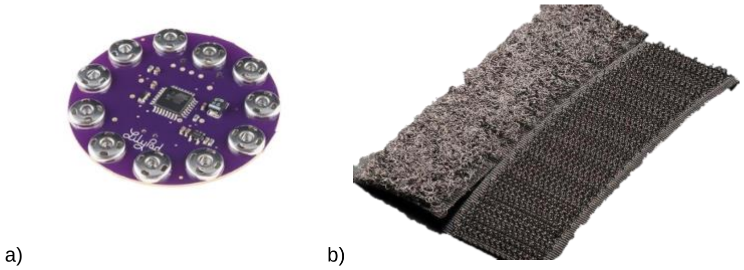


Figure 7. Examples of detachable connections that are also fixed on the substrate.
a) Lilypad with snap fasteners, b) Conductive Velcro strip. (Source: Google)

Also, it's important to note that even a detachable connector, must have a fixed part on the substrate. Figure 6 illustrates how those connectors are only detachable at one end. One side attaches permanently to a substrate, while other is detachable and may be connected and disconnected multiple times. Thus, any connector, even if detachable, needs fixed joining techniques such as gluing or crimping to fix it in place on the substrate.

In the next subchapter, we will analyze more in detail the various connection methods, using the information found both in *Review on the Integration of Microelectronics for E-Textile* and in *A review of connectors and joining technologies for electronic textiles*. [8]

2.5.1 Fixed Connection Techniques

a) Sewing and Embroidery

Sewing and embroidery technologies are traditional methods for interconnection of electronic components in which designs are created by stitching strands of some material onto an appropriate substrate. [9]
Embroidering connections with conductive thread can be performed by hand or with a sewing or embroidery machine, on fabrics made of insulating materials. [8] With these conventional methods, chip elements, PCBs (such as in Figure 1) and sensors that are placed on the substrate are attached by sewing to provide a rigid mechanical connection between the circuit elements and the conductive fabrics. [7]

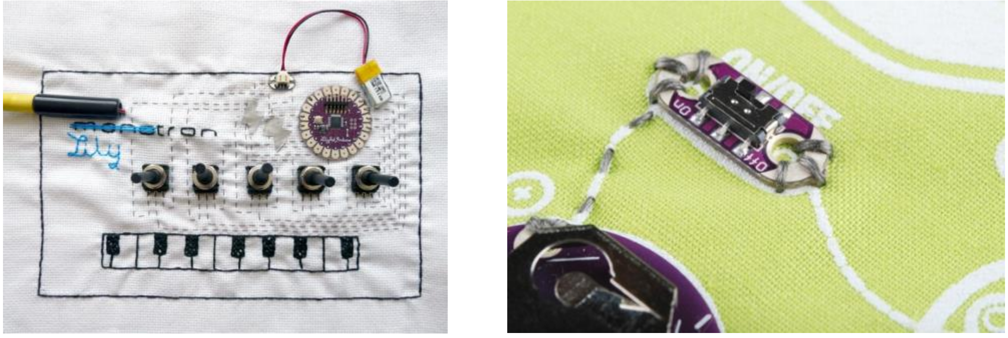


Figure 8. Examples of embroidered or sewn connections.

(Source: LilyTron by Afroditi Psarra, Sewing with conductive thread, Google)

There are no limitations to the kind of fabric used, since it could be woven, non-woven, or knitted.

One of the advantages of this process of fabric circuit formation is that the conductive threads can be embroidered in any shape on the fabric irrespective of the constituent yarn path in a fabric. Moreover, one does not need to perform a lot of machine preparation before fabric circuits can be formed. [9]

However, embroidery and sewing with conductive thread can present a challenge, moreover if normal machines were to be uses. Conductive threads have special characterization that may need custom machinery in order to enable the desired finished product or the use of threads that have high strength and flexibility because of the stresses due to bending and shear and the struggle to form a secure stitch. [9]

Also, another issue to be taken into account is that, when embroidery is used in near-body applications, the electronic and conductive paths should be shielded by conductive substances that may damage the system. For example, on a garment to be used in contact with the skin and its generated sweat, conductive components could be encapsulated or protected with an adhesive film, to avoid any kind of abrasion, or contact with contaminants such as moisture and salt.

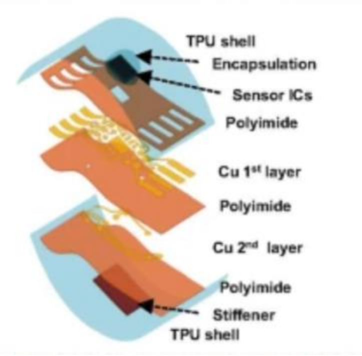


Figure 9. Example of body sensor protected by TPU shell (Source: Google)

b) Soldering

Soldering is a basic technology used for joining two or more electronics or conductors contacts. It works by melting a metal, usually an alloy with a lower melting point that the material of the contacts to be joined, and applying it in-between the contacts.

It's a technique that has been used in e-textiles to connect components to flexible substrates such as conductive thread, flexible copper wire, or polyimide. Soldered connections have low contact resistance but are mechanically brittle, and connections that are subject to any bending or stretching must be reinforced to avoid breakage in a textile application. [8] Also, this connection method is not suitable for temperature-sensitive textiles since as, temperatures above 200◦C, typically required for standard soldering, are high enough to burn or melt most fabrics or any other plastic components used for e-textiles.

Some, but not all, conductive materials used in e-textiles can be soldered. Common conductive threads, such as stainless-steel ones and silver-coated nylon threads, are not solderable, however the ones composed of small diameter brass or copper wire, braided with heat-resistant carrier thread, are.

Approaches to improve the strength of soldered connections to textiles have included laser soldering of components to copper wires, ultrasonic soldering, hot bar soldering, and increasing the permeation of conductive ink into fabric for soldering components to printed conductive tracks. [8]

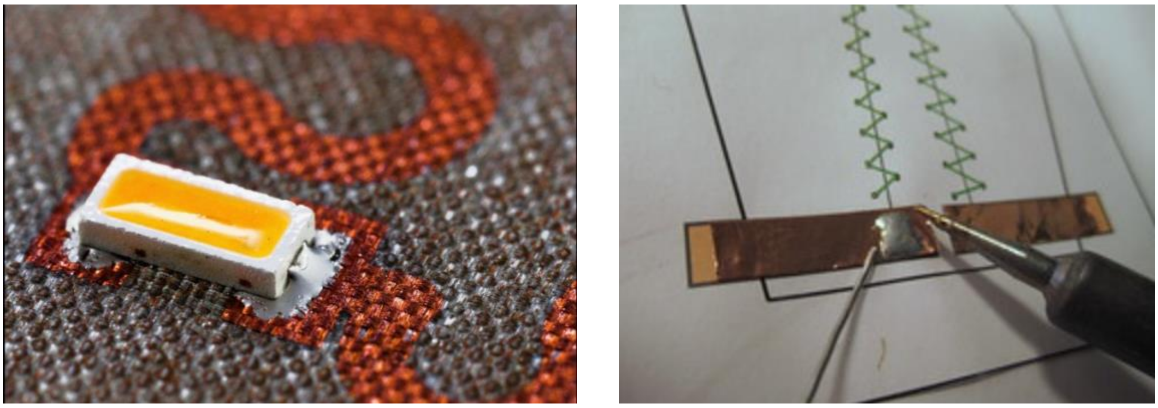


Figure 10. From left to right.

Led module soldered on conductive pattern. (Source: Integration of electronics onto textiles, re-fream.eu)

Soldering of metal strip to conductive yarn pattern. (Source: kobakant.at)

Soldering of components was found to be viable method of fabricating e-textile circuits. However, some functional challenges were due to excessive backstitching over the traces and thread trimming. These problems led to possible risks of electrical shorts. [7]

c) <u>Welding</u>

Welding is a process similar to soldering however in soldering the metals are heated, but never melted, to be bonded by the third alloy.
We refer of welding as a joining process that creates a continuity of materials by heating or pressure, and with or without any additional joining materials.

Various welding methods exist, most commonly used on an industrial scale since the whole process can easily be automated. In the paper, *Contacting Smart Textiles by Welding of Electronics to Textiles,* they evaluate various welding processes for the application of sensors and actuators in textiles and consider that Ultrasonic welding, Laser welding and Resistance welding offer the greatest potential for automation. [10]

On this research it's shown how Ultrasonic welding has a good chance of establishing itself in the field for the development of e-textiles, because there is no danger for the surrounding textile being damaged by the joining process and very reliable contact points are created.

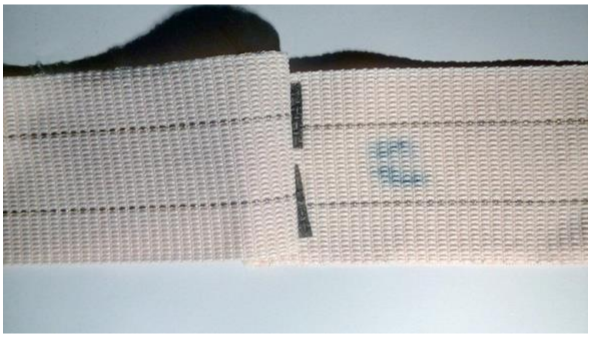


Figure 11. Ultrasonic welding of narrow fabrics with conductive yarns

(Source: texprocess-blog.com)

On another earlier research, *The use of hot air welding technologies for manufacturing e-textile transmission lines,* they investigated the potential possibilities for obtaining textile transmission lines by incorporating conductive yarns into fabrics through a hot air welding process. [11]

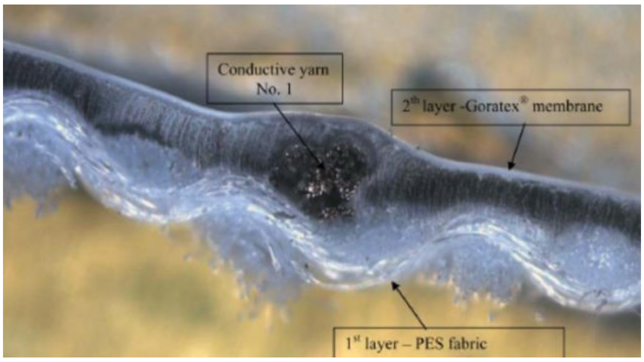


Figure 12. Detail of cross section of hot welded seam with conductive yarn (Source: [11])

The use of hot air welding technology was proven to be a convenient technique for constructing reliable and durable transmission lines while preserving the textile aspects, thus representing a great challenge and significant contribution to the e-textile research arena. However, hot air sealing parameters need to be carefully controlled to avoid excessive melting and polymer degradation. [11]

Overall, the pros of welded joints is that they have very high mechanical strength. Furthermore, welding processes are also used for coatings or remitting. In addition, some welding processes do not need any filler material and the whole process has very low running costs. [10]

However, when having to work with metals, because of various issues related to this method, welding is not a commonly used joining technology in e-textiles. As we can see the main issue to this is the high temperature needed that may disrupt the textile structure of cause damage to other conductive elements of the system.

d) Adhesives

Several types of adhesive bonding are used in electronics, the most common in e-textiles being:

- non-conductive adhesive bonding (NCA),
- isotropic electrically conductive adhesives (ICA),
- anisotropic conductive adhesives (ACA). [8]

Adhesive bonding has the advantage of lower curing temperatures than soldering requires, making it suitable for a wider range of fabric applications. Conductive adhesives also have the potential to replace lead-based solder with more environmentally friendly alternatives. The trade-off is that these typically have higher contact resistance and lower mechanical strength than soldered connections, but future developments in material science may change this. [8]

It is important to note that all of the upcoming methods can be done on an industrial scale utilizing specially made machine. However, such high precision processes aren't necessary for every textile application, [12] but can provide a technological development since the process and its variables (temperature, pressure, etc.) can be controlled more thoroughly.

In NCA, a layer of thermoplastic adhesive is applied on the parts wanted to be in contact. Successively, the assembly is pressed together to displace the adhesive out of the contacting area and then the part is cured at the desired temperature.
One advantage of a thermoplastic adhesive is that it can be remelted and thus such contacts are potentially repairable and components potentially reusable. An important second advantage emerges if the adhesive for the bonding process is identical with the thermoplastic insulator material on the textile circuit: after bonding, the insulator forms an integral part of the bonding adhesive, i.e. there will not be an additional interface which could jeopardize reliability. [13]

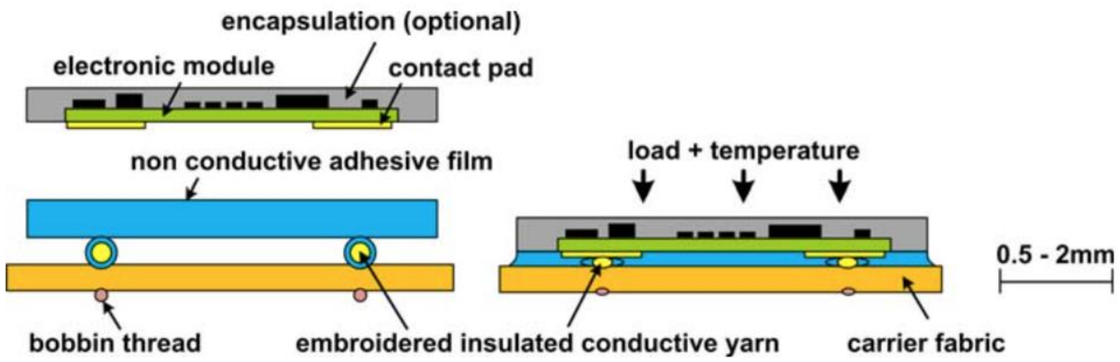


Figure 13. NCA bonding process adapted to e-textiles (Source: [13])

Pros of this method is that the choice of substrate and the choice of electronic component are not affected by each other, as to say, it's a versatile way of connecting to contacts.
It is a reliable technology for connecting highly conductive insulated (as they are insulated by a thermoplastic) and also non-insulated ones. Furthermore, it blends in well with the current manufacturing reality which is that electronics and textiles are two, much separated industries. The approach keeps textile processes and electronics processes separated until the very last step which is the bonding one. [13]

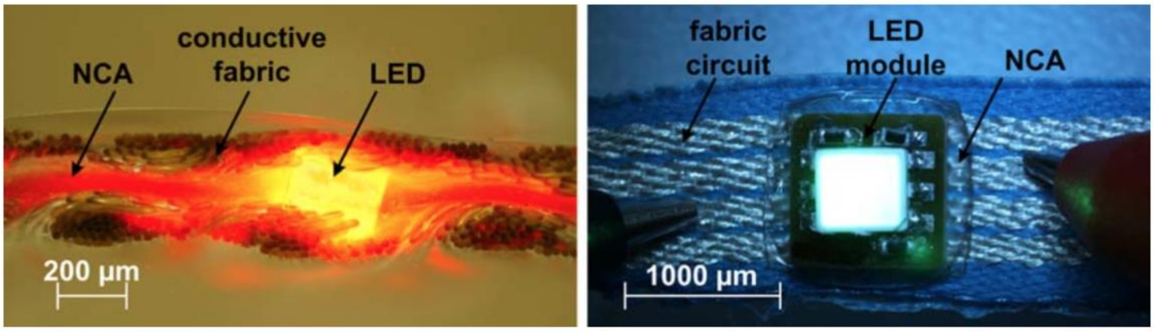


Figure 14. Two Led sources integrated into textiles using NCA bonded contacts. (Source: [13])

Both ICA and ACA are ECAs use conductive adhesives to allow the connection of the contacts, the main difference being that ICA bonding involves adding a conductive filler to an adhesive material and ACA have a much lower concentration of conductive filler.

This means that when ACA is sandwiched between two contacts stacked on top of each other it conducts electricity in the vertical direction, but the concentration of conductive particles is not high enough to conduct in the x-y plane. This makes it suitable for fine pitch connectors, and means it is sometimes called z-axis tape/film, but also means it has higher contact resistance than ICA. In the following figure, the differences between both methods can easily be seen. [8]

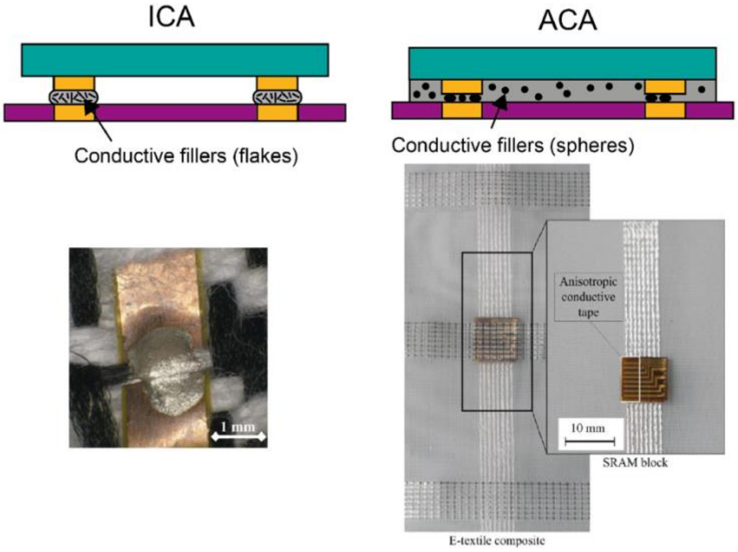


Figure 15. Detailed illustration of ICA and ACA methods. (Source: [8])

ECAs can be synthesized by employing two methods where conductive fillers are dispersed within an insulating polymer matrix, and where inherently conductive polymers are blended with an insulating polymer matrix. Conductive fillers can include metal fillers, carbon fillers, ceramic materials and metal-coated fillers and inherently conductive polymers cover poly-pyrroles, polyanilines, polythiophenes, polyacetylenes, etc. which can be mixed with an insulating matrix to enhance the latter's electro-conductibility. [14]

Both methods can be employed in e-textiles applications including die fitting, solderless interconnections, heat dissipation, etc. More in detail ICAs possess numerous applications such as electrical interconnection for those substrates where soldering isn't possible like ceramics, plastics, etc. and replacement of solder on thermally sensitive components, so they are frequently called "polymer solders".

ACAs have applications which include flat panel displays containing film ACAs, flip-chip on glass, smart cards and flip-chip board, where application of solder isn't possible due to heat sensitivity of the substrates. They can also be used for high adhesive strength applications where electrical conductivity isn't important. [14]

Cons of ECAs are related to limitations such as lower conductivity than solder methods, sensitivity to the type and quality of component and board metallization, requiring longer time to cure, and possessing lower durability in various climatic environments. Thermal stress could also be caused by coefficient of thermal expansion mismatch between the conductive textile and electrical component. [7]

e) Crimping

In situations where soldering and welding cannot be applied due to heat, brittleness and stress, mechanical gripping can be the correct solution to create connections.

In electronics, crimping is the process of deforming a metal barrel around a conductor (usually a wire) to form a gas-tight, permanent connection. Sometimes called cold welding, it is a method commonly used in the automotive industry. For clarity, crimping is a fixed joining technology, but there are many (detachable) connector products which may be described as crimp connectors, but we will see in the next chapter. These usually use crimp terminals to create permanent contact with a flexible substrate at one end, and have a connector such as pin headers at the other end, as seen in figure 16. [8]

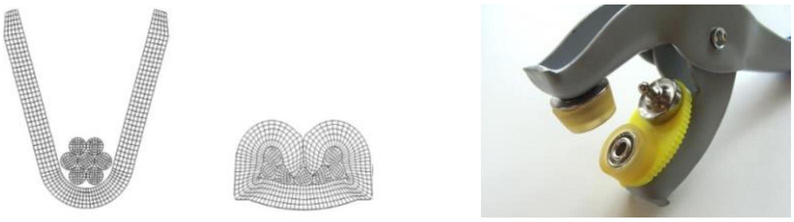


Figure 16. Open crimb barrel and wire before and after crimping (left) [15].

Standard snap button crimping tool (right) (Source: Google)

This method opens opportunities to the manufacturing of e-textiles as it uses standard manufacturing technologies as well as a robust, low-cost, and low temperature interconnection technology. Their advantages are their high reliability and easy and fast processing. Being able to use this technology for smart textiles systems would offer the possibility to use a low-cost technology and allow competitive prices. Work has been done in both fields that are smart-textiles and crimp technology.
However, the combination of those two is relatively new. [15]

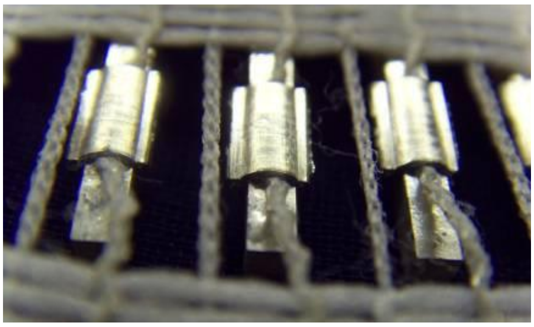


Figure 17. Crimp contacts for seat pressure sensor. (Source: [15])

2.5.2 Detachable Connection Techniques

a) <u>Snap connections</u>

Snap connection, fasteners, buttons, etc. consist of two parts attaching to each other. There is a spring embedded in the female button to clip and hold the male button when engaged. This spring mechanism forms solid and reproducible mechanical and electrical connections. [16] They are currently one of the most used methods of connection for e-textiles because of their low cost, ability to be replaced or repurposed and user-friendliness.

However, despite their popularity, limited research has been carried out on the suitability of snap fasteners as electronic connectors, since standards do exist only on their mechanical resistance when used as garment fasteners. [8]

Figure 18. Common snap button (Source: Google)

To attach to fabrics and textiles, there are four holes on the base of both male and female buttons for sewing propose, as seen in the figure above. The mechanical compatibility of these buttons with textile materials and most electronics is clear, since they can be sewed or soldered on them respectively. [16]

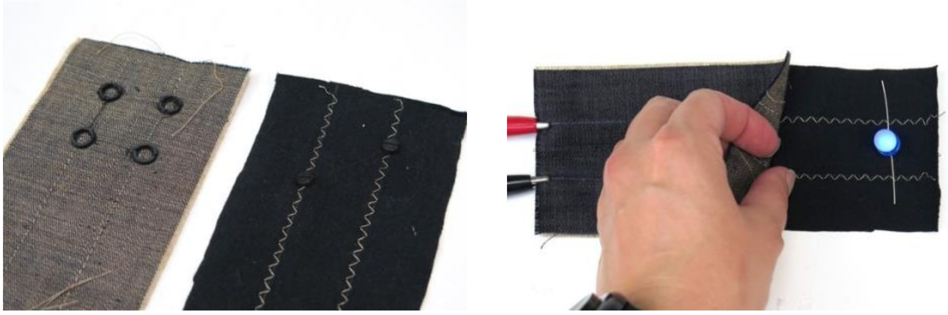


Figure 19. 3D Printed conductive snap buttons on fabric. (Source: [17])

Experimental prototypes are developed lately thanks to the advances in additive technology, such as 3D printing directly onto fabric using conductive filament (Figure 19), snaps with a flat base, which can be soldered or glued in place, or snaps with a crimp terminal for attachment to wire, are also available. [8]

b) Pogo Pins and Magnets

Pogo pins are used in rigid electronics applications such as connecting a camera body to a lens, or for charging, as seen in many laptop chargers.
A pogo pin, consists of an encased spring-loaded pin that is designed to mate with a flat contact pad as we can see in the figure below. [8]

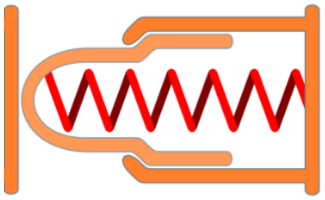


Figure 20. Cross section of Pogo Pin in contact with a pad. (Source: Google)

They are commonly used to establish electrical contact between two objects whose relative mechanical position cannot be well-controlled, or for a connector system where there will be high numbers of mating/unmating cycles.

The connection is kept firm by mechanical methods such as the use of magnets, snaps or clips. In case of these last two, external pressure is required to bring the two in contact with each other to make an electrical connection. One known example is the smart sock made by Sensoria™, where a Bluetooth module with pogo pins is connected to the garment using a press-fit plastic enclosure. [18] In the image below we can observe the contact pads and the module housing (131) on the left figure.

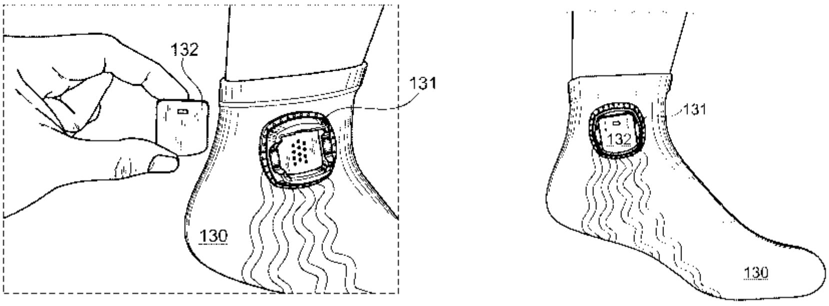


Figure 21. Sensoria smart sock Bluetooth module (Source: Google Patent)

As for the magnets, as well as being used for alignment, there are some instances where they can behave as electrical contacts themselves or also used as a temporary connector in prototyping of e-textiles.
In "*Reversible contacting of smart textiles with adhesive bonded magnets*", it's studied how to use adhesive bonded magnets as reversible electrical contacting method for smart textile applications. The adhesive bonding protects the conductive textile material from damage and allows an excellent electrical contact. Magnets are electrically conductive and have the ability to come together without external forces while allowing an easy separation again. [19]

Magnetic force must be so high that it can carry electrical components and can withstand everyday pulling load. The surface of the magnet is of greater importance, because adhesive bonding ability, electrical resistance, corrosion and solderability are essentially surface-dependent factors. Neodymium magnets are the most commonly chosen, because they are available in different shapes and sizes, have relatively high bond strength and low costs. [19] Lastly, magnets tend to not damage the surface of the textiles.

c) Hook and Loop Fasteners, Zippers and Buttons

The appeal of these types of connectors lies in the fact that they blend functional circuitry with features users expect to see in a garment. They enable e-textile clothing to look and feel like clothing, rather than electronic devices. [8]

The connection made by using hook and loop fasteners, are also known as their brand name, Velcro. The only difference in the one used for e-textiles is that it is made electrically conductive by coating the small hooks and loops, that make it up, with a conductive metal, usually silver since it's high conductivity. [20]

This method can be used as a conductive fastener in many ways. The conductive part of the Hook and Loop makes it a great electric switch, it works for power distribution and also data transmission. When both parts are not in contact the circuit is "open", and when they are the circuit is "closed", allowing current to flow, as seen in the figure below.

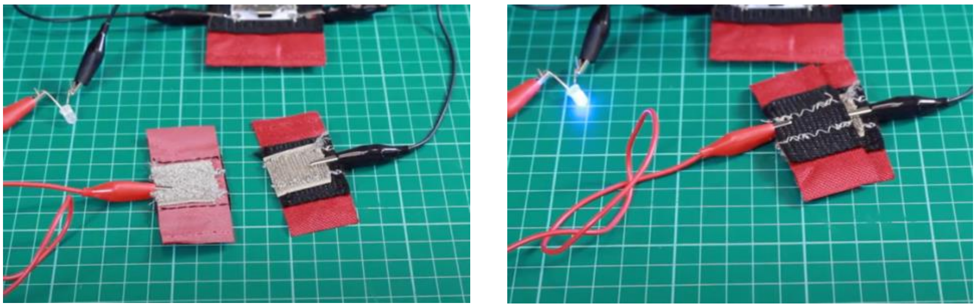


Figure 22. Operating a hook and loop switch. (Source: [21])

Hook and Loop connections are durable, capable of keeping its conductivity for a high number of working cycles. Nowadays, it's applications are mostly related to work environments, where these strips are used to protect people or equipment from high intensity electromagnetic fields by acting as grounding strips, or in applications where a high amount of vibration is present, such as automotive ones. [20,8]

However, in e-textiles this connection technique is still being investigated since the contact resistance of conductive Velcro is inconsistent, as the number of hooks and loops coming into contact with each other varies when the two parts are connected, and that the conductive coating tends to peel off quickly. [8]

Zippers and buttons, like hook and loop fasteners, are also textile closure mechanism that are starting to be adapted for their use in e-textiles.

Figure 23. Conductive zipper (Source: [22])

Using zippers in e-textiles (Figure 23), new application possibilities be found due to the electrical conductivity values that are more stable when comparing them with the ones that a Velcro connection could give. Closing the zipper connects two electrical contacts present on either side of the object itself, with a strong and reliable connection.

Button connectors (Figure 24), work on the principle of a metal button making contact with conductive thread sewn around the buttonhole. These do not appear as popular as zippers, likely because the connection created is looser and therefore less reliable. [8]

Figure 24. Detail of a e-textile button. (Source: [23])

d) Flexible electronic connectors

As a newly developed technology, flexible and stretchable electronics are emerging and achieving a great variety of applications. Because the material can be compressed, stretched, twisted, and have the flexibility to allow complex patterns, there is a high demand for its application in e-textiles. [7]

A wide range of connectors exist for use with flexible electronics; both flexible printed circuits (FPC) and flexible flat cables (FFC), usually to connect a flexible module to a rigid PCB. [8] This can be achieved, because the conductive elements are deposited onto stretchable substrates, or also by embedding them completely, in a stretchable material such as sheets of plastic or stretchable alloy foils and silicones. [7]

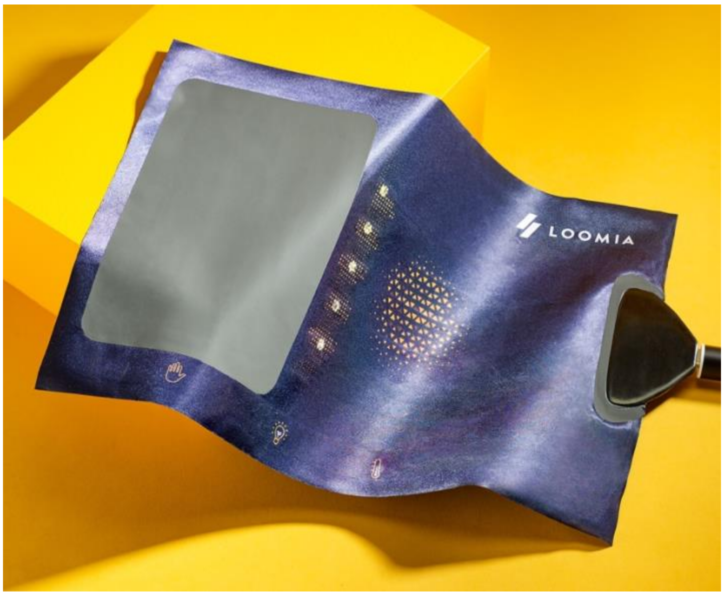


Figure 25. Soft circuit system made by Loomia™ (Source: loomia.com)

These kinds of connections are being developed for their imperceptibleness to the user and because they won't affect the wearability and comfort of the textile. [24]
On the other hand, the circuits must be robust enough to withstand the stress to which our everyday clothes are subjected, like wrinkling or a number of washing cycles.

The limitation of flexible and stretchable electronics is that the device performance may be lower than conventional rigid electronics. Flexible and stretchable electronics may not be able to compete with rigid electronics device performances because when the substrate is changed from rigid silicon wafer to plastics, the device reliability would be decreased significantly. [7] However, as seen in "*A stretchable knitted interconnect for three-dimensional curvilinear surfaces"* (Figure 26), a super fine enameled metal wire has been integrated into an elastic knitted fabric substrate. The interconnection exhibited satisfactory conductivity, large stretchability and durability. [25]

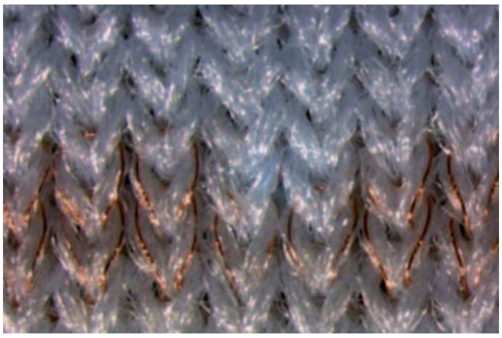


Figure 26. Enameled metal wire integrated on knitting structure. (Source: [25])

Other concerns are that there have not yet been many long-term endurance and safety tests. In addition, the effects of electrical resistance property of stretchable electronics, the capacity, and inductance behavior of stretchable electronics also changed due to the stretchable property. [7]

e) Pin headers and USB connections

Pin headers are commonly used in rigid electronics for stacking PCBs or connecting sensors or flexible circuit modules to a rigid PCB. In e-textiles, they have been used to interface between soft circuits and rigid modules and can be soldered to conductive fabric or to solderable conductive thread. They are available as long strips that can be cut to size and are convenient for interfacing with microcontrollers such as the Arduino, which usually has female headers soldered to its pins. This method uses crimp-style connectors on one end that make a fixed connection with fabric (Figure 27) or flexible plastic substrates, and a male or female pin header contact at the other end. [8]

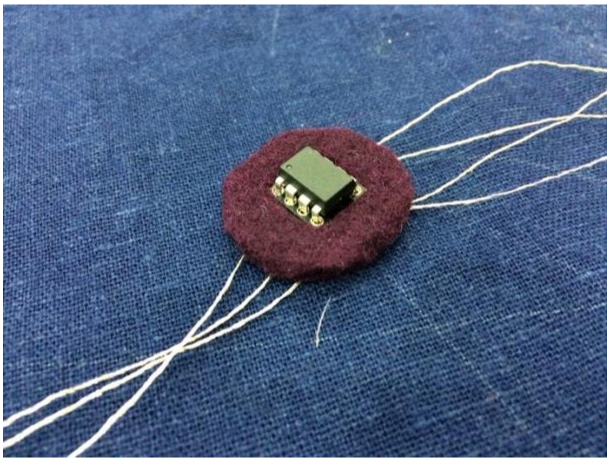


Figure 27. Felted dip socket. (Source: [23])

To understand better the methodology behind this connection methods, I believe that the article of Kristina Panos, "*Get you an E-textiles sensors that can do both"* explains it perfectly. A software developer has discovered that any e-textile project requiring more than a few connections must need some kind of textile-friendly multi-point connector. Through trial and error, he designed a robust solution for use with an embroidery machine. [26] The wires are made from conductive thread and soldered to a row of male header pins to make the transition out of fiber space, as you can see in Figure 28.

Figure 28. Row of male header pins embedded onto a textile (Source: [26])

You can see the connector works as a capacitive multi-touch. It does so because two pieces of fabric are stacked, each with a wire bus made of conductive threads, with the traces at right angles. Both sensors are wired and a sensor matrix is created. In this way, as something approaches the fabric, the capacitance sensors show graphs on a display previously connected as seen in Figure 29. [26]

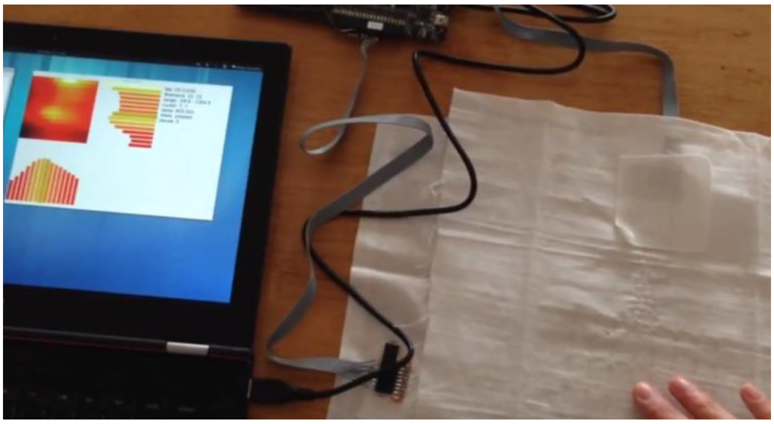


Figure 29. Capacitance sensor matrix displayed in action (Source: [26])

f) <u>Wireless connections</u>

Not a form of physical connection, but a well-established method for transmitting power or data in electronics. In this group we find technologies such as Bluetooth and near field communication (NFC) for communication between devices, textile integrated antennas, charging of power units using inductive coupling, etc. All these connection methods are among the pillar technologies for developing e-textiles wearable connected to the IOT. [27]

Inductive coupling, for example, has been proposed as a method to enable 3D integration in integrated circuit technology, or as a connector for smart glasses, where power and data must be transmitted across hinges. [8]
On the other hand, in *"Smart Textiles: Technology and Wireless System Network Applications"* the viability of a radiofrequency-based wireless networking technology that interconnects tiny nodes of sensor and/or actuator allocated in, near and around a human body, is studied, as shown in Figure 30.

A WBAN identifies the wireless technology mainly dedicated to the human body. This field is an interdisciplinary area, which allows inexpensive and continuous monitoring with real-time wireless updates. [28]

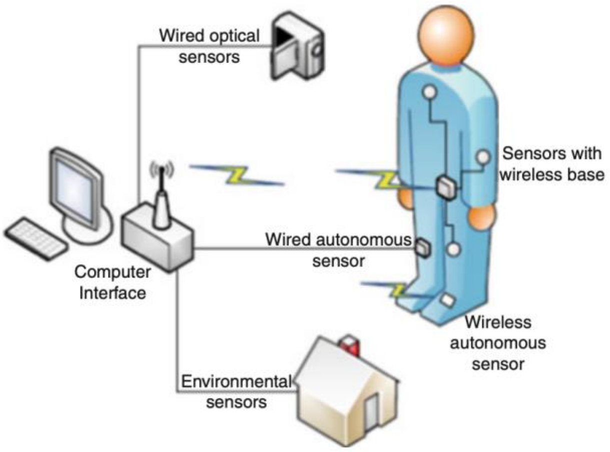


Figure 30. A structure showing a complete set of sensors today available for monitoring movement (Source: [28])

More specifically, a WBAN relies on the feasible integration of very small intelligent sensors onto a textile substrate placed on the human body by means of the wearability of an E-textile garment, with the aim of providing a comfortable interface that does not impair normal activities. The sensors will collect several physiological signs in order to monitor the patient's health status. [28]

g) <u>Connectors for prototyping and testing</u>

Current e-textile tools for rapid prototyping either require makers to use custom components that will likely not be used in the end product, or they limit creativity by constraining makers to pre-designed forms. The need for rapid prototyping tools for e-textiles is highlighted by the difficulties associated with debugging threaded circuitry. [29]

Upon finding a project does not perform as intended, e-textile makers face the disheartening task of disassembling their work to isolate and identify bugs. Once they find a bug and attempt a fix, the maker must then restitch portions of their project in order to test it. The typical novice strategy of trial-and-error is time intensive and frustrating with the regular unstitching and restitching of circuits. [8, 29]

Threadboard, Figure 31, is a e-textile prototyping kit that uses an array of magnets to route conductive elements and connect them to components. [29] It's a novel way of prototyping e-textile projects, and facilitates the whole process because the materials that will be used in the finished product can be used since the beginning.

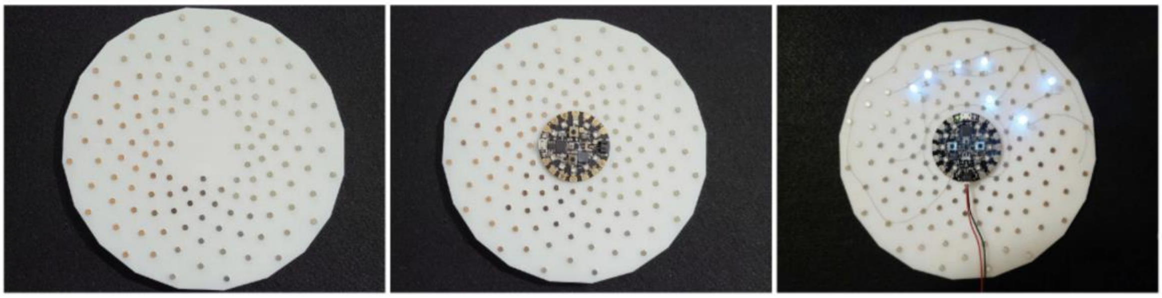


Figure 31. Threadboard with Adafruit playground classic. (Source: [29])

Another project, presented at the International Conference on the Challenges, Opportunities, Innovations and Applications in Electronic Textiles, is based on a Modular E-Textile toolkit for prototyping.

The modular, Arduino-compatible toolkit incorporates various sensors, control and communication modules which are all presented below in Table 1. After prototyping, the toolkit modules can be directly transferred to reliable industrial integration using advanced machinery. This allows users to combine different electronic functionalities into one working prototype with minimum effort. [30]

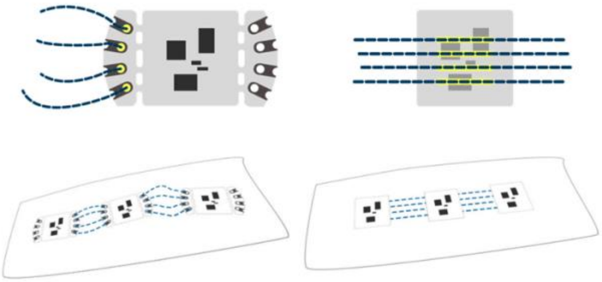


Figure 32. Illustration of toolkit with options for sewing at prototyping stage (left), and using adhesive bonding on conductive threads at manufacturing stage (right). (Source: [30])

Textile Prototyping Lab's e-textile kit takes a slightly different approach, with rigid PCB modules with sewable contacts for making garment prototypes. For higher volume production, these contacts can be removed, reducing the overall size of the module, and components connected to conductive fibers using NCA bonding instead, [8] enabling a mechanically and electrically reliable connection with low contact resistances. [30]

Table 1. Textile toolkit module overview. (Source: [30])

Module Name	Description	Electric Specification
main control unit	Main controller board	Cortex-M0 Microcontroller/USB-Interface/User LED
light emitting diodes (LED) module	Programmable RGB LED	Red/Green/Blue
inertial measurement unit (IMU) module	Inertial sensor	Accelerometer/Gyroscope/Magnetometer (10 bit)
analog-to-digital (ADC) module	6× Analog-to-digital converter	6 Channel/8 bit
temperature/humidity (T/H) module	Temperature and humidity sensors	Humidity accuracy ±2%/temp accuracy ±0.2%
bus expander	Connects additional I^{2}C sensors	2-way switch

3 Discussion

In this chapter we will make a resume of all the connection methods seen before, trying to explain how to choose a technique, based on the desired application.
Later on, an analysis of reliability of said connection methods will be made, focusing either on the properties and opportunities or the issues and challenges.
To conclude, an analysis of the environmental aspects and sustainability of e-textiles will be made.

3.1 Selecting a Connection Technique

Choosing the right connection method, is a matter of studying what is needed for the intended application.
E-textiles, are constantly creating new challenges in developing joining connection, since the users demands functional electrical connections and at the same time all the comforts given by a fabric.

As said in *“Joining of wearable electronic components”*, the most important adoption factors are convenience and compatibility, and the least important are perceived social prestige and observability. As for performance, consumers will not purchase products that degrade quickly or fail. The major concerns here are robustness in wear and washing fastness. The product will experience numerous stresses and strains in use, and the connections may start to weaken leading to impaired functionalities. [31]

The author summarizes, in a few pages, useful criteria for choosing a joining technology for e-textiles: physical strength, electrical reliability, ease of attachment, repeatable re-attachment, aesthetics, size, comfort, cost, and availability. [8]

As for manufacturing, many wearable electronic products bear the marks of inadequate new product development and the ‘limited editions’ should be regarded as prototypes rather than commercial products. [31]

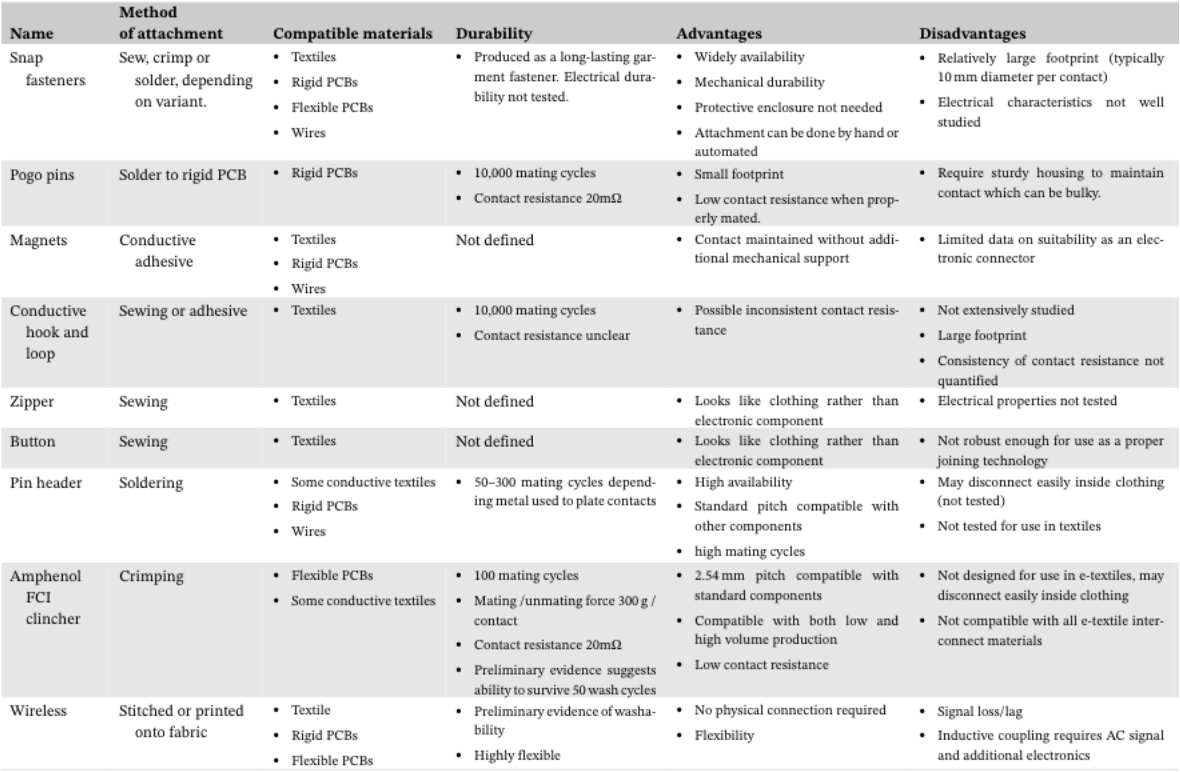
To this list, it is necessary to add:
a) what kind of electrical signal is being transmitted, that is, signal or power;
b) the stage of development of the product, as a joining technology that requires custom machinery will not be suitable for a one-off prototype, but one that is time-consuming to install will not suit a product ready for batch manufacturing;
c) the limitations of the fabric used in the e-textile garment, as some fabrics will require joining technologies that can be done at low temperature or room temperature. [8]

The tables 2 and 3, help resume all the information mentioned until know, related to the characteristics, advantages and disadvantages of each method.

Table 2. Comparison of fixed joining technologies (Source: [8])

Name	Method of attachment	Compatible with	Durability	Advantages	Disadvantages
Machine embroidered conductive thread	Embroidery machine. For some conductive threads, or more complex designs, specialist machinery required.	• Textile • Rigid PCB with sewable pads • Flexible PCB • Wire	• Can be damaged by temperature (affecting contact resistance) • Conductive coating can flake off during washing	• Compatible with most textiles • Scalable with right equipment • Flexible • Looks and feels like textile	• Durability is not well studied • Temperature and washing can relax connection • Specialized machinery • Not suitable for joining discrete electronic components directly • Some conductive threads not compatible with standard embroidery machines
Hand stitched conductive thread	Hand sewing tools (needle and conductive thread)	• Textile • Rigid PCB with appropriate sewable pads • Flexible PCB • Wire	• Preliminary washing tests show continued function after washing at 20 °C	• Does not require specialized equipment or technical knowledge	• Reliability not well documented, but expected to be lower than machine stitching • Time consuming, therefore not suitable for manufacturing at scale
Soldering	Soldering equipment, heat. Typically above 250 °C, low temperature options still require >150 °C	• Rigid PCB • Metal wire • Limited conductive textiles • Some conductive inks • Standard components	• Strong electrical connection • Not flexible, requires protection against breakage at interfaces between solder joints and flexible substrates.	• Compatible with standard electronics processes • High availability • Adaptable to both high and low volume production	• High application temperature even with low temperature solder paste • Not compatible with many conductive textiles • Not flexible
Welding	Heat (produced as a by-product) Welding equipment.	• Some conductive textiles • Metal wires	• Contact resistance <1 Ohm • Requires encapsulation to survive washing	• Compatible with wider range of conductive threads than soldering (e.g., stainless steel thread)	• High temperature can damage delicate textiles and some printed conductive tracks on textiles
Crimping and rivets	Crimping tool (manually operated or automated)	Depending on product: • Textiles • Rigid PCBs • Flexible PCBs • Wires	• Preliminary evidence of washability • Supports repeated connection/disconnection	• Room temperature application • Compatible with both high and low volume production	• Not compatible with all types of e-textile material • Some types of crimp connector do not survive washing
Adhesives: NCA	Heat and pressure, supplied by die bonder or custom equipment.	• Bonding rigid modules or components to conductive textiles or wires	• Resistant to temperature and humidity cycling	• Demonstrated to work with 1.27 mm pitch components	• Requires die bonder or custom equipment • High bonding temperature (197 °C)
Adhesives: ICA	Some variants are heat curable, others cure at room temperature. Applied manually or dispensed by machine.	• Textiles • Rigid PCBs • Flexible PCBs • Standard components	• Encapsulation is required to prevent breaking	• Lower curing temperature than soldering • Compatible with printed conductive tracks	• More mechanically brittle than soldering • Higher contact resistance than soldering • Absorbs moisture if not encapsulated
Adhesives: ACA	Can be cured at room temperature. Heat or pressure reduce cure time. Applied manually or dispensed by machine.	• Textiles • Rigid PCBs • Flexible PCBs • Surface mount components	• Mechanically strong but electrical connection unreliable under strain	• Suitable for components with very fine pitch • Low curing temperature	• High contact resistance relative to ICA or soldering • Inconsistent contact resistance under strain

Table 3. Comparison of detachable joining technologies (Source: [8])



Name	Method of attachment	Compatible materials	Durability	Advantages	Disadvantages
Snap fasteners	Sew, crimp or solder, depending on variant.	• Textiles • Rigid PCBs • Flexible PCBs • Wires	• Produced as a long-lasting garment fastener. Electrical durability not tested.	• Widely availability • Mechanical durability • Protective enclosure not needed • Attachment can be done by hand or automated	• Relatively large footprint (typically 10 mm diameter per contact) • Electrical characteristics not well studied
Pogo pins	Solder to rigid PCB	• Rigid PCBs	• 10,000 mating cycles • Contact resistance 20mΩ	• Small footprint • Low contact resistance when properly mated.	• Require sturdy housing to maintain contact which can be bulky.
Magnets	Conductive adhesive	• Textiles • Rigid PCBs • Wires	Not defined	• Contact maintained without additional mechanical support	• Limited data on suitability as an electronic connector
Conductive hook and loop	Sewing or adhesive	• Textiles	• 10,000 mating cycles • Contact resistance unclear	• Possible inconsistent contact resistance	• Not extensively studied • Large footprint • Consistency of contact resistance not quantified
Zipper	Sewing	• Textiles	Not defined	• Looks like clothing rather than electronic component	• Electrical properties not tested
Button	Sewing	• Textiles	Not defined	• Looks like clothing rather than electronic component	• Not robust enough for use as a proper joining technology
Pin header	Soldering	• Some conductive textiles • Rigid PCBs • Wires	• 50–300 mating cycles depending metal used to plate contacts	• High availability • Standard pitch compatible with other components • high mating cycles	• May disconnect easily inside clothing (not tested) • Not tested for use in textiles
Amphenol FCI clincher	Crimping	• Flexible PCBs • Some conductive textiles	• 100 mating cycles • Mating /unmating force 300 g / contact • Contact resistance 20mΩ • Preliminary evidence suggests ability to survive 50 wash cycles	• 2.54 mm pitch compatible with standard components • Compatible with both low and high volume production • Low contact resistance	• Not designed for use in e-textiles, may disconnect easily inside clothing • Not compatible with all e-textile interconnect materials
Wireless	Stitched or printed onto fabric	• Textile • Rigid PCBs • Flexible PCBs	• Preliminary evidence of washability • Highly flexible	• No physical connection required • Flexibility	• Signal loss/lag • Inductive coupling requires AC signal and additional electronics

It is also significant to note that, as there are not standardized tests for e-textiles to analyze their qualitative and quantitative behavior, a comparison cannot be done with certainty. However, in the next years, more organizations will develop e-textiles standards, and it will be easier to collect all of the information needed.

3.2 E-textiles Properties and Opportunities

In the last decade, e-textile research and development have expanded the function of clothing beyond basic physical protection. Now, we begin to see these textiles as potential interfaces that aid their users, depending on the desired application. These electronic textiles (e-textiles or wearable textiles) have both electronic functionality and textile properties.

One possible future scenario for e-textiles depends on the manufacturing advances in electronics and textiles. New hybrid structures will include more electronic functionality at the fiber level, until we eventually end up with electronic textiles where all advanced electronic functions are all embedded in the textile fibers. [33]
Improvements will be done on already existing technologies, and wireless, waterproof and environment resistant systems will be developed.
More e-textile and e-textiles prototyping kits will find their way in each household. The commercialization of these smart objects, will help people on their everyday life.

Researchers and developers, are constantly innovating trying to create better flexible, deformable, stretchable, and durable conductive textiles. The appearance of these objects most of the time will be determined by the need of manufacture.
Creating simple and reliable connectors for integrating electronic components, or creating washable, flexible and highly stretchable, durable, and reliable electronic component is now possible and it is within everyone's reach. [7]

As for conductors, promising and more attractive solutions are beginning with the development of more wear resistant material such as ionomer and carbon nano-tube blends. The same development trend also enables improved color and appearance for the textiles. Further progress is towards the creation of entirely new, superconductive and performing fiber materials based on the new nanofibers and carbon nano-tubes. [9]

Today, the advances of Industry 4.0, have also welcomed the world of e-textiles in the concept of Internet of Things (IOT). In this way these products will be viewed as an interface connecting humans to other numerous objects with digital functionalities, making possible faster connections between users and textiles.

Surely, the next steps in e-textiles development, will be to fulfill the user's needs for interactivity, developing easier connection methods and easy to use interfaces for processing the information given by these e-textiles. There will be more potential applications and from a research point of view, it will be easier to find information related to this topic and a new generation of e-textile will begin to take shape.

3.3 E-textiles Issues and Challenges

The vast majority of challenges when it comes to electrically conductive fabrics are strictly related to the manufacturing of said smart textiles, their long-term usage and the overall user opinion and relationship with the product.

As for manufacturing, the interaction between the soft and flexible fabrics and the rigid electrical components is one of the most common problems when developing e-textiles. Most of the textile developed for the applications previously seen in this study, are constantly deformed by movement or affected by the environment.

In addition, this constant movement paired with the integration of conductive material leads to a buildup of static electricity that may short the electrical components present in the system. However, Anti-static properties can be conferred by coating fibers with metallized films, intrinsically conductive polymers, polyelectrolytes, or by low molecular weight anti-statics in solution. [7]

Current advances in textile technologies made possible the development of smaller and safer electronics through nanotechnology, making wearable systems more feasible and efficient [34] but at the same time more affected by these threats on a daily basis.

Related to textile structures, 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 yarns there will be an electrical contact with an associated contact resistance (The existence of these contact resistances is sometimes used to develop sensors).

When thinking about to long-term usage, consistent performance through use and time is the number one challenge.

One of the most common problems is related to washing fastness. In particular, the performances of e-textiles, can be degraded because of the mechanical deformations induced during the washing cycles. Moreover, the hardness of water and the presence of washing detergent can shorten the life of metal connectors.

In addition, one of the problems is the absence of standardized methods and regulations for testing the washability of e-textiles. [7]

In Figure 33, we can observe a way to simulate and predict the behavior of e-textiles during washing presented in the research "*Smart E-Textile Systems: A Review for Healthcare Applications*". The proposed idea works predicting the washing damages caused by specific stresses. As a result, the actual washing process can be replaced by mechanical tests, and the reliability of the e-textile components can be tested at each step during the manufacturing process of the e-textile systems. [36]

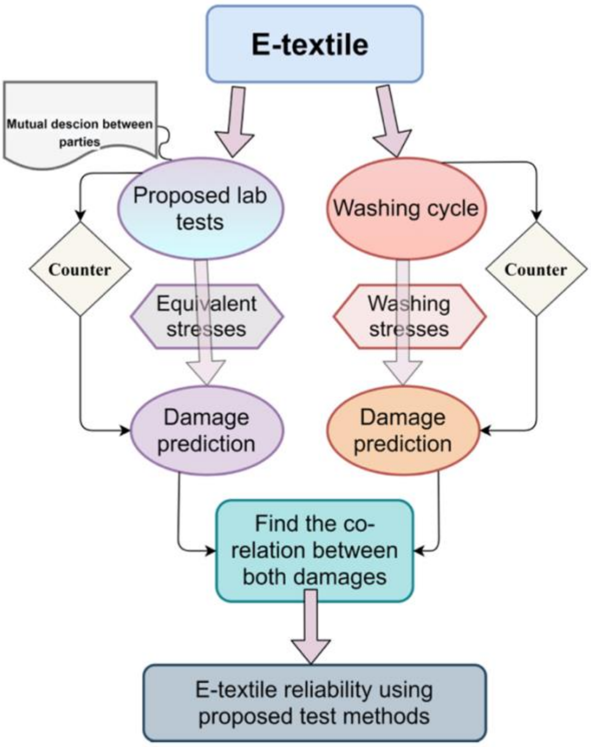


Figure 33. Washing prediction protocol (Source: [36])

Temperature is also one of the characteristics to be taken into account when working with elements that generate heat when in use. [35] Heat dissipation, distance between components and the overall characteristics of the textile substrate are all parameters to be taken into account to avoid shortening the life span of the e-textile.

As for user experience, the market for wearable electronics continues to be uncertain, as most of its products are launched as prototypes or limited editions.
At the same time, early e-textile researchers, developers, and inventors have various patents in these areas, which developed a considerable entry barrier for newcomers and have equally frustrated cost-reduction and product-improvement efforts by the existing research. [7]

Another key challenge in e-textile joining technologies for user experience is balancing the trade-off between flexibility and reliability: many joining technologies rely on rigidity to ensure reliability, whereas garments must be flexible, with minimal rigid elements that may even cause injuries in the case of an impact.

3.4 Sustainability and Environmental considerations

The impact on the environment of e-textile can be quite significant. Developing and creating these products, involves the use of a lot of energy and lots of different materials that on the long-term will be quite difficult to repair or recycle. If we add to this, the lack of durability analyzed in the previous chapter, we can affirm that e-textiles may have negative consequences for sustainability if biocompatibility and environmental safety of the materials is not taken into account. [8, 37]

Designing a sustainable e-textile and its application, means that it will have a positive impact on both the environment and human beings. That's the reason why there are various strategies or methodologies for assessing the impact of a product.

One of these possible strategies, to develop sustainable e-textiles, is through Eco-design. This is both a principle and an approach that takes into account the integration of environmental aspects into technology development and product design. The final aim of eco-design is to reduce adverse environmental impacts throughout a product's lifecycle. [38]

From an eco-design point of view, and focusing on the first life cycle phase (material extraction) the trend is to move towards smaller parts and less material used for creating them. As the component size decreases and their efficiency increases, the same functionality can be achieved with use of less material. Also, the recent developments in conductive fiber materials and the shift towards bio based and non-metallic solutions for e-textiles, do fit well with the eco-design approach. [39]

With reference to the end-of-life phase of e-textiles two main topics come to our attention, circularity and waste processing.
As explained in "*Review of the end-of-life solutions in electronics-based smart textiles*", in e-textile products, the level of integration has a remarkable influence on the materials' recyclability and the end-of-life solutions of the product. As a result, e-textiles require specified end-of-life treatment methods and standardized waste processing. It is vital to tackle the topic early to avoid mistakes made in textile waste management. End of product lifetime or EOL (End-of-Life) of the product is the point when it is not usable anymore or just not needed by the user anymore. Thus, it should be reused, recycled, remanufactured or disposed of (landfill or incineration). [40]

Further, development should focus on a limited class of materials that can be easily recycled, either by separation or melting. Ideally, the selected materials will be versatile so that good electrical and mechanical properties can obtained. For example, carbon-based e-textiles are slowly forming part of the next generation developed products.

In the end all of these concepts follow the principles of circular economy.
Circular economy means integrating and managing all the aspects of sustainability, emphasizing the responsibility of each operator in the product value chain. Eco-design considers the same issues, but circular economy goes a step forward by studying for example renewable energy usage, avoiding waste generation and promoting a clean production.

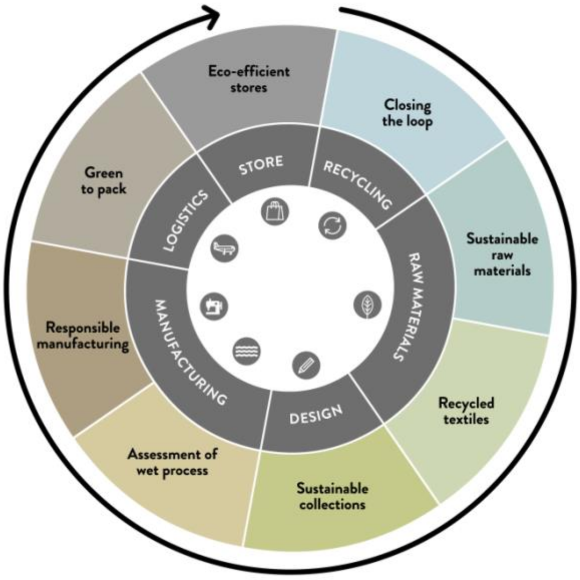


Figure 34. Circular Economy explained. (Source: Inditex)

Thankfully, there are also quantitative method such as LCAs, to perform environmental assessment according to international standards.

It is a method widely used to study the potential environmental impacts of processes, products and services through the whole life cycle from cradle to grave. This encompasses the raw-material acquisition, the production processes leading to products, transport processes, the product's use phase and its end-of-life stage, as seen in Figure 35.

By means of the LCA methodology, the environmental impact of a product can be assessed and compared with other products or alternative design solutions to develop a better alternative. [39]

Figure 35. Life Cycle Assessment (LCA) illustrated. (Source: Google)

Although the issue of sustainability in e-textile is much more than recycling and reuse, prioritizing techniques such as modular design, means that connectors have an important role to play in the sustainability of e-textiles.

Most current e-textile products are modular to some degree, as they feature detachable control modules that are attached to the garment and removed for washing. However, this could be extended so that circuitry embedded inside clothing is more easily disassembled, which means that very small or flexible connectors need to be developed to potentially replace fixed joining technologies such as embroidery or soldering. [8]

4 Conclusions

The main objective of this investigation was to provide information about the common knowledge related to the production of e-textiles, emphasizing the importance of connection methods for the conductive elements that form part of these products.
As for the background part, a brief background in smart textiles was presented also adding common applications. The basics of textiles and textile structures were given. A short explanation of conductors and how they can be used in textile structure was also made successfully.

Later on, the connection methods were discussed, and opportunities and challenges presented. A chapter was dedicated to sustainability since there are future strategies that will have a great impact on the development of e-textiles.

In the end, all the topics needed for the reader to grasp the pillars that sustain this investigation have been thoroughly explained since the desired project flow has been followed.

As for future work, I personally believe that this investigation could benefit a little more attention and time, given its importance, since the focus in e-textiles will be directed to improve the existing techniques and introducing new approaches that are able to cope with the advancement of material science and electronics.

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