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Scuola del Design

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Design & Engineering

MAKE YOUR OWN SMART TEXTILE

Experimentation of EdM conductive ink on textiles and development of a specific writing instrument for ink deposition on fabric

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Abstract Ita

Questo lavoro di tesi è nato dalla collaborazione tra le univerisità Ecole des Mines di Saint Etienne e il Politecnico di Milano partendo da un tirocinio presso la scuola francese.
Il tema da affrontare riguardava un nuovo inchiostro conduttivo sviluppato dall'Ecole des Mines.
L'obiettivo di questo progetto prevedeva la sperimentazione dell'inchiostro conduttivo sui tessuti e la sua stesura tramite lo sviluppo di uno specifico strumento di scrittura.

Il lavoro svolto è stato suddiviso in tre aree: ricerca, sperimentazione e progettazione.
Nella prima fase si trattava di reperire la documentazione necessaria per gestire al meglio le successive fasi di sperimentazione e progettazione. Sono stati individuati e analizzati gli attori principali coinvolti nel progetto: l'inchiostro conduttivo, i tessuti e gli strumenti di scrittura. La fase di ricerca è poi proseguita parallelamente alle altre due aree per analizzare possibili scenari d'impiego nel contesto dei tessuti intelligenti e dell'elettronica indossabile.

La fase sperimentale è stata suddivisa in due parti: la prima svolta nei laboratori dell'università Ecole des Mines, la seconda al Politecnico di Milano. La prima parte si è focalizzata sull'interazione dell'inchiostro conduttivo con i tessuti per verificare la sua adesione alle fibre e la conduttività. L'inchiostro depositato su diversi campioni di tessuto ha mostrato una buona adesione e conduttività dopo l'essiccazione.
Durante la fase di test la conduttività misurata sui tessuti è stata inferiore a quella ottenuta dall'Ecole des Mines avvenuta me-

diante deposizione in piccole forme di silicone. Questo risultato ha evidenziato l'influenza del substrato, i tessuti, nella stesura dell'inchiostro conduttivo.
Per rispondere a questo problema, è stata fatta leva su alcuni punti fondamentali, come la scelta del tipo di tessuto con differenti valori di assorbimento, l'aumento dello spessore dell'inchiostro de depositare sul tessuto modulando la viscosità, e per finire, la scelta delle modalità di deposizione dell'inchiostro. Questi punti sono stati fondamentali per tutta la fase sperimentale e hanno permesso di proseguire lo sviluppo focalizzando l'attenzione sul miglioramento delle prestazioni dell'inchiostro in vista delle dimostrazioni e dello scenario d'uso ipotizzato, il "fai da te".

La seconda parte sperimentale è proseguita lavorando su i dosaggi della formulazione dell'inchiostro per incrementare la conduttività. La gamma dei tessuti da testare è stata ampliata, con maggiore interesse verso quelli elastici. Per rendere la stesura dell'inchiostro facilmente replicabile, in vista degli scenari di utilizzo sul mercato, si è passati allo sviluppo di uno strumento di scrittura specifico per EdM conductive ink.

Per concludere, come verifica dei risultati ottenuti si è deciso di utilizzare l'inchiostro conduttivo per una piccola applicazione elettronica. Due piste di inchiostro conduttivo EdM sono state disegnate con il prototipo su un tessuto di cotone. Ad un'estremità delle piste è stato collegato un dispositivo LED, mentre all'altra estremità una piccola fonte di alimentazione. I due percorsi di inchiostro in sostituzione dei comuni fili di rame hanno permesso il passaggio di corrente e l'accensione della luce LED.

Abstract Eng

This thesis is the result of a partnership between Ecole des Mines Saint Etienne and Politecnico di Milano. The subject of the internship proposed by Ecole des Mines concerned a new conductive ink developt in the school. The aim of the project involved the experimentation of the conductive ink on textiles and its lay down through the development of a specific writing instrument.
The work has been divided into three areas: research, testing and design.
The first phase concerned gathering the necessary knowledge to better manage the following phases of experimentation and design. The main actors of the project were identified and analysed: the conducutive ink, textiles and writing instruments. The research part went on in parallel with the other two areas in order to explore possible use scenarios in the context of smart textiles and wearable electronics. The testing phase was divided into two parts: the first took place in the Ecole des Mines, the second at Politecnico di Milano. The first part focused on the ink behaviour about the interaction with fabrics. The ink deposited on different fabrics samples showed stability and conductivity after drying.
Along the testing phase, the measured electrical resistance was higher than that obtained by Ecole des Mines via free standing in molds. This result pointed out the influence of the substrate, the textiles, about the ink lay down. To conteract this issue, it is done leverage on some key factors, such as the selection of the fabrics, based on the absorption value, the increase of the ink thickness on fabrics adjusting the viscosity, and finally, the choice of the ink deposition mode. These points have been the key to the whole experimental phase and they allowed to go on the deve-

lopment by focusing on the improvement of the ink perfomance, in view of the fabrication of a demonstrator and the use in the supposed scenario of “Do-it-yourself“.
The second experimental phase went on by increasing the percentage of graphene solution in the composite blend in order to increase the conductivity. The range of fabrics to be tested was expanded, with considerable care on elastic textiles.
To make the ink lay down repeatable in an easy and conventional way, in view of the use on the market, there was the need to develop a specific writing tool for Ecole des Mines (EdM) conductive ink.
In conclusion, as result of a demonstrative “product”, it has been achieved light opening from a LED connected to a battery through two paths of conductive ink in replacement of classical copper wires.

Introduction

The subject of the thesis project concerns the experimentation of a conductive ink on textiles and the development of a specific writing instrument for ink deposition on fabric.

The context of this work focuses on smart textiles applications, with the incorporation of conductive materials on the fabric.

Among possible functions considered, there are anti-static, thermo-regulating and electronic functions.

Different approaches can be applied to produce electrically conductive fabrics. First, by weaving conductive yarns into the textile structure : with this technique, the softness and comfort of the final composite textile can be degraded.

Another approach is to develop surface treatment adequate for application of existing conductive inks meaning inks that were developed for non-flexible substrates.

More recently, conductive coatings and inks have been applied onto fabrics and papers to provide flexibility to the systems and reduce stress on the substrate. The conductive coating can be deposited on a non-conductive substrate through classical printing techniques.

While conductive inks remained fairly stable for decades, in recent years, there have been improvements, as well as innovative new inks to meet the challenges offered by printed electronics. Printed electronics (PE) is the term that defines the use of traditional graphic printing methods to manufacture circuits on media such as polymer films, paper, textiles, and other materials. The promise of low-cost, high-volume, high-throughput production of electronic components or devices that are lightweight, small, thin, flexible, inexpensive and disposable has spurred the recent growth in development of PE technology.

Over the past ten years, flexible electronics raised a strong interest and many applications were developed, such as flexible screens, ships for security (RFID) or recently wearable electronics. This new concept enables to transform traditional textile and apparel products into lightweight, wireless and wearable intelligent devices.

The movement towards flexibility has impacted on conductive inks that must be able to work with new substrates as they become more flexible, bendable and/or stretchable.

The research part will show in detail the competitive landscape of the current conductive inks area, while the experimental phase of Ecole des Mines (EdM) conductive ink on textiles will point out the ink behaviour.

The first part of testing will focus on depositing EdM conductive ink on different textiles in order to study the influence of applying the blend on fabric. In the second part, the focus won't be on the influence anymore, but on the fabrication of demonstrative products made of printed textiles using the formulated ink.

A specific pen for ink deposition on fabric will be developt to make the system repeatable in an easy and conventional way.

The use scenario visualize for the thesis project will bring the use of EdM conductive ink on everyday textiles by using a conventional writing instrument in the context of "Do-it-yourself".

"Do-it-yourself" refers mainly to the opportunity for everyone to create something new freely with the great opportunity to express yourself creating/adding new values on "products", developing new functions for existent "objects" or creating really interesting new concepts.

Research part

Chapter 1 | State of the art in wearable technology

The process of creating smart clothing and wearable technology has to consider so many factors that it has to be collaborative between end-users, textile specialists, electronics, fashion and clothing designers and manufacturers all the way from the concept for new garment or wearable device through to point of sale. The collaboration between these sectors is sometimes difficult, with differences in language, working practices, development time-frames and marketing strategies. [1]

The complexity and broadness of knowledge required makes smart textile research interesting but also challenging.

From a slow start, this new industry sector now seems to be growing at a good pace, with many new products being released and new companies getting involved in the development of smart clothes and wearable technology. There are two distinct types of companies within the sector: those that have their core business based around smart clothes and wearable technology; and those that produce a few products that sit within a larger mainstream product range. The first set of companies is usually supplying the technology to the second set. Clothing and electronics have traditionally been separate industry sectors. Now they have to work together to develop products and this cross-disciplinary work has caused problems. Some of the products that have being produced do not always fit neatly into existing product categories. This was very noticeable for very early products: were they clothing or electronics? [2]

Most electronic textiles available today are made by attaching either permanent or removable electronic functionality.

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[1] J. McCann, D. Bryson, *Smart Clothes and Wearable Technology*, Woodhead Publishing in Textiles, CRC Press, 2009.

In the first generation of these systems (1980s), electronic devices were simply attached to garments or included in pockets. In the second generation (2000s), electrical connectivity and function were introduced by the inclusion of conducting yarns within the fabric structure. [3]
Conductive fabrics have been widely used for nearly two decades to dissipate static energy and protect from electromagnetic fields alongside other attributes such as thermal regulation, antiallergic and anti-bacterial properties. However, it was soon realised that fabrics constructed with conductive fibres such as carbon, gold, stainless steel, silver, or copper could offer great potential by facilitating the integration of 'soft' networks into fabrics, thus making them 'smart'. Unlike most technical textiles, smart textiles are not passive in their function, they can sense and respond to stimuli such as touch, temperature or heartbeat.
Intelligent textiles can incorporate antennas, global positioning systems (GPS), mobile phones and flexible display panels, without compromising the inherent characteristics of the fabric. The conductive yarns can look, feel and behave like a traditional fabric. The fabric itself is often used as a 'switch' in an electronic circuit to perform a function for another external electronic device. [4]
In electronic textiles, the conductive elements can provide power, deliver input and output signals or act as a transducer. They sense and react to mechanical, thermal, chemical, magnetic or other kinds of environmental stimuli.

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[2] *ivi,* p. 25

[3] Tilak Dias, Electronic Textiles, Smart Fabrics and Wearable Technology, Woodhead Publishing, 2015.

Depending on the application, electronic functionality can be fully integrated or a modular approach can be chosen, where clothing provides a kind of 'platform' for several possible modules. [5] Wearable computing has developed in parallel, being more focused on the development of advanced highly portable computing technology, but it has had an important influence on smart clothes and wearable technology. In the past (before 2000s), large-scale uptake of smart clothes have been inhibited by the lack of sufficiently advanced technologies. This would often lead to products not meeting the required needs and expectations of potential users. The technology is now starting to mature and the products that are being introduced are beginning to live up to consumer expectations. The industry is still in its infancy and has a long way to go, but the journey is going to be very exciting. [6]

[4] J. McCann, op. cit., p. 151-152

[5] Tilak Dias, op. cit., p. 355

[6] J. McCann, op. cit., p. 25

1.1 A brief history of wearable technology

Modern technology has brought many changes in our daily lives with the intention to facilitate more and more the user giving the opportunity to do things never thought possible. Over the years it has introduced a branch of technology that works closely with the human body, leaving the user free without hindering movement. Starting from portable/personal devices to carry in the pocket until the recent development of embedded electronics into the textiles.

The first wearable device was created in the early 60s, this type of technology was invented to help casino players to win easily and more likely. The first wearable computers had, in fact, a function rather illegal and they were used by a small circle of people (figure 1).

By the time the wearable technology has evolved purchasing functionality noblest and in 1975 was invented the first wristwatch (figure 2), followed in 1987 by digital hearing aids designed to help people with hearing problems. The popularity and familiarity of the wrist watch may be the reason for the placement there of many current wearable control systems.The mobile phone is another example of personal/portable electronics. The earliest mobile phones were introduced around the 1950s, but they were very different from the devices that we use today. Personal or portable electronics really took off in the 1980s with the popularity of the Sony Walkman (figure 3). Meanwhile VHS cassettes and consumer-grade camcorders were becoming more prevalent, these were a cheap and comparatively compact way to capture video. During the 1990s, portable Compact Disk (CD) and MiniDisk became more popular.

Figure 1
Chasing shoe, 1961.

can be found under http://www.wareable.com/wearable-tech/a-brief-ch/a-brief-history-of-wearables, 2015.

Figure 2
Pulsar calcolator watch, 1975.

can be found under http://www.wareable.com/wearable-tech/a-brief-ch/a-brief-history-of-wearables, 2015.

Figure 3
Sony Walkman 1979.

can be found under http://www.wareable.com/wearable-tech/a-brief-ch/a-brief-history-of-wearables, 2015.

In 1994 was designed and distributed wearable wireless webcam, a webcam positioned on a strap to put in front of and used for video subjective result from unique and extravagant. Wireless webcams are widely used by extreme sports enthusiasts who like to resume their adventures and share them on the web.
In the mid-1990s, the wearables community was convinced that body-worn computing devices would be a sure hit within a decade. Instead, many of the concepts initially designed wearable, such as positioning and imaging found their way into mobile phones. In the 2000s were introduced devices for Bluetooth wireless communication and medical devices for fitness, able to read the heart rate and the performance of your body during a sports session. When wearable computers evolved beyond PC hardware built in a backpack, and the number of people involved in wearables increased, the issue of textiles became relevant. The industry started to think from carrying devices in pockets to body-worn computing devices. Clothing and electronics have traditionally been separate industry sectors. In this way, initial collaboration started between end-users, textile specialists, electronics, fashion and clothing designers and manufacturers, by facilitating the integration of 'soft' networks into fabrics, thus making them 'smart'.
Electrical connectivity and functions were introduced by the inclusion of conducting yarns within the fabric structure. Electro-textiles and other electro-conductive materials are currently proving to be very popular. There are nowadays several companies specialised in the development of smart clothes and wearable technologies, sush as Softswitch (Peratech), Fibretronic and Eleksen. [7]
Recently Smartlife Technology has designed and developed garment-based sensor systems, allowing for personal vital sign

monitoring, such as electrocardiogram (ECG), respiration and temperature (figure 4). The company has developed garments for application in three main areas: sports, dangerous and critical situations, healthcare. Smartlife Technology's garment system is based on knitted sensor structures integrated to the garment's manufacture.

From different fields such as Sports, Healthcare/Medical, Fashion/Entertainment and Military/Public sector, smart clothes and wearable technology now seem to be growing at a good pace, with many new products being released and new companies getting involved in this sector. [8]

[7] J. McCann, op. cit., p. 3

[8] *ivi,* p. 36

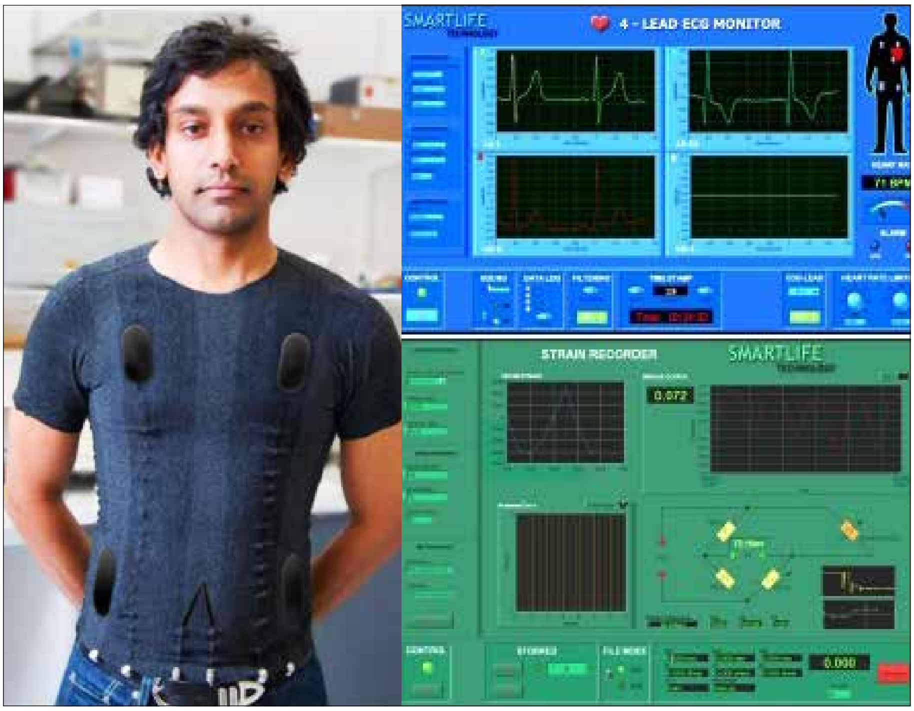

Figure 4
Smart life technology's garment, 2007.
[8]

Figure 5
Data logging compression shirt, 2010.

can be found under http://www.northeastern.edu/news/stories/2010/02/baseball_shirt.html.

Figure 6
Garment with fully integrated LEDs.

Tilak Dias, Electronic Textiles, Smart Fabrics and Wearable Technology, Woodhead Publishing, 2015.

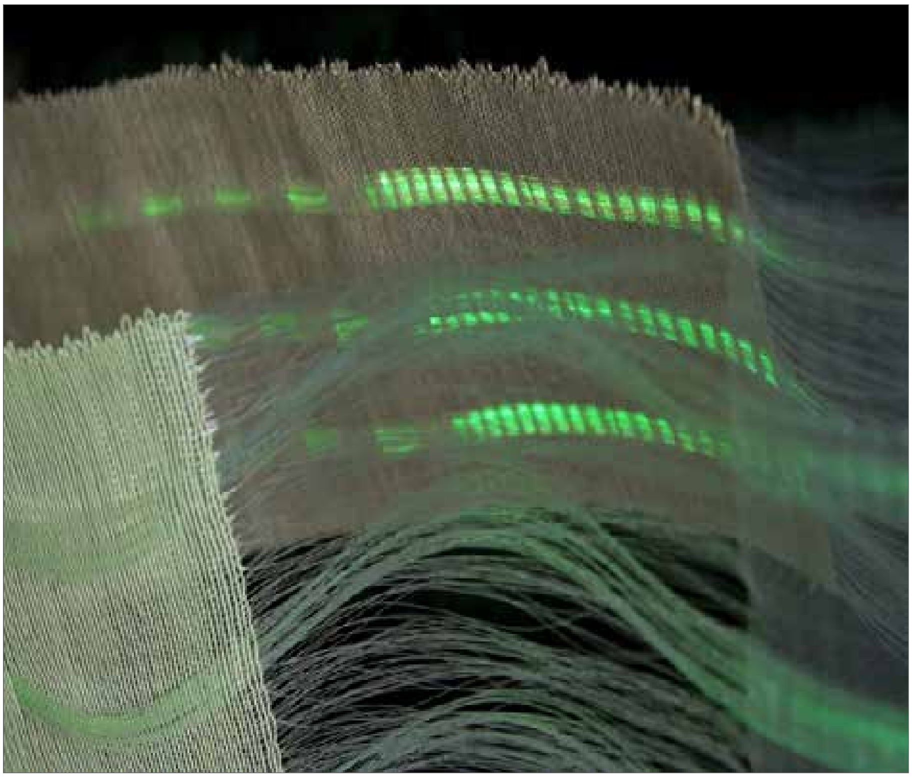

Figure 7
Optical textile, 2015.

R. Sinclair, Textiles and Fashion, Materials design and Technology, Elsevier Science, Woodhead publishing in textiles, 2014.

1.2 Understand the concept of smart textiles

1.2.1 Basic definitions

Wearable technology

Wearable technology products are textiles where electronic or mechanical components are attached to the textile material, and the textile part does not have any intelligent properties. For istance, by attaching solar panels and wires to a jacket, Ermenegildo Zegna has designed a product that can recharge your mobile phone battery. The textile parts of the jacket are made of conventional and non intelligent fabric.

Wearable electronics

Intelligent textiles are defined as products where the intelligence is directly embedded in the textile structure. Wearable electronics means that electronic devices are attached directly to the body of the wearer or to clothing. In this way, the piece of clothing becomes a platform for carrying electronic devices, such as microprocessors, transmitters, cameras, etc. Most of the first attempts to commercialize intelligent textiles were actually garments with wearable electronics designed for entertainment, like the music ICD jacket by Philips and Levi's in 2000.

Conductive materials

Conductive textile materials are, strictly speaking, not intelligent. They do not react to their environment, but they make many smart textile applications possible, especially those that monitor body functions. They are widely used in smart textile applications such as sensors, communication, heating textiles and electrostatic discharge clothing. Electroconductive materials are required *in sensors, actuators and heating panels, and the best-suited materials are highly conductive metals such as copper, silver and steel. Stainless steel and copper yarns can be made flexible, soft and durable enough to be woven or knitted, and electroconductive plastics can be created by mixing conductive polymers, electroconductive fillers such as carbon black, and metal particles.*

Intelligent textiles

Based on information received, intelligent textiles (also called smart textiles) interact with the environment. They can sense and react to mechanical, thermal, chemical, magnetic or other kinds of environmental stimuli performing predetermined actions repeatedly and often reversibly.

Tehcnically advanced textiles

Technically advanced textiles are materials that have noninteractive special properties, and the material itself stays unchanged despite environmental change. Clothing made of Gore-Tex is water repellent and breathable, i.e. technically very advanced, but it is not considered intelligent, as its properties are always static and it does not react to environmental changes. [9]

[9] R. Sinclair, Textiles and Fashion, *Materials design and Technology*, Elsevier Science, Woodhead publishing in textiles, 2014.

1.2.2 Different types of smart materials

PCMs

PCMs are thermal storage materials for regulating temperature. Microcapsules filled with paraffin wax are attached to textiles by coating or in the spinning process. When the wax changes its phase from solid to liquid and back, heat is absorbed and released. By cooling and warming the wearer, phase change textiles maintain the microclimate temperature within the comfort zone.

Shape memory materials

In response to external stimulus, shape memory materials change shape, and once stimulus is removed, return to their original shape. Thermally responsive SMPs are used in textiles for added temperature regulation and permeability. The shape change takes place at the transition temperature due to kinetic properties of molecular chains.

Chromic materials

Chromic materials change colour due to an external stimulus, which can be light, heat, electricity, pressure, liquid or electron beam. Inks and dyes are used for making chromic prints on textiles or for dyeing embroidery yarns.

Photonics

Photonics is a research topic for combining electrochromic materials, fibre optics and LEDs to textiles.

Stress-responsive materials

Stress-responsive materials change their shape when stress is applied to them. They may instantly turn rigid under a shock and return to a flexible state soon after. Such a property could be used in body protection.

Biomimetics

Biomimetics is a research agenda for mimicking biological re-

actions and properties in nature. The lotus leaf effect, chameleon-like colour change, the extreme strength of spider silk, the ability of a shark's skin to reduce friction in water, and ultralight butterfly wings are some of the current research topics.

Conductive materials

Textiles made of conductive yarns are used for sensors, communication and heating. [10]

1.2.3 Smart textiles classified by their functionality

Research and development of smart textiles is often multidisciplinary, besides textile know-how, researchers need skills in areas such as electronics,telecommunications, biotechnology and medicine. Networking and knowledge exchange with academic institutes and businesses is often the only way to carry out successful smart textile research.
According to Schwarz, Langenhove, Guermonprez, and Deguillemont (2010), a smart textile system can incorporate many functions: sensing, actuating, communicating, data storing and interconnecting to other systems. Smart textiles can be classified by their functionality (Tao, 2001).

Passive smart textiles

Passive smart textiles can sense the environment. A sensor is an example of these materials, it recognizes an impulse from the environment, but does not perform any activity.

[10] *ivi,* p. 374

Active smart textiles

Active smart textiles sense a stimulus from the environment and perform an actuating function.
Phase change material (PCM) absorbs and releases heat based on the temperature of the environment, and because PCMs can sense temperature and then perform a function based on that input, they are called active smart textiles.

Very smart textiles

Very smart textiles adapt their behaviour according to environmental circumstances. Shape memory materials are often called very smart, as they can remember their original shape and return to it (Hu, 2007). Ultimately these materials are textiles that can learn and adapt to various stimuli.

Sensing, monitoring, computing, communications, and heat and energy management, are expected to be the main functions for the intelligent textile products of the future. [11]

1.3 Architecture of wearable electronic system

1.3.1 Functions of conductive fabrics

Conductive fabrics that dissipate static energy and protect from electromagnetic fields alongside other attributes such as thermal regulation, antiallergy properties and anti-bacterial properties,

[11] *ivi,* p. 359

have been widely used for nearly two decades. However, it was soon realised that fabrics constructed with conductive fibres such as carbon, gold, stainless steel, silver, or copper could offer great potential by facilitating the integration of 'soft' networks into fabrics, thus making them 'smart'. Unlike most technical textiles, smart textiles are not passive in their function: they are capable of sensing and responding to their surrounding environment in a predictable manner. Depending on the application, electronic functionality can be fully integrated or a modular approach can be chosen, where clothing provides a kind of 'platform' for several possible modules.
Methods of creating electrically conductive fabrics:

- *filling synthetic fibres with carbon or metal particles*
- *coating fibres with conductive polymers or metal*
- *using continuous or short fibres that are completely made of conductive material.*

These fibres can be woven, knitted or embroidered into fabrics. [12]

Conductive ink technology offers another alternative in the development of electronic textiles. The benefits offered by digital printing techniques have prompted many conductive ink developers to experiment with printing onto textile substrates. [13]

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[12] J. McCann, op. cit., p. 151-152

[13] X.M. Tao, *Wearable Electronics and Photonics*, Woodhead Pu blishing Ltd, 2005.

1.3.2 Wearable electronic system

A typical system architecture design of a wearable electronic/ photonic product is shown in fig.8 . It comprises at least several basic functions: interface, communication, data management, energy management and integrated circuits.

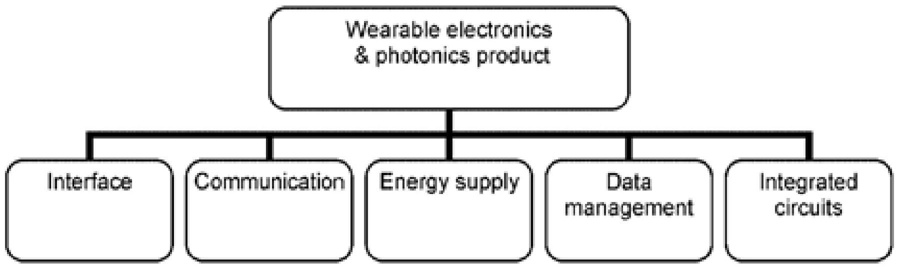

Figure 8
General system configuration of a typical wearable electronics and photonics product.

J. McCann, D. Bryson, Smart Clothes and Wearable Technology, Woodhead Publishing in Textiles, CRC Press, 2009.

The main components of a wearable system that provide the showed functions are:

- ***sensor unit:** registration of biometric and environmental data and of user commands;*
- ***network unit:** transmission of data within the wearable computer and to external networks;*
- ***processing unit:** calculating, analysing and storing data;*
- ***power unit:** supplying energy;*
- ***actuator unit:** adapting to situations, creating an effect on the user, displaying data.*

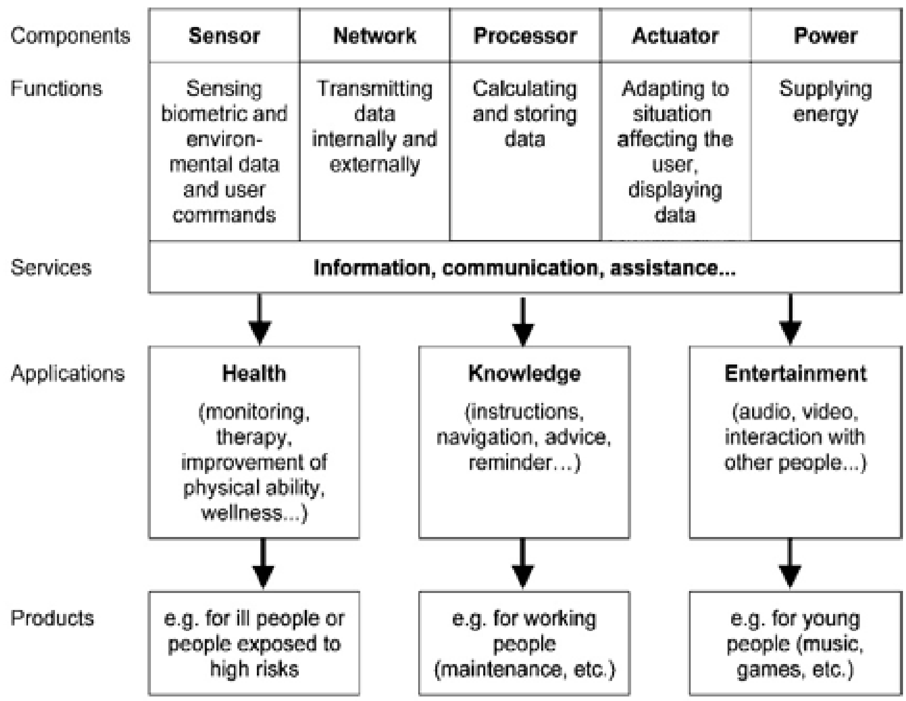

Figure 9
Systemisation of wearable electronic systems. [14]

Several of these functions are combined to form services. Providing information, communication or assistance are possible services. Mobility is now a fundamental aspect of many services and devices, there are an almost unlimited number of application ideas, e.g. in the fields of health, knowledge and entertainment. [14]

An example of intelligent system with enabling the three key components of smart textiles, (sensors, electronic circuits and actuators) is shown in fig.10.
Sensors are required to detect signals, electronic circuits to process the signals and then make an intelligent decision for

[14] *ivi,* p. 178

actuators to react on it. In order to send and receive information all devices must be connected, which can be achieved by embroidery, conductive Velcro tape, electroconductive yarns, snap buttons and others that will be explained in detail in the next part. [15]

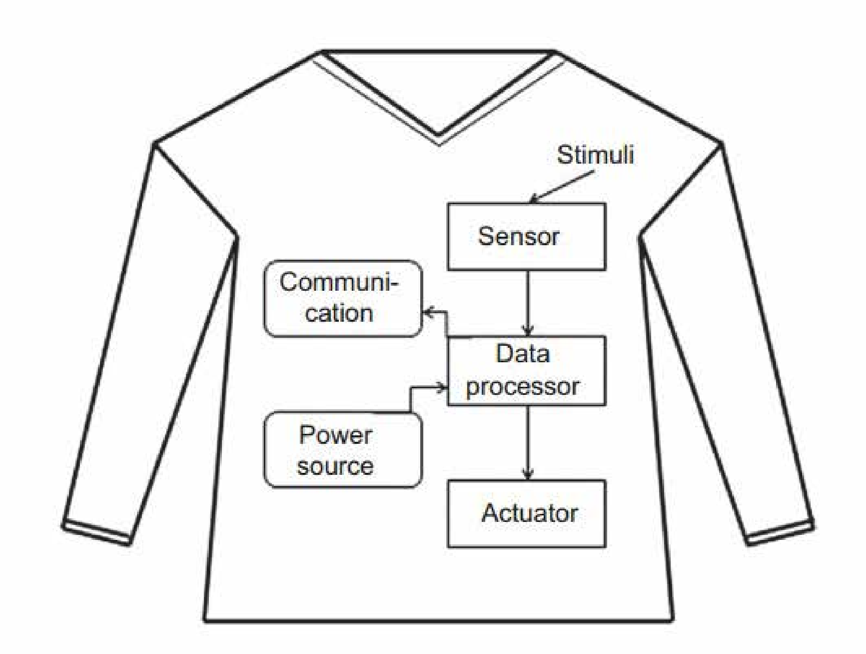

Figure 10
Three key parts of an intelligent system with enabling technology. [15]

1.3.3 Description of the main components

Electrical networks

Electrical networks are responsible for data and power transfer. On-body communications in wearable systems can be wired or wireless. A textile network means that fabrics are used to replace conventional wires, whole circuit boards or antennas. The first efforts to use conductive textiles for electrical circuitry were made at the MIT Media Lab in the E-broidery project. Sensors,

[15] J. McCann, op. cit., p. 214

actuators and data units must be connected in order to send and receive information (fig.11). Communication refers to the transfer of information, this can be between two wearable devices on the user (short-range communications) or between two users via the internet or a network protocol (long-range communications). The first one can be made wired or wireless by using RFID or Bluetooth tecnologies. It includes internal communications and personal space communications. Instead, long-range communications traditionally is created by GSM and 3G technologies, and it takes part in external communications. [16]

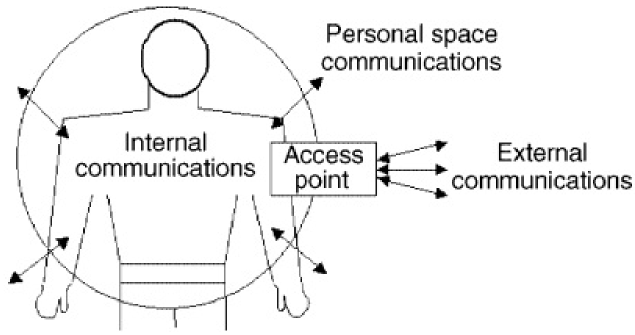

Figure 11
Relations between internal, external and personal space communications. [16]

Textile processors

Processing includes arithmetic operations and the storage of data. Transistors, diodes and other non-linear devices are needed for these functions. Manufacturing technologies have already been developed to create organic devices ('all-polymer' transistors and batteries). Such devices, as well as thin silicon integrated circuits (ICs) can be fabricated on flexible polymer

[16] *ivi,* p. 180

substrates. Such flexible chips can be attached to textiles but they are not textiles themselves. Preliminary efforts are being made to create textile fibres from electroactive polymers that can act as transistors. One of the main challenges is to improve the stability of such conductive fibres.

Textiles power supply

As the power supply is usually the biggest and heaviest part in the wearable computers of today, there are several approaches to decrease power consumption by power management or power performance trade-offs and to develop novel power supply technologies (e.g. lithium polymer batteries, micro fuel cells). The operation of the devices requires energy and they cannot work without electrical power. Batteries are an obvious choice, but they are bulky and require frequent replacement or recharging. Ideally, an electrical power source that is suitable for smart textile applications should be flexible, light weight and self-renewing. The alternative to batteries is to use different sources of energy available on the body which can be transformed into electrical energy, e.g. sunlight using solar cells, body temperature using thermoelectric devices, body motion using piezoelectric converters. Some efforts have been made to embed miniaturised or flexible energy supplies into textiles, but few to create a textile power supply.

Established portable power sources

Rechargeable batteries

The Lithium Ion battery provides the highest energy density with a large charge cycle, making it the fastest growing and most promising battery for numerous portable applications. Lithium Ion

Polymer is a potentially lower cost version of the Li-ion and it can be potentially flexible.

Flexible batteries

Fabrication of polymer electrolytes using screen-printing or inkjet techniques. The cells are made of proprietary inks that can be printed or pasted onto virtually any substrate, to create a battery that is thin and flexible. The ultimate goal is to develop a fully compatible battery that is totally comfortable to wear and can be laundered. Towards this goal, researchers at Stanford Research Institute (SRI), USA, are developing a technology to fabricate anode and cathode materials onto thin carbon fibres that can be packaged around thin strands of electrolytes. These fibre batteries can then be woven into textiles, turning a garment into a mobile power source. [17]

Fuel cell

High performance computing requires a relatively large power supply, usually in the range of 50 W.

Fuel cells have a substantially large theoretical energy density of over 50 000 W h/kg and are seen as a possible technology to meet the power requirement of wearable computing at the high performance end (Vielstich et al., 2003). A fuel cell is an electrochemical device that converts hydrogen and oxygen into water and, in the process, produces electricity and heat (Vielstich et al., 2003). Commercial products based on this technology have already been available on the market. However, in terms of high energy density, small dimension and flexibility, significant

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[17] *ivi,* p. 183

effort toward research is still needed to realise its full potential as a solution to the power problems of wearable computing. [18]

Energy harvesting devices

The history of energy harvesting dates back to windmills and waterwheels, which convert gravitational energy into kinetic energy to ease or replace manual labour. The first wearable power harvesting device was a 'self-winding' watch that winds-up automatically from the wearer's arm movements. Modern energy harvesting devices that generate electricity include photovoltaic cells from light, piezoelectric devices from human motion and thermoelectric modules from body heat.

To develop a sustained power supply which covers the lifetime of smart textiles is an extremely difficult challenge. A medium-term solution is to combine power harvesting with energy storage. Power harvesting devices continuously convert various forms of ambient energy into electricity, while the storage devices accumulate the generated electrical energy for the intermittent consumption usually required by smart textiles. All these devices have the potential of being fully integrated with smart textiles. The challenge is to efficiently convert the limited energy available from/around the human body into electrical power.

Energy from the human body

A human body carries a sufficient amount of energy in various forms. Even if only a very small fraction of this energy can be converted into electricity, the power required by many of the present-day low power devices can be met. The development of miniature thermoelectric devices in recent years opens up a possibility for wearable applications. A more adventurous attempt is to develop flexible thermoelectric thin films or polymers that can *be woven into fabrics. [19]*

Thermoelectric generator

A thermoelectric generator is a semiconductor device which converts heat into electricity based on the Seebeck effect (Nolas, 2001). Commercially available thermoelectric generators are bulky and rigid. They are not suitable for wearable applications. The development of miniature thermoelectric devices in recent years opens up a possibility for wearable applications.

It has been suggested that such miniature devices can be embedded into smart textiles for power harvesting. However, a more adventurous attempt is to develop flexible thermoelectric thin films or polymers that can be woven into fabrics. Thermoelectric generators have been incorporated into the pillows of surgical beds for patient comfort (Buist, 1989). Attempts have been made by the USA air force to develop helmets for astronauts and fight-jet pilots, which incorporate thermoelectric devices to keep them cool and alert in a hot environment, or by just flicking the switch, keep them warm in a cold environment. [20]

Piezoelectric devices

A mechanical strain on a piezoelectric material produces an electric field (Yang, 2006). This effect (namely the piezoelectric effect) can be employed to convert mechanical energy into electrical energy. Electrical energy can be generated simply by compression, bending or

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[18] *ivi,* p. 221

[19] *ivi*, p. 222-223

[20] *ivi,* p. 224

slapping of piezoelectric materials. Piezoelectric elements are being imbedded in walkways to recover the human energy of footsteps (Starner, 1996). They can also be embedded in shoes to recover the 'walking energy'. Starner considered the use of PVDF materials as a part of shoe stiffeners for recovering some of the power in the process of walking. He estimated that 5 W of electric power can be generated by a 50 kg user at a brisk walking pace (Starner, 1996). Such a power level is sufficient for many demanding wearable applications. Significant effort towards research is needed to improve the power level without causing inconvenience or requiring significant body movement.

Photovoltaic cells

A solar cell is a semiconductor device in which solar energy of certain wavelengths can be absorbed to generate free electrons (negative charges) on one side and holes (positive charges) on another. Coating process may be applied to fabricate the TiO-2solar cells on a fibre.

By weaving such 'solar fibres' into textiles, a totally compatiable energy harvesting device can be achieved for smart textiles applications. Similar synthetic fibres have also been reported by researchers in Germany (Schubert and Werner, 2006). They believe that the fibres could be woven into machine-washable clothes to make wearable solar cells. [21]

Wireless recharger

Radio frequency radiation is another potential source of energy, which comes from radio, television, mobile phone and wireless network transmitters (Griffiths, 1998). A power transmitter generates electromagnetic energy which is limited to a small space around the transmitter. If flexible and light-weight receivers of this *kind can be developed, this technique could be employed to re-charge smart textiles.* [22]

Energy storage and power management

Among the body-driven energy harvesting devices discussed above, piezoelectric and photovoltaic devices cannot generate power continuously. They require power storage devices to store some energy during power generation cycles in order to maintain continuous power output during the converter's 'sleeping' periods.

Challenges and opportunities

Compared with the typical power requirements of today's electronic systems, the power level that can be obtained by existing energy harvesting devices is still relatively low. The efficiency of these devices usually decreases further when they are implemented into flexible forms that are required for most wearable applications. A major challenge is to develop flexible energy converters which can be fully integrated into textiles with high efficiency and at low cost. The most exciting idea mentioned above is the development of energy harvesting fibres that can be woven into textiles or form a part of textiles.An analysis of the energy inventory of a human body indicates that sufficient energy input is available for harvesting. It is estimated that a total electrical power of 5–10 W is obtainable if these devices can operate close to their efficiency limits. In order to realise such a potential, a key challenge is to increase the conversion

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[21] *ivi,* p. 225-226

[22] *ivi*, p. 227

efficiency of these energy devices. Over the past few decades, batteries and existing energy harvesting devices have made only moderate improvements in terms of improving energy density and size reduction. In contrast, microelectronic technology continues to advance rapidly. The size of the electronic circuits and the energy needed for operation have been reduced drastically. Wireless communication systems using only 50 μW are realistically possible. Progress on this front will help to ease the problems encountered by energy harvesting devices required to provide a relatively large power level. It is anticipated that the solutions to the wearable power supply problem may come from the improved energy density of advanced energy harvesting devices, as well as reduced power consumption by future electronic circuits. [23]

Textile sensors & actuators

The next substantial progress will be to use textiles not only for transmitting signals but also for transforming them. Transformation of signals can happen in two ways:

- ***sensor:*** *transformation of physical phenomena into processable electrical signals;*
- ***actuator:*** *transformation of electrical signals into physical phenomena.*

Textile technologies have been developed to create fibres and fabrics with a significant and reproducible change of properties caused by defined environmental influences. Sensors can be used to measure biometric or environmental data, but also to act as an input interface. Actuators can adapt themselves to a situation, affect the human body or serve as a display. Actuators react to signals coming from sensors, with *motion, sound or substance release. Thermal actuators can be used for warming or cooling. A drug-release actuator releases chemicals, for example for skin care. A sensor is a passive but important part of a smart textile system, it is created by weaving or knitting electroconductive yarns into fabrics as signals are electrically transmitted. Sensors are used for monitoring heart rate, EKG, position, velocity, temperature, humidity and pressure, including pressure-sensitive sensors used in textile-based keyboards.* [24]

The most common sensors are explained below:

Acoustic sensor

The microphone is a familiar acoustic sensor found within many devices today. Sound is essentially variations in air pressure that our ears detect and interpret as music, speech and other noises. An electronic microphone contains a small diaphragm that vibrates in response to variations in air pressure, moving a magnetic coil. The electrical signals produced when the magnetic coil moves can be converted into a digital format and used for applications such as noise level sensors, audio recording, or with sophisticated software, speech recognition.

Motion sensor

Basic motion can be detected using vibration sensors or simple tilt switches. However, they are of limited use within wearable applications. More commonly, a sophisticated electronic

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[23] *ivi,* p. 228-229

[24] X.M. Tao, op. cit., p. 180

device known as an accelerometer is used to detect motion in two or three directions. *[25]*

Location systems

GPS detect the timing signals sent by the satellites and apply a mathematical algorithm to calculate its location. [26]

Biophysical monitoring

Many potential users are identified as beneficiaries of the WEALTHY health monitoring garment; these included soldiers, athletes, high-risk personnel such as fire fighters, older people, newborn babies, sleep apnoeas (people who stop breathing in their sleep) or long-distance drivers. The subsequent MyHeart (2008) research programme examined the use of this technology for patients with cardio-vascular diseases. [27]

Printed sensors

Printing luminescent (OLED/LED) inks on textiles realistically offers huge potential and represents a quantum leap in general and in the printing industry in particular. A wide range of deposition and patterning techniques can be used for the development of electroluminescent (EL) OLEDs. Most prominent in this context are various deposition techniques such as chemical and physical vapour depositions, and printing techniques ranging from reel-to-reel processing to non-contact printing methods.

[25] *ivi,* p. 194-195

[26] *ivi*, p. 197

[27] *ivi,* p. 200

Table 1
Range of wearable related input sensors and output devices. [27]

Type	Input	Output
Optical	Light dependent resistor (LDR) Photodiode CMOS (e.g. camera phone) CCD (e.g. video camera) Laser range-finder Infrared camera Passive Infrared (PIR) Image recognition/gestures	Light emitting diode (LED) Organic LED (OLED) Polymer LED (PLED) Liquid crystal display (LCD) E-ink display Projected laser display Infrared LED (non-visible)
Acoustic/ atmospheric pressure	Microphone Speech recognition Audio recording Ultrasonic detector Barometer/altimeter	Loudspeaker Piezospeaker Headphones In-earphones (wired or wireless) Pre-recorded sound Speech synthesis Ultrasonic transmitter
Movement/ vibration	Tilt-switch Vibration sensor Accelerometer (2D and 3D) Potentiometer Electronic induction Piezoresistive fabrics Pedometer	'Tactors' (phone vibrator) Electronic motors Solenoids Shape memory alloys (SMA) Electroactive polymer Actuators Pneumatics
Buttons/touch input	Mechanical switches Textile switch (i.e. Elektex) Fabric keyboard Polymer switch (i.e. softswitch) Laser keyboard Capacitive touch screen	
Temperature	Thermistor Resistance temperature detectors (RTD)	Heat (via electrical resistance) Thermochromic Inks
Biometric	Electrocardiogram (ECG) Heart-rate (e.g. polar sports) Galvanic skin response (GSR) Electroencephalography (EEG)	Electricity (i.e. pacemaker) Mechanical (exo-suit)
Location	Global positioning system (GPS) Ultra wideband (UWB) radio WIFI, Bluetooth and Cell ID Ultrasonic Infrared beacons Visual markers (barcodes) Radio frequency identification (RFID)	Location can be transmitted via a communications system, such as a 3G or WIFI network. Sensors within the environment could also detect wearable transmitters, e.g. Bluetooth, RFID, Image recognition, infrared beacon, visual markers

Printing of the luminescent products can be done using different technologies:

(a) Conventional screen technologies (flatbed or rotary screen);
(b) Digital inkjet technology (drop-on-demand): piezo and valve-jet technologies, both representing the state of the art in digital printing.

Inkjet printing represents an innovative printing technique for textile materials and will become considerably important in the near future, because this technology will shorten the time to print and fulfil the strong industry need to respond in real-time to customer needs. [28]

1.4 Power requirements of portable devices

Electronic devices have become a necessity of modern life. Almost everybody carries something that is electronic by nature: watches, mobile phones, music players, cameras and laptop computers. More important, some special electronic devices are essential for healthcare applications such as cardiac pacemakers, hearing-aids, and temperature or pulse rate monitors. All of these devices require a power supply to work. Because of the portable nature of these devices, batteries have been employed in almost all of them. Table 2 shows the typical power levels required by some of the commonly used portable electronic

[28] Tilak Dias, op. cit., p. 103

devices, together with corresponding battery type and operating period. It can be seen that power consumption by portable consumer electronics covers a wide range of power levels, from a few micro-watts to tens of watts.

Table 2
Power levels required by commonly used portable electronic systems [29]

Electronic systems	Power	Battery type	Operating period
Watches	3–10 μW	Silver oxide button	1–2 years
Pacemakers	25–80 μW	Lithium button	7–10 years
Hearing-aids	N/A	Zinc-mercury oxide	25–30 days
Digital clock	13 mW	Silver oxide button	6–10 months
Red LED	25–100 mW	Silver oxide button	6–12 months*
Pedometer	250 mW	Silver oxide button	1–2 years*
Portable radio	500 mW	AAA	3–6 months*
RF circuits	300–800 mW	AA	<10 hours
iPod	N/A	Li-ion rechargeable	16–32 hours
Mobile phones	4–10 W	Li-ion rechargeable	7–10 days
Laptop computer	50–80 W	Li-ion rechargeable	3–10 hours

Note: *The data in the table are typical values, which can vary depending on manufacturer and specific model, etc.; * The devices operate in non-continuous mode and the period depends strongly on the frequency of the usage.*

Low end power

At the low end, the power required by watches, pacemakers and hearingaids is only about tens of micro-watts. Typical button-type batteries (such as silver oxide) have a nominal capacity of around 10–120 micro-ampere-hour (μAh) at 1.5 V. This can provide an operating period over 1–2 years for these devices. Button batteries are small and light weight. They can readily be embedded into smart textiles without much trouble or causing inconvenience to wearers.

Mid range power

For wireless communications, current radio frequency (RF) circuits require an average power of around 500 mW. Embedding these batteries into smart textiles for RF circuits could be awkward due to their size and weight.

High end power

The power required by an average laptop computer is about 50 W, which is currently provided by a Lithium-ion (Li-ion) rechargeable battery. The size, weight and operating period of the battery have been 'bottle-neck' problems in the development of laptop computers. This will become even more challenging for wearable computing. Solutions may require research efforts in two directions:

- Reducing power consumption of electronic circuits

- Developing new power sources. [29]

1.5 Integration level of electronic components in smart textiles

A smart textile can be classified into categories of sensing, actuating and adaptive functions (Tao, 2001). The functions may be in the form of an additional electronic component or a part of the textile structure. Three levels of the integration of electronic components and circuits can be distinguished:

- **textile-adapted**
- **textile-integrated**
- **textile-based**

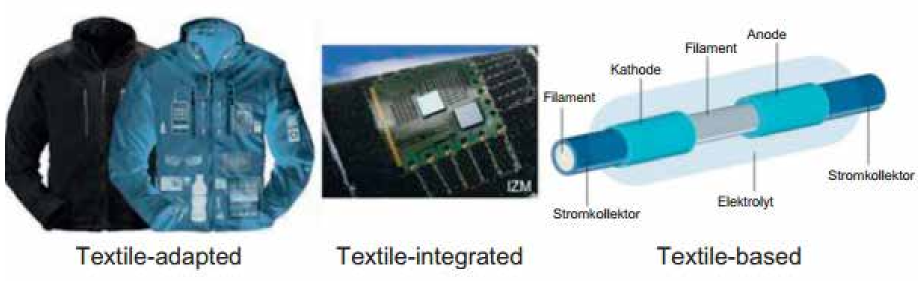


Figure 12
Levels of integration of electronic components. [30]

The first level, textile adaption, refers to the manufacturing of special clothing accessories to put in electronic devices (e.g., MP3 players). In the second level, the integration of electronic components means creating an interconnection between electronic elements and the textile within (e.g., metal push-buttons), for possible removal. The last level of integration of electronic components is based on the textile structure itself (e.g., with electro-conductive or metallic-coated multi-filament yarns). [30]

1.6 Joining technologies for electronic textiles

At present, smart textiles play a significant role in multidisciplinary research by bringing together competences from different fields of engineering, information technology and design. They can be generally described as a complex system that consists of two basic components. These include textile structures that carry specific functions and their corresponding electronic parts.
One of the key issues in the development of electronic-based smart textiles is the investigation of how to bring together textile technologies with the desired electronics. Most electronic textiles available today are made by attaching either permanent or removable electronic functionality. There are two different methods:

[29] J. McCann, op. cit., p. 215-216

[30] Tilak Dias, op. cit., p. 75-76

the first one is about inserting the chip directly into a textile fibre or encapsulating the chip within a bundle of fibres. The second one combines several approaches in order to bond on the textile surface the electronics. In the latter way the piece of clothing becomes a platform for carrying electronic devices, even removable. [31]

1.6.1 Methods of joining electronic devices

Integration of micro electronics

Textiles can be an inseparable component of the circuit wiring and contact systems as well.
Due to the variety of electro-conductive materials, including monofilament metal wires and conductive yarns, conductive circuits can be implemented directly into the textile structure by technologies such as weaving and knitting. The two main techniques of integrating chips are discussed below.

Inserting the chip into a textile fibre
It can be achived with only man-made fibres, by inserting the chip during the extrusion of the fibres. Although this technique can protect the chip from the tensile and bending stresses and the temperature, pressure and other chemical stresses to which the textile fibre will be subjected during post-processing, this method will not protect the chip from the torsional deformations of the textile fibre.

[31] *ivi,* p. 133-134

Encapsulating the chip within a bundle of fibres

This method can protect the chip from all the aforementioned deformations and stresses (fig. 13), and it is not limited to man-made fibres. [32]

Figure 13
Scheme of electronic functional yarn.
[32]

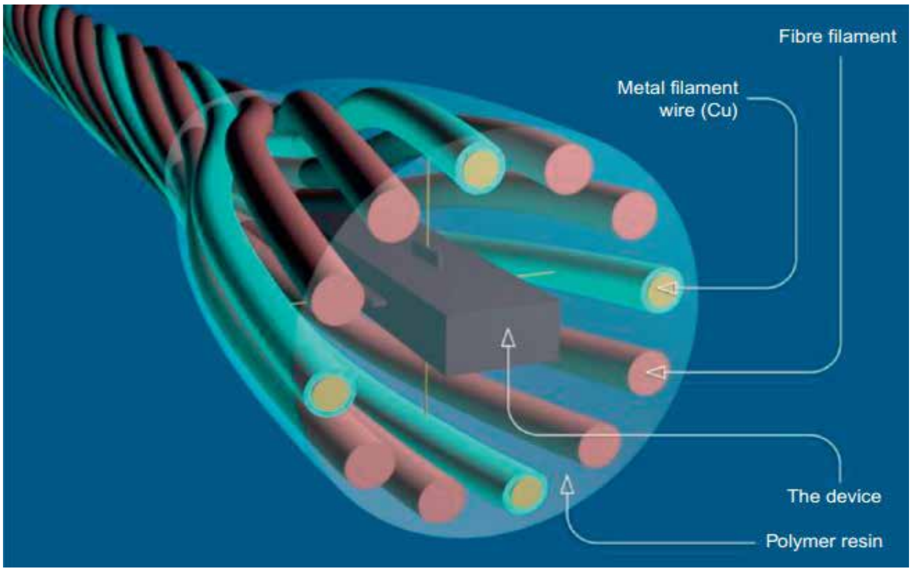
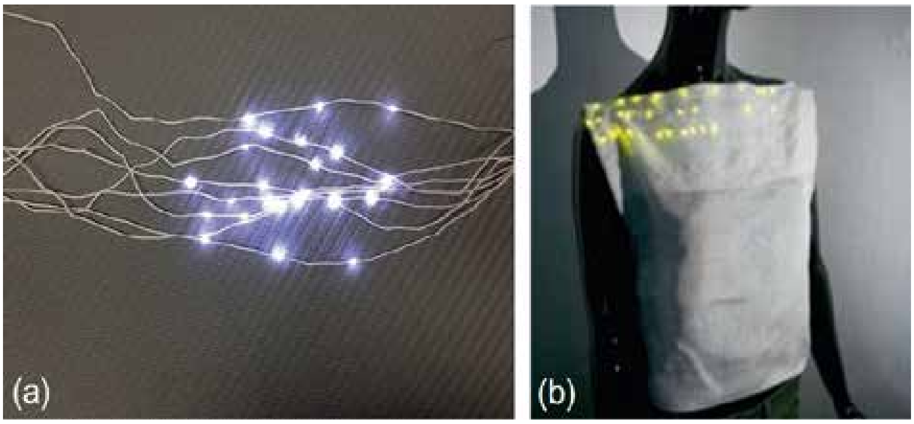


Figure 14
(a) LED yarn and
(b) LED garment.



[32] *ivi,* p. 134-135

Conventional textile joining

Conventional textile technologies such as weaving, knitting, embroidery, sewing, crimping and staking can all be used in smart textile development in order to enable proper circuit wiring and contact between the textile and electronic units. Agent locking as a method of bonding in smart textiles can be also implemented more traditionally by soldering. The picture below (fig.15) displays a combined approach to integrate a matrix of electronic modules on textiles. The wiring was initially developed by the tailored fibre placement (TFP) embroidery technique, using a metal monofilament. Then, solder was used to secure the electrical contacts of the electronic modules to the textile surface.

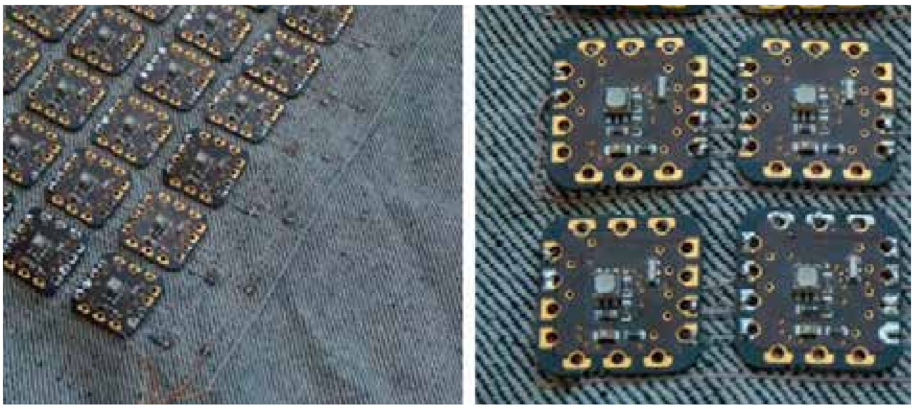


Figure 15 electronic modules integrated onto textiles by embroidery and soldering. [33]

One of the crucial aspects of serial production is the automation of the manufacturing process. At present, the development and transfer of such manufacturing tools to industry is relatively expensive, due to the limitations of the smart textile market. One of the promising markets for smart textiles is interactive systems. LEDs have limited functionality in textiles, they are a reliably simple tool to add desirable optical effects to textiles. For these applications, technical embroidery is a beneficial technology that ensures efficient and reliable manufacturing. A Swiss company, Forster Rohner, has developed an embroidery-based approach *to manufacture luxury interior textiles and clothing outfitted with integrated LEDs. [33]*

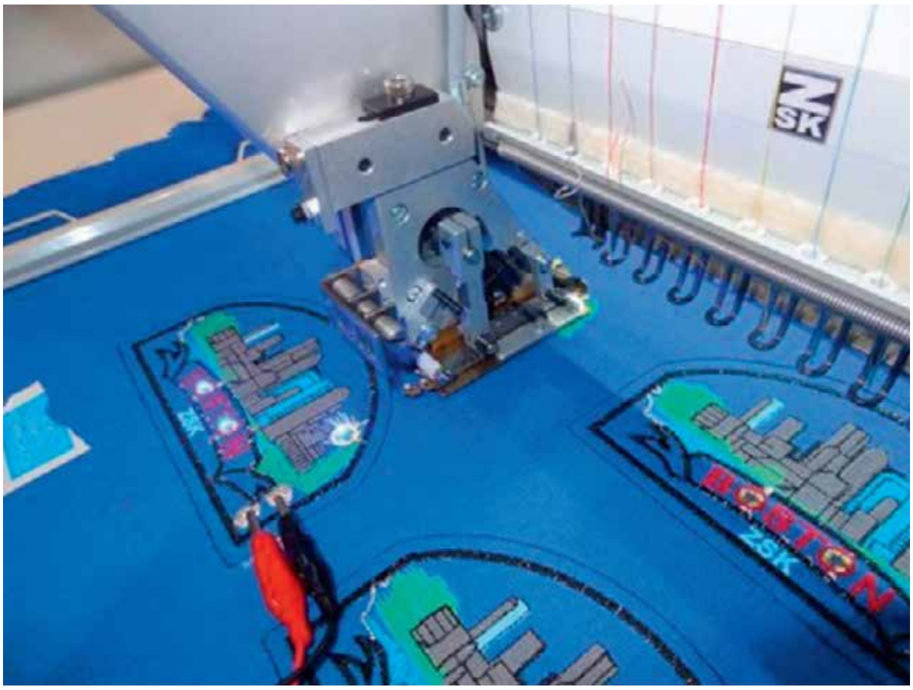


Figure 16
Automated attachment of LEDs by embroidery. [33]

Generally, the solutions for textile bonding and electronic interfacing combine several approaches, in order to ensure a predictable, conductive and reliable wiring. These bonds, or interfaces, can even be designed as permanent or reversible. The main techniques of conventional textile joining are discussed below.

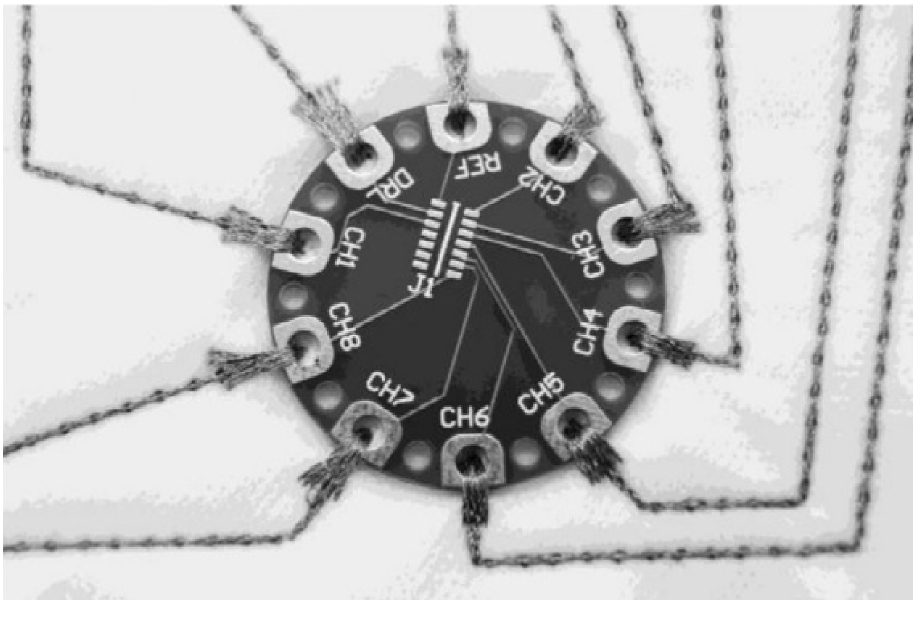
Embrodery

One of the main issues concerning the automated manufacturing of smart textiles is ensuring a continuous multi-stage process. At present, this key condition stays beyond the industry's manufacturability due to the limited-lot production of smart

[33] *ivi,* p. 135-136

textiles. The advantage of embroidery is the possibility of using a single technology to combine the conductive paths with the supporting electronics in complex and useful geometries. To ensure that the contact between the electronically conductive part and the textile lasts through washing, different solutions have been created to encapsulate the embroidered contact.The results show that a combination of a local application of epoxy adhesive to the embroidered contact, combined with a subsequent encapsulation by hot melt, is necessary in order to provide a good electrical contact between the textile and the electronic parts. The electronic and conductive paths have to be placed on the outside of the fabric, as they generally should be shielded from naturally occurring conductive substances like sweat. Then the functional parts, like electrodes for sensors or actuators, are placed on the body side of the fabric, as they generally have to contact the skin directly. Therefore, the conductive parts have to be placed on the opposite side of the electrodes. Hence, the future of embroidery must focus on improving double-sided embroidery technology. [34]

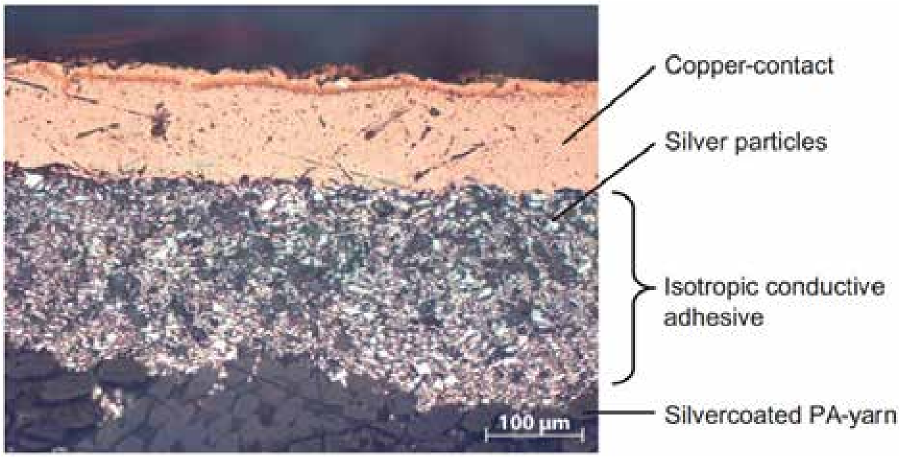
Figure 17
Joining of a PCB due to embroidery. [34]



Adhesive bonding

In the area of the cohesive joining technologies, the use of adhesive bonding is an attractive method for connecting different joining parts. Adhesive bonding utilize a combination of conductive and non-conductive materials, it has a lot of advantages, and also some restrictions such as high cost and the low mechanical strenght, thus it's often combined with other techniques as embrodery. [35]

Figure 18
Joint between copper-contact and conductive fabric through ICA; silver particle content of 80 wt.% [35]



Reversible joining

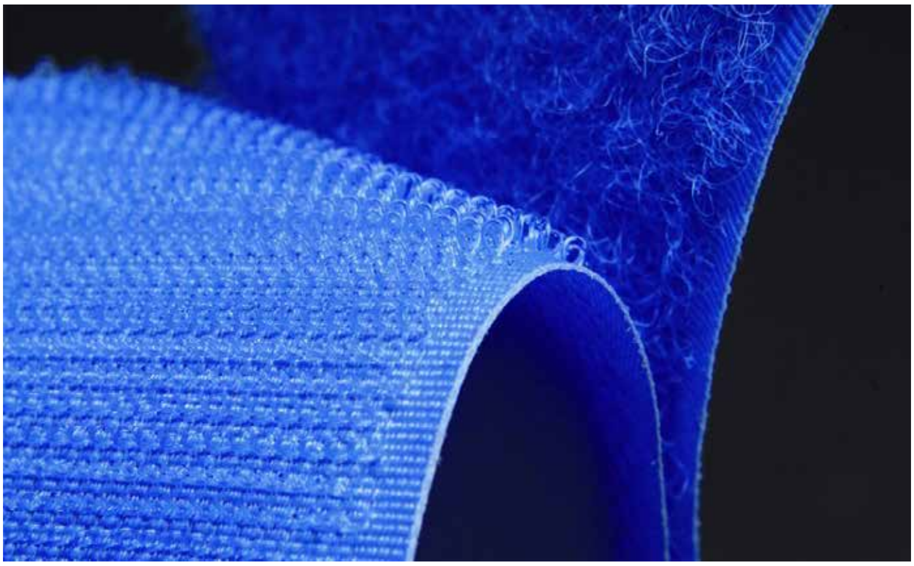
Reversible joining is beneficial for many smart textile applications where the functional modules must be detached from the textiles. Some researchers attempt to solve this issue by using fastener buttons, conductive Velcro (fig.19), magnets and bolting. [36]

[34] *ivi,* p. 138

[35] *ivi*, p. 145

[36] *ivi,* p. 135

Figure 19
Conductive hook and loop, or the so-called Velcro tape can be used for electric connection. [36]



1.6.2 Summary

The designed product should incorporate properties such as the flexibility and durability of textiles and the intelligence of electronics. Manufacturing and joining technology should be organized as a direct or joined process in order to achieve a reasonable and cost-efficient solution. Tool handling, cutting, feeding and removal of the textile for automatic assembly must be solved to optimaze the multi-stage manufacturing. [37]

1.7 Consumer design needs

Most of the first attempts to commercialize intelligent textiles were actually garments with wearable electronics designed for entertainment, like the music ICD jacket by Philips and Levi's in 2000. None of the smart textile innovations between 2000 and 2010 was commercially successful. It seems that understanding *consumer needs must be the starting point when designing wearable electronics products, and design needs to address the challenges of attaching electronic devices to clothing:*

- *Electronic devices cannot be bulky or rigid. The appearance and wearing comfort of the garment must be the same as it would be without electronics.*
- *Devices must be encapsulated in order to make them washable, requiring the removal of all devices before washing is not practical.*
- *Visible cable or wiring is not aesthetic and consumers also may be concerned about electromagnetic radiation.*
- *Energy sources should be embedded in textile structures. Carrying batteries in pockets is not a robust solution. [38]*

Table 3
Design guidelines for wearability. [38]

Guidelines for wearability	
Placement	Explains where extra components should be placed on body
Form language	Defines shape for additional components
Human movement	Considers the dynamic parts of human body structure
Proxemics	Perception of space by human brain
Sizing	Should be able to fit a number of users
Attachment	Extra components that can be fixed to the body comfortably
Containment	Considering what is inside the form
Weight	Balance across the human body; should not hinder human movement
Accessibility	Additional components should be easily approachable
Sensory interaction	Active or passive interaction between user and component
Thermal	Thermal comfort to the wearer
Aesthetics	Appearance or perceptual appropriateness
Long-term use	Effects of prolonged use on the body and mind

[37] *ivi,* p.133

[38] R. Sinclair, op. cit., p. 367-368

1.8 Environmental and waste issues concerning the production of smart clothes and wearable technology

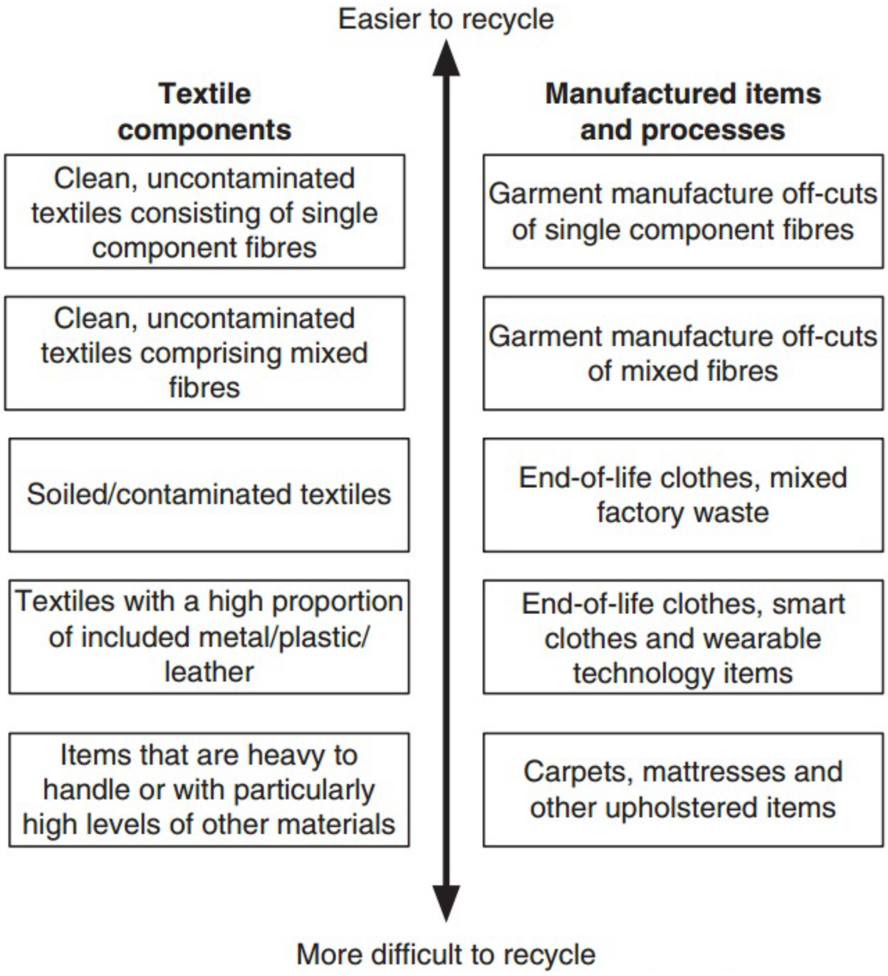
Any manufacturing process produces waste, and any product eventually, at the end of its life, becomes waste, too. Textile-based products are no exception, and over the ages ways have been found of minimising textile waste in the first place, and where possible recycling and reusing the waste, perhaps in very different products. With the advent of Smart Clothes and Wearable Technology (SCWT) products, an additional set of new factors comes into play. Although, at present, production of these items is much lower than for traditional textile-based items, the production of SCWT involves incorporating non-traditional materials into, for example, items of clothing. These materials, most usually electronic systems, energy supplies, and interconnecting wires or fibre optic cables, represent a collection of materials now seen to have a particularly bad impact on the environment when landfilled or incinerated. From the middle of 2007, Europe-wide legislation demands that many items of waste electrical and electronic equipment must be collected and disposed of separately, and this legislation is likely to apply to at least some items of SCWT.
New legislation is designed firstly to restrict the use of certain traditionally used substances, and secondly to control legacy substances in already manufactured items.
The first regulation contain as it does a requirement for producers or importers of consumer equipment to arrange to take back end-of life electrical and electronic equipment for environmen-

tally-sound and safe disposal. It's applyed to ten product types, covering a wide range of consumer equipment.
The second can be seen as applying prohibitions to manufacturers making or importing electrical and electronic items, rather than the public buying products. It's designed to prevent the use of six substances recognised as particularly hazardous to the environment.
These include lead, traditionally used in solder as well as mercury and cadmium, often found in miniature power supplies.One way of understanding the problems associated with disposal of these mixed substance items, whether they represent those with a SCWT content or not, it is to consider how firmly the 'contaminant' is attached to the item. Those that are loosely attached can be removed and perhaps reused, but those that are firmly attached and closely integrated into the item become difficult to remove.
As an example, within a garment, system interconnections such as wires could be woven or knitted into the fabric structure before the garment is made up. This would be regarded as a very high degree of integration, and would thus represent a situation where reuse/recycling would be made more difficult. A design where such interconnections could be added after a garment is constructed, possibly under an openable flap designed into the seams, would help eventual recycling because they could be more easily removed. This would represent a much lower degree of integration. [39]

[39] J. McCann, op. cit., p. 319-320

Below there is a scheme of the degree of recycle textile items. (fig.20)

Figure 20
Recycling level of different textile products. [39]



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Chapter 2 | Smart textiles applications

In the past few decades, many desk electronic appliances have been made portable because of constant miniaturisation in electronics. It is reasonable to assume that, in the future, some of these portable devices will become so small and convenient to carry that they will be wearable. Applications of the technology will be widespread and far reaching. [1]

The Industry can be broken into four loose areas:

• Sports;
• Healthcare/Medical;
• Fashion/Entertainment;
• Military/Public sector.

The areas do overlap in some places, often with similar or even the same technology being repackaged for a different end-use.

2.1 Sports

The sports sector has historically been an early adopter of technical textiles and 'high tech' solutions, and this early adopter status has not changed for commercial smart clothes and wearable technology products. This category can also be broadly divided into training/professional sports and casual sports. Each category uses different types of technology. Training and professional sports use bio-physical monitoring technologies, overlapping with healthcare. Casual sports have largely been incorporating

[1] X.M. Tao, Wearable Electronics and Photonics, Woodhead Publishing Ltd, 2005, p. 8

entertainment and communication technologies into clothing. Adventure sports such as snowboarding and mountaineering have recently been leading this trend. [2]

PoloTech Shirt

The inconic Polo shirts from Ralph Lauren (fig. 2.1) have now gone to the high tech world of smartclothing. Silver fibers woven directly into the fabric read heart rate and breathing depth and balance, as well as other key metrics, which are streamed to your device via a detachable, Bluetooth-enabled black box. Biometric data is stored and can be manipulated on an app through a smartphone or tablet. [3]

Figure 2.1
PoloTech Shirt, Ralph Lauren. [3]

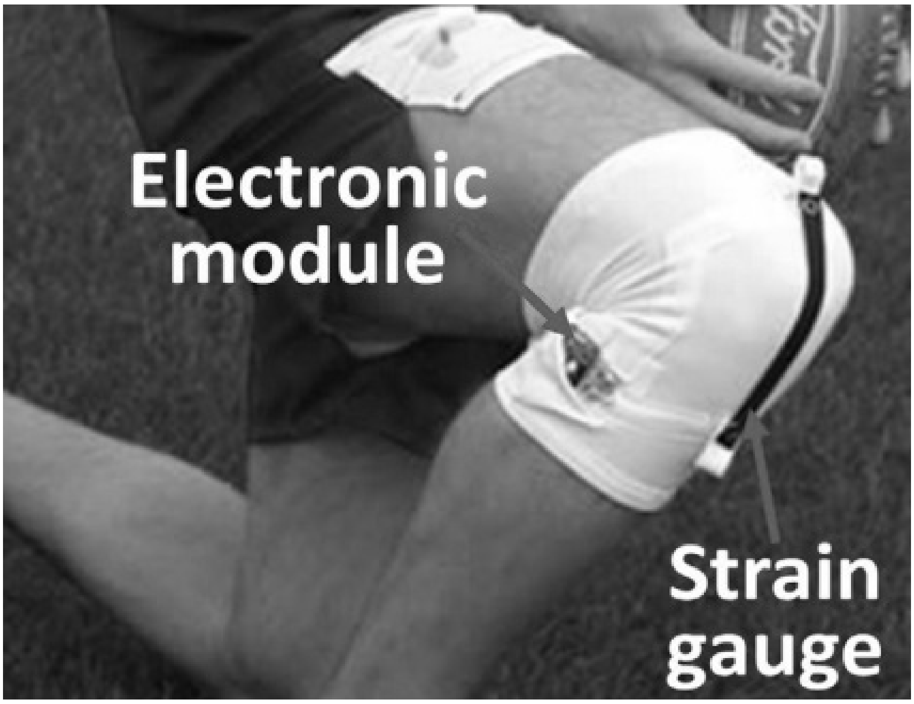
[2] J. McCann, D. Bryson, Smart Clothes and Wearable Technology, Woodhead Publishing in Textiles, CRC Press, 2009, p. 39.

[3] www.ralphlauren.com

Intelligent Knee Sleeve

University of Wollongong has developed an Intelligent Knee Sleeve (IKS; CSIRO Textile and Fibre Technology, Clayton South, VIC, Australia) for injury prevention (fig. 2.2). It provides immediate audible feedback to the wearers with respect to their knee angle. A fabric sleeve is worn around the knee, with a flexible strain gauge attached over the knee-cap and linked to small electronics. The electronic module has been miniaturized into a few centimeters and simply snapped to the side of the sleeve (Munro et al., 2008). The core-sensing technology is a piezoresistive sensor, which is applied to detect local strain on the fabric. A flexible strain gauge is created by coating the Lycra fabric with a thin layer of polypyrrole, which is inherently conductive (Wang et al, 2011; Li et al., 2005). [4]

Figure 2.2
Intelligent Knee Sleeve.
[4]



[4] Tilak Dias, Electronic Textiles, *Smart Fabrics and Wearable Technology*, Woodhead Publishing, 2015, p. 265.

2.2 Healthcare

There are many wearable technology solutions for medical monitoring. They are usually designed with just one thing in mind, getting the readings, which is usually accomplished very effectively. However, these devices are often uncomfortable, unsightly and awkward to use, leaving patients feeling self-conscious and lacking the desire to use the devices. Medical healthcare products have a greater emphasis for constant monitoring of biophysical data; for example, ECG, respiration rate, blood pressure, temperature and movement. Medical testing of these products is essential, with each country having its own set of clinical testing requirements that need to be achieved before a product can be used in a clinical environment. This is often an important factor for companies developing bio-monitoring technologies, as it can cost large amounts of money for product testing. Several companies have targeted the sports industry initially and have later moved onto the medical industry as their products have been developed further, gaining the levels of accuracy and consistency that are required for clinical use. There are two main types of healthcare products: those that are prescribed by a physician (medical healthcare) or those that are purchased by individuals who are concerned with their general heath (well-being).

Examples of the latter products and developments include the Wealthy project (Wealthy, 2005), LifeShirt (Vivometrics, 2007), MyHeart Intelligent Biomedical Clothes (MyHeart, 2008) and HeartCycle (Phillips Research 2008).

As there is a greater awareness of the need to keep fit and personal wellbeing, continuous monitoring and keep-fit solutions overlap with sports products.

Wealthy project

The "Wealthy project" (fig. 2.3) was one of the first EU-projects aiming to set up comfortable health monitoring system based on textile sensors, advanced signal processing techniques and modern telecommunication systems. The focus areas were cardiac patients during rehabilitation but also to assist professional workers to consider physical and physiological stress and environmental and professional health risks. In this project two types of sensors were developed for the integration in garments. The first sensor was a lycra based fabric coated with carbon black and rubber for the recording of breathing rate. The other sensor was made of metal-based yarns for the monitoring of heart rate. All sensors were integrated in a fully garment knitting process. Together with the textile development a miniaturized short-range wireless system was developed in order to transfer biophysiological signals from the garment to a computer or a mobile phone. [6]

[5] J. McCann, op. cit., p. 319-320

[6] www.smartex.it

Figure 2.3
Wealthy project, wearable wellness system. [6]

WarmX - silverSun

WarmX (fig. 2.4) is a manufacturer and distributor of heated knitted underwear system. The company has an own worldwide-patented technology for heating textiles called warmX-technology and " know how" and partners in both textiles and electronics. The warm heatable underwear from warmX will keep the wearer nice and warm on those freezing winter days. Silver-plated polyamide threads have been woven into the underwear and warm up directly on the skin. The small battery control unit, of similar shape and size to a cell phone, has three settings and supplies sufficient energy to keep warm for up to six hours at a stretch. The heated underwear works without heater wires of any kind, it is kind to the skin and is machine washable. Incidentally, sufferers from muscular tension and certain back or renal problems will benefit from the soothing and analgesic effect provided by heat applied directly to the skin, an effect which can be enhanced still further by well-insulated outer clothing. [7]

Figure 2.4
WarmX SilverSun, heated knitted underwear system, WarmX company. [7]

[7] www.wellness.warmx.de

2.3 Fashion and entertainment

A fascination with technology means that the incorporation of cutting edge technology is common in the fashion industry. Designers such as Alexander McQueen, Erina Kasihara, Diana Drew and Hussein Chalayan have all produced ranges that explore the integration of technology into clothing. Suzanne Lee's book Fashioning the Future: Tomorrow's Wardrobe(Lee, 2005), takes an in-depth look at the relationship between fashion and technology. The incorporation of electronic technologies into everyday clothing remains relatively uncommon. Entertainment in the form of music and communications is currently leading the way, with the integration of iPod and mobile phone control systems being examples of the few attempts at promoting smart clothes and wearable technology for everyday use. This is likely to expand in the future to include more sophisticated devices such as portable media and games players. [8]

Hub snowboard jacket

Infineon Technologies and O'Neill Europe unveiled the result of a joint product development project on January 2014, a wearable electronics snowboard jacket (fig. 2.5) with functions such as an MP3 player and mobile telephony by Bluetooth.

Conductive yarns are woven into snowboard jacket, which connect the chip module to a fabric keyboard and built-in speakers in the helmet. The chip module contains a full-featured MP3 player and a Bluetooth module via which the snowboarder can control

[8] J. McCann, op. cit., p. 40

a mobile phone. If the snowboarder wants to make a phone call, the stereo system acts as the headset. The microphone is integrated in the collar of the jacket. [9]

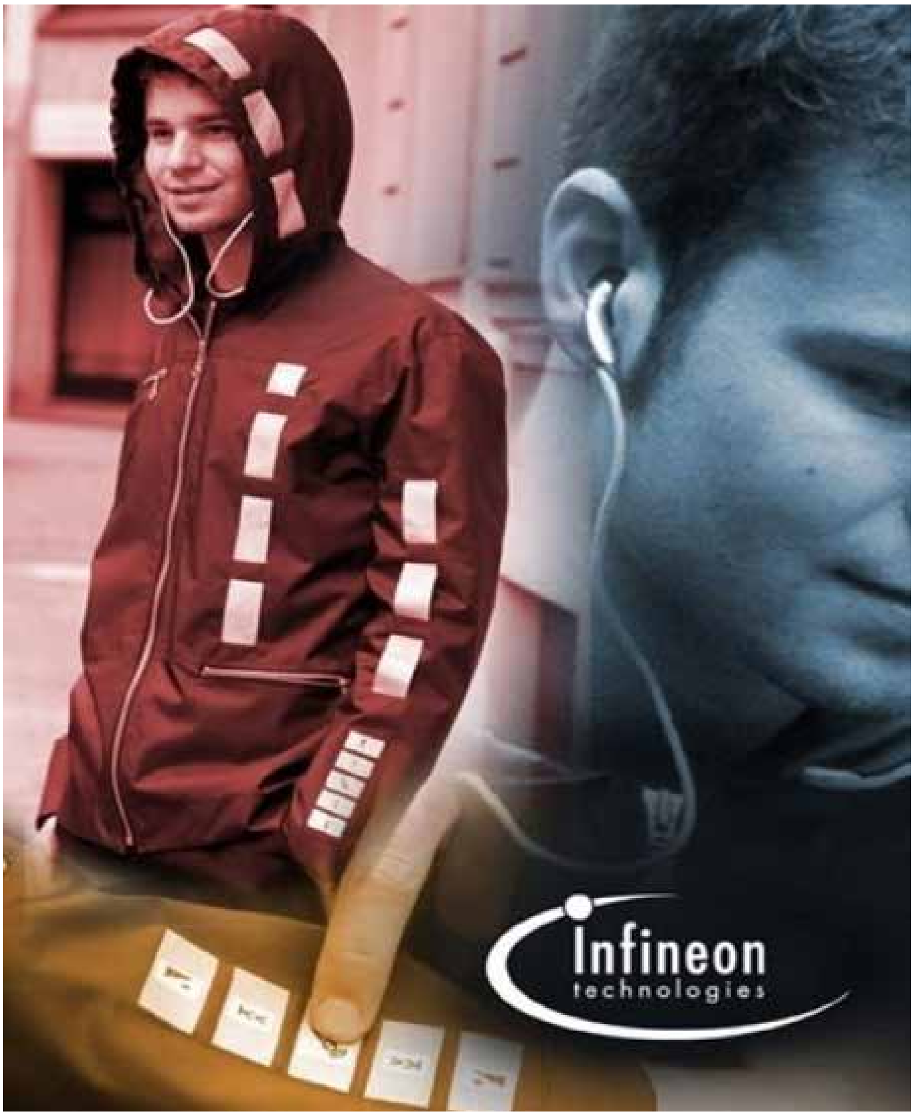


Figure 2.5
Hub snowboard jacket, Infineon Technologies and O'Neill Europe, 2014. [9]

[9] www.infineon.com

Solar-powered jacket

Solar cells have been used in certain smart textile applications, for example in SilverLining's GO solar power collection (Fig. 2.6). Kinetic energy, perhaps in combination with solar energy, is an interesting option. Excess body heat could be recovered and used for powering embedded electronics by capitalizing on the Seebeck effect. The Seebeck effect was discovered by East Prussian scientist Thomas Seebeck in 1821. He noticed that a temperature difference between two metals in a circuit converts into thermoelectric current. Kinetic energy could also be harvested from a flexible piezoelectric-textile system, for example with a disk that generates voltage when deformed under pressure. [10]

Figure 2.6
Solar-powered jacket, SilvrLining Company. [10]

[10] R. Sinclair, *Textiles and Fashion, Materials design and Technology*, Elsevier Science, Woodhead publishing in textiles, 2014, p. 371

2.4 Military, public sector and safety

The military has been one of the largest funders of wearable computing and wearable technologies. Communication and battlefield command systems use a combination of personal, vehicle (ground, air and water), static and satellite technologies that all work together. The US military in particular has been very active in the development of smart clothing and wearable technology solutions. The Naval Air Technical Training Center's (NATICK) Future Force Warrior programme is developing fully bionic warrior suits that it hopes to introduce by 2020. This suit would include intelligent armour, biomonitoring, weaponry, communications and exoskeleton (NATICK, 2006).
First responder services, such as the police, fire and ambulance, are now also beginning to use smart clothes and wearable technologies. In some parts of the UK, police forces are now using head mounted cameras and Personal Data Assistants (PDA) for storage and transmission systems to record information as they patrol and interview suspects and witnesses. This will act very much like the in-car video recording systems that are widely used. Safety products for monitoring personnel in hazardous or remote environments are also highly desirable, such as monitors of chemical exposure levels and biophysical status. [11]

ProeTEX project
Financed by the European Commission, universities, research institutions, industries, and organizations operating in the field of emergency management, a new generation

[11] J. McCann, op. cit., p. 40-41

of "smart" garments were developed, for emergency-disaster personnel. This project, called ProeTEX (Protection e-Textiles: Micro-Nano-Structured fiber systems for Emergency-Disaster Wear) started on February, 2006. ProeTEX has developed textile and fibre based integrated smart wearables for emergency disaster intervention personnel with a goal of improving their safety, coordination and efficiency and additional systems for injured civilians aimed at optimising their survival management (fig. 2.7). The system enables detection of health-state parameters of the users (heart rate, breathing rate, body temperature, blood oxygen saturation, position, activity, and posture) and environmental variables (external temperature, presence of toxic gases, and heat flux passing through the garments), to process data and remotely transmit useful information to the operation manager. [12]

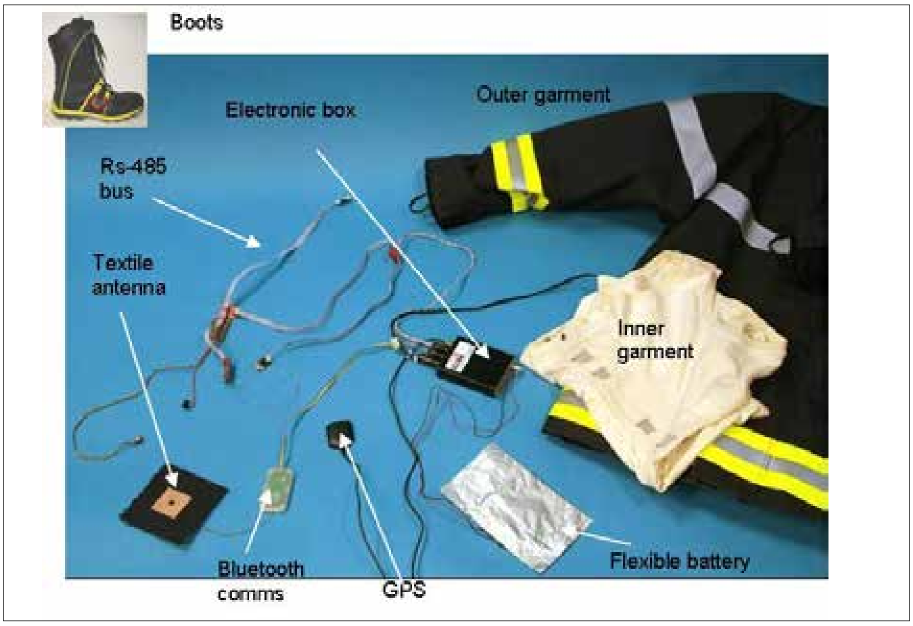


Figure 2.7
ProeTEX project, Financed by the European Commission, 2006. [12]

[12] R. Chapman, *Smart textiles for protection*, Woodhead Publishing, 2013.

Zackees Turn Signal Gloves

A new company aims to make turn signals a much simpler, more secure, and cooler safety feature with a pair of bike gloves that have blinking LED lights inside them. The lights can be turned on easily by the rider simply pushing his index finger or thumb together and activating a contact pad. The product, called Zackees (fig. 2.8), it can support a rechargeable battery or use a long lasting non-rechargeable one along with battery-saving features. "Zackees Turn Signal Gloves" is shown below. [13]

Figure 2.8
Zackees Turn Signal Gloves, Zackees Company. [13]

[13] www. zackees.com

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'Wealthy project' can be found under http://www.smartex.it/index.php/en/

‘WarmX silverSun’ can be found under http://www.wellness.warmx.de/index.php/silversun.html

‘Hub snowboard jacket’ can be found under http://www.infineon.com/cms/en/about-infineon/press/press-releases/2004/128309.html

R. Chapman, *Smart textiles for protection*, Woodhead Publishing, 2013.

‘Zackees Turn Signal Gloves’ can be found under
https://zackees.com/

Chapter 3 | Conductive yarns

Different approaches can be applied to produce electrically conductive fabrics:

1. By weaving conductive yarns into the textile structure: with this technique, the softness and comfort of the final composite textile can be degraded.
2. Recently, conductive coatings and inks have been applied onto fabrics and papers to provide flexibility to the systems and reduce stress on the substrate. The conductive coating can be deposited on a non-conductive substrate through classical printing techniques.
3. Another approach is to develop surface treatment adequate for application of existing conductive inks meaning inks that were developed for non-flexible substrates.

The following chapters 3-4 will focus on the first two approaches. Chapter 3 will give an overview of conductive yarns integrated into textiles. Chapter 4 will focus on conductive inks for printed electronics.

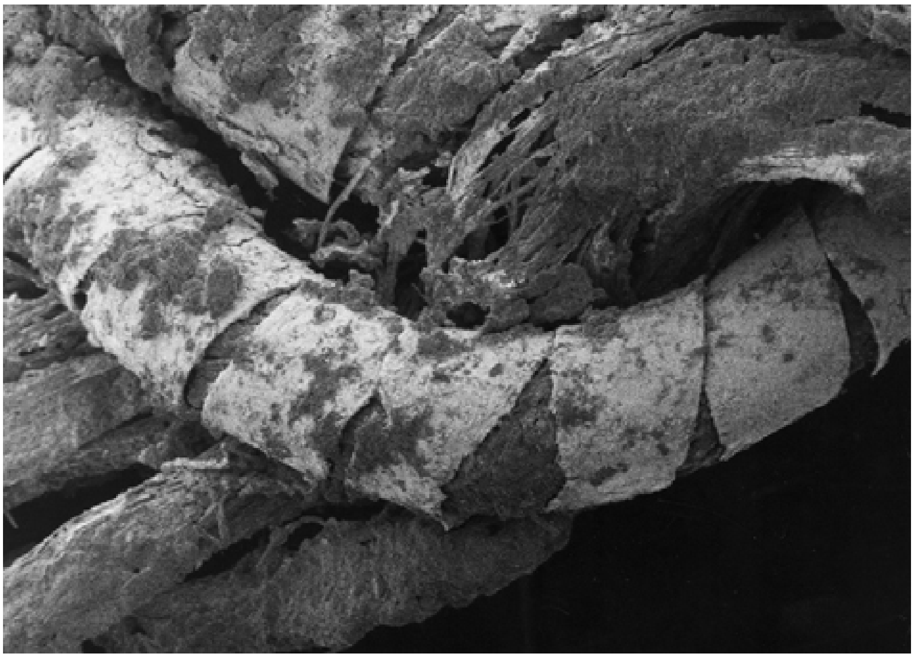
3.1 A brief history of conductive yarns

Electrically conductive textile fibres have a long history that goes back to antiquity. For example, gold-coated threads were produced in ancient times before the modern discovery of electricity but they were, clearly, designed for aesthetic purposes alone. After the modern discovery of electricity, various electrically conductive wires such as copper, iron, steel, brass, platinum, silver, German silver and gold have been used (Noad, 1859) in non-textile applications. Fibres specifically designed for electrical con-

ductivity started to appear in the late nineteenth century. Thomas Edison took out a patent for an electric lamp in 1880. The filament was made from carbonized cotton and linen threads, wood splints and paper (Edison, 1880). The early twentieth century saw thinking focus on more practical combinations of electrical functionality and textiles. For instance, a patent from 1911 describes electrically heated gloves for drivers (Carron, 1911). A major development was the discovery and development of conducting polymers by Heeger, MacDiarmid and Shirakawa in 1977 (Shirakawa et al., 1977). Heeger, MacDiarmid and Shirakawa won the Nobel Prize for chemistry in 2000 for their work (NobelPrize.org, 2014).

In modern times, metal wires, metal-wrapped yarns, metal-coated yarns, inherently conductive polymers and other technologies have been employed to confer electrically conductive pathways to textiles.

Figure 3.1
Silver-wrapped silk thread from the seventeenth century.
[1]



3.2 Conductive fibres & yarns

With the high growth in wearable devices and electronic textiles in particular, there will be an added impetus for the development of electrically conducting pathways with properties more in line with conventional fibres and yarns.
A fibre may be defined as a structure that is fine, flexible and exhibits a high length to-width ratio.
A conductive fibre can be defined as an electrically conductive element having the structure of a fibre. Thus, a metal nail and thick copper wire are electrically conductive but not fibres, as they are neither fine nor flexible. In contrast, for the present purposes, a fine copper wire and silver-coated polymer fibre can both be categorized as conductive fibres. Electrically conductive fibres can be used for anti-static, anti-microbial, anti-odour, shielding and other applications. In electronic textiles, the conductive elements can provide power, deliver input and output signals or act as a transducer. The electrical resistance of metals is of the order of 10^{-5} Ωcm, whereas that of a typical insulator would be 10^{12} Ωcm. The electrical resistance of natural fibres is governed by the humidity of the air to which they are exposed. [1]

[1] Tilak Dias, Electronic Textiles, Smart Fabrics and Wearable Technology, Woodhead Publishing, 2015, p. 3-4.

3.3 Process of creating conductive fabric

Methods of creating electrically conductive yarns could be categorized in these main classes:

- *filling synthetic fibres with carbon or metal particles*
- *coating fibres with conductive polymers or metal*
- *yarns twisted/embedded with metallic filaments*
- *using continuous or short fibres that are completely made of conductive material.*

One or more strands of these conductive yarns are integrated into the fabric substrate to form a textile transmission line. Successful integration creates reliable conductive traces on the fabric while protecting the traces against repeated dimensional changes or abrasions in order to maintain long-term conductivity.
Main integration methods found in the literature to create conductive fabrics are divided in:

- *woven*
- *knitted*
- *sewn*
- *embroidery*

The simplest way to embed conductive yarn in fabric is to weave it as one of the warp or weft yarns. Empirically, plain weave has been preferred because its construction represents the most elementary and simple textile structure, in which no lateral yarn movement is possible and a very stable fabric structure is created. Consisting of interconnected loops, knitted structure is known for its stretchability. No other textile materials can be incorporated *except the conductive yarn itself because only one continuous yarn is interlaced. Knitting requires more flexible yarns than do any other structures because the yarn is highly curved to form a loop.*

A conductive yarn can be stitched on the fabric surface to create a conductive trace. A sewn trace forms a similar structure to the plain fabric woven with conductive yarns. It is beneficial that a sewing line can cross over seams in apparel composition. Embroidery was previously understood as being just for decorative purposes, but it opens much potential for smart textiles. Conductive threads can be either embroidered or couched by traditional embroidery threads. In this case the fabric becomes more rigid and offers poor flexibility. [2]

3.4 Types of conductive fibers & yarns

With the rapid development of the electrical and, particularly, the electronics industry, flexible electrically conductive and semi-conductive materials, such as conductive polymers, conductive fibers, optical fibers, threads, yarns, , coatings and inks, are receiving widespread attention. They are playing a more and more important role in realising lightweight, wireless and wearable interactive electronic textiles.

Metal fibres

Nowadays polymers are very strong. For example, weight-for-weight nylon and the para-aramids are stronger than steel. However, most polymers are electrically insulating (Bakhshi, 1995).

[2] www.textileworld.com

The advantage of metals is their very low electrical resistance. (The resistance of typical metals is shown below, tab. 3.1)

Table 3.1
Resistivity of metals
(Chung, 2010)
[3]

	Resistivity at 20° C (Ωm)
Silver	1.59×10^{-8}
Copper	1.72×10^{-8}
Gold	2.44×10^{-8}
Iron	1.0×10^{-7}

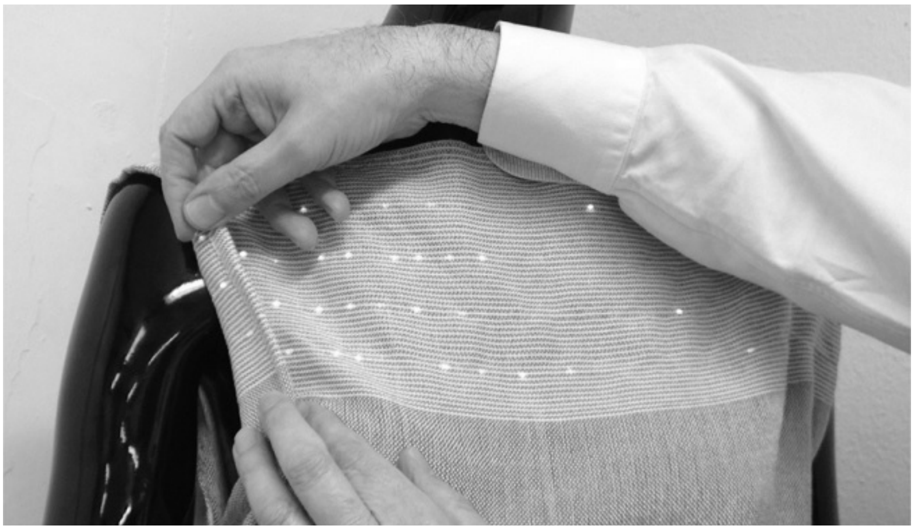
A disadvantage of metal wires is that they have low elasticity and strength and can break (Cherenack and van Pieterson, 2012). Some metal-coated fibres and fabrics can corrode and crack after time (Buechley, 2007).

Conductive fibres are usually woven into the fabric, creating a bus to connect conventional printed circuit board (PCB) electronics or as shielding in high-performance interconnect cabling. Fine metal wires may be directly integrated into the fabric or yarn structure. In some applications, there is a need to insulate the wires. This can be achieved by the application of an insulated coating.

Recently, fine polymer-coated copper wires have been introduced into the core of yarns (Cork et al., 2013) to power electronic components. Keeping the electronic components and interconnects within yarns ensures that the electronics are not visible on the surface and that the textile retains its desired mechanical characteristics.

An example of a garment produced using this technique is shown below (fig. 3.2).

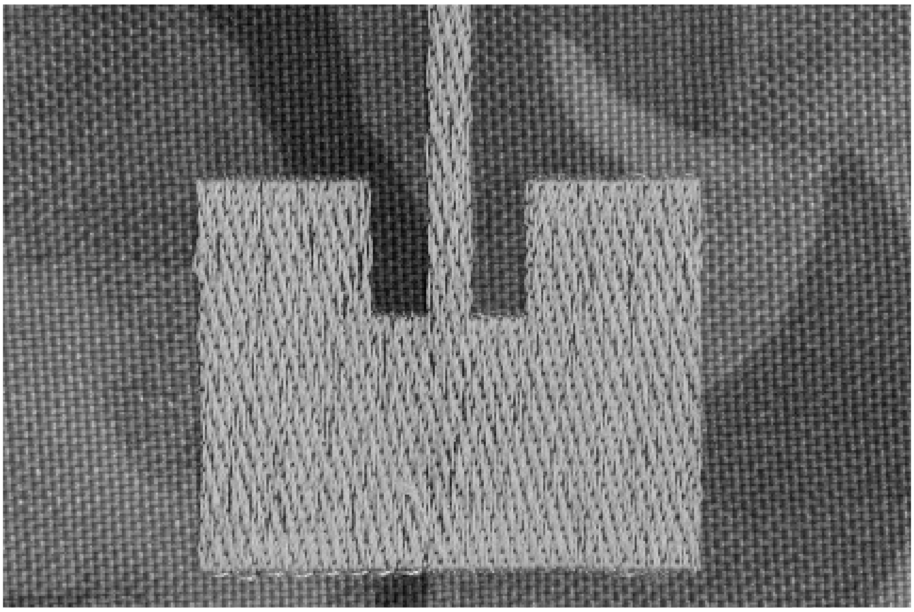
Figure 3.2
Garment with fully integrated LEDs.
[3]



Metallized fibres

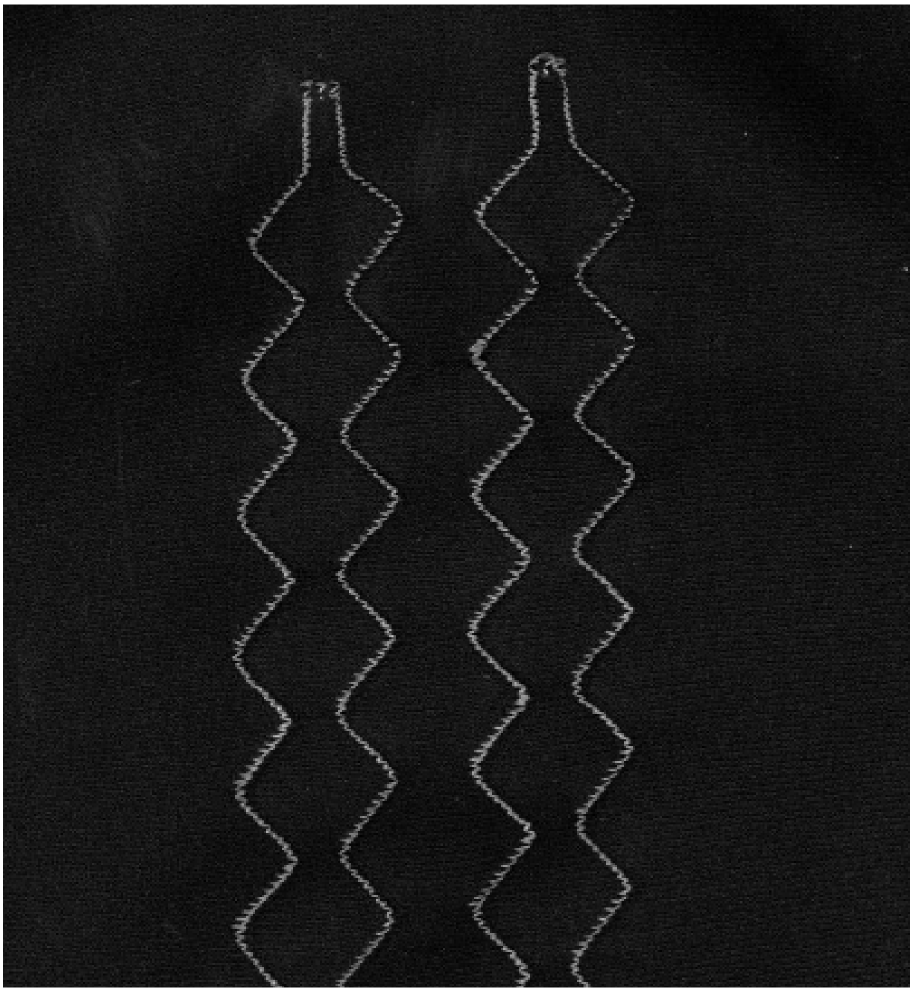
Another approach is to add a metallized coating directly to a core yarn. In the commercial products, a number of base fibres are used. Coatings include nickel, copper and silver. An embroidered antenna produced at Nottingham Trent University is shown in figure 3.3.

Figure 3.3
Embroidered antenna
[3]



Noble Biomaterials also markets X-Static, a polymer fibre coated with metallic silver (X-Static, 2014). X-Static fibres are produced by coating conventional fibres with 100% surface area coverage of 99.9% pure silver.
These are primarily marketed for their antibacterial properties. The use of silver-coated nylon has been utilized for the construction of knitted strain sensors (Atalay et al., 2013). Figure 3.4 shows a textile strain sensor created at Nottingham Trent University by incorporating silver-coated yarns into the structure. [3]

Figure 3.4
Stretch sensor knitted by silver coated yarns, (Atalay et al., 2013).
[3]



[3] Tilak Dias, op. cit., p. 7-9.

Conductive carbon nanotubes and fibres

Carbon nanotubes hold much promise but are currently very expensive to produce. The fibre is produced using a wet spinning technique based on the short carbon nanotubes. Carbon nanotubes (CNTs) possess extraordinarily high mechanical properties combined with electrical and thermal conductivity. The challenge is to organize these building blocks into macroscale structures that express similar properties. Without considering their detailed atomic structures, CNTs are nanoscale fibres that resemble the diameter of microfibrils in plant and animal fibres. The CNTs used to spin yarns are very long relative to their diameters, with aspect ratios at least one order of magnitude greater than common textile fibres (Miao, 2013). CNTs can be processed into fibres and yarns in several ways: (1) extruding a fibre from a CNT/polymer solution, (2) spinning a yarn from a vertically aligned array (known as a forest) of multi-walled CNTs (MWCNTs) grown on a substrate, (3) spinning a yarn directly from an aerogel of CNTs as they are formed in a chemical vapour deposition (CVD) reactor and (4) twisting or rolling a macroscale CNT sheet into a yarn. Yarns fabricated by dry-state drawing and spinning of CNT forests have demonstrated the best mechanical properties to date. Figure 3.5 shows the resultant yarn used to both power and support a light. [4]

[4] *ivi,* p. 12.

Figure 3.5 Carbon nanotube fibre.

Figure supplied by Professor Matteo Pasquali of Rice University. [4]

Electrically conductive strips

The Wearable Computing Lab at ETH Zurich has developed a process for mounting devices on flexible plastic strips. The 2-mm-wide strips contain the metal bond pads and interconnect to link components, they are woven into the textile in the weft direction in place of standard yarns (Zysset et al., 2012). In another paper, the functionality of the strips coated with copper after bending is described (Cherenack et al., 2010). Another approach is to print conducting lines onto insulating plastic strips. Figure 3.6 shows an illuminated fabric, created by Nottingham Trent University and the University of Southampton (Beeby et al., 2014), where light-emitting diode (LED) chips have been mounted on such a strip before embedding into a fabric. When not illuminated, neither the LEDs or strips are visible on either surface. [5]

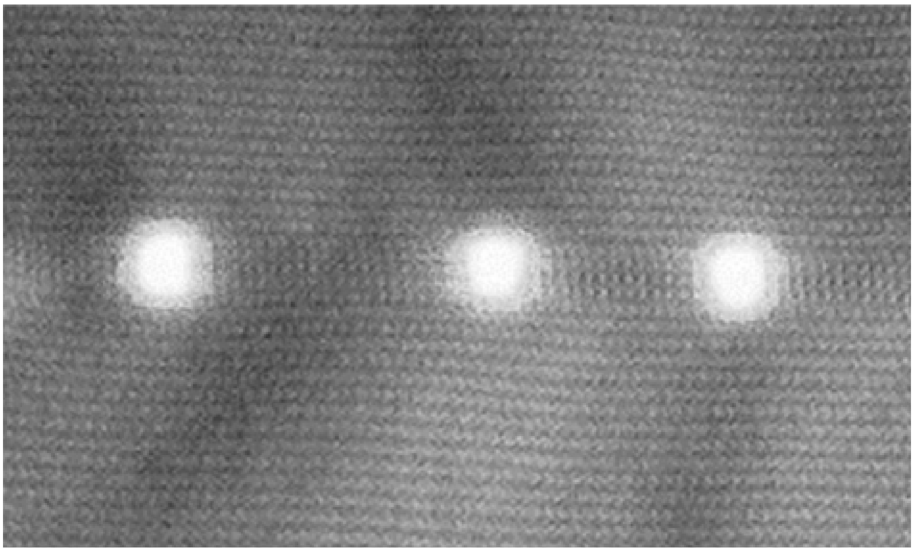


Figure 3.6
Illuminated plastic strips within a fabric.

Nottingham Trent University and the University of Southampton (Beeby et al., 2014)
[5]

[5] *ivi,* p. 10-11.

Inherently conductive polymers (polyaniline, polypyrrole)

There is increasing use of intrinsically conductive polymers in smart clothing as sensors and actuators (Cho, 2010). In 2000, the Nobel Prize in Chemistry was awarded jointly to Heeger, MacDiarmid and Shirakawa for the discovery and development of conductive polymers. Electrically conductive yarns can be created using polyaniline (PANI) and polypyrrole (PPy) by either melt spinning or a coating process (Kim et al., 2004). PANI has low cost, good processability and good stability features (Razak et al., 2014). [6]

Conductive polymer yarns

Many of the conductive yarns used in the current generation of smart textiles are fabricated from metal yarns/fibers made from copper, stainless steel (SS), silver, brass nickel, and their alloys (swicofil, n.d.a). These metallic yarns, though featuring relatively high electrical conductivities, are generally heavier and stiffer than commercial textile yarns based on the polymer materials such as nylon, wool, and cotton. This would not only add weight to the textiles or garments fabricated thereof, but also make the garments physically uncomfortable or even unwearable, thus resulting in inconvenience for daily application. Therefore, a strong motivation has arisen for the development of polymer-based conductive yarns.
An overview of recent progress in the development of conductive polymer yarns (CPYs) could be classified into two categories: ***bulk CPYs*** *and* ***surface CPYs.***

[6] *ivi,* p. 11.

Bulk CPYs

Bulk CPYs is divided into three subclasses:

1. intrinsically CPYs

2. polymer yarns twisted/embedded with metallic filaments

3. polymer yarns filled with conductive additives.

1. Intrinsically CPYs

Intrinsically conductive polymers (ICPs), also known as conjugated polymers, are organic polymers that can conduct electricity. ICPs have been under intense investigation during the last 50 years; however, fibers or yarns based on the pure ICPs were not reported until the 1980s, because it was believed that ICPs were intractable from a conventional polymer-processing viewpoint (Skotheim and Reynolds, 2006). The majority of ICPs are nonthermoplastic materials that decompose at a temperature lower than their melting point, such that these ICPs cannot be melt-processed. One, therefore, has to resort to a solution-spinning method for fabrication of ICP fibers/yarns. This method is mainly focused on ICP fibers based on polyaniline (PANI) and polypyrrole (PPy), because these two ICPs are readily dissolved in a number of solvents.

2. Polymer yarns twisted/embedded with metallic filaments

One of the simplest methods of fabricating polymer conductive yarns is to blend metal filaments or wires directly into traditional textile polymer yarns. Such conductive yarns can be readily fabricated by conventional yarn-spinning techniques such as the ring-spinning method or open-end spinning method. Generally speaking, the resistance of metal-wire-blended polymer yarns is relatively low (0.2–200 O/m), owing to the high conductivity of me-

tal fibers in the yarns. Typical structures of hybrid polymer–metal yarns (fig. 3.7) is categorized into three subclasses: metal-core yarns, polymer-core yarns, and polymer–metal braided yarns. Generally speaking, metallic wires (e.g., SS wires) are stiff, which makes them difficult to weave or knit directly on conventional weaving looms or knitting machines (Maier et al.,2005).

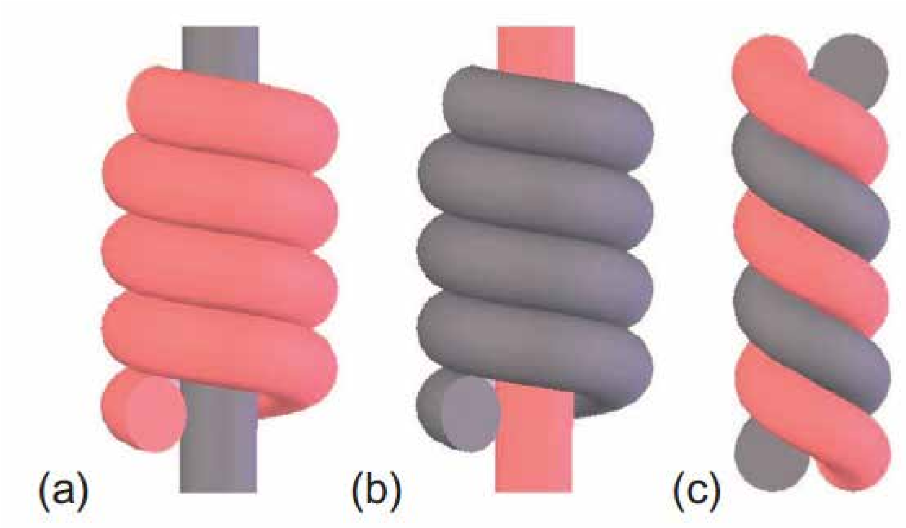


Figure 3.7
Three typical structures of hybrid polymer–metal yarns: (a) metal-core yarns, (b) polymer-core yarns, and (c) polymer–metal braided yarns.

(Polymer fibers are shown in red, while metallic fibers are shown in gray). [7]

Wrapping metallic wires with a polymer sheath could effectively reduce the friction between the yarn and a textile-weaving loom, which is favorable for textile fabrication. In addition, the polymer sheath could provide the metallic core with effective protection against mechanical abrasion (Byrnes and Haas, 1983; Toon, 1994), thus avoiding loss of yarn conductivity due to routine utilization. On the negative side, the yarns using this structure normally suffer from relatively low extensibility.

3. Polymer yarns filled with conductive additives

CPYs can be fabricated by dispersing carbon based (CB) particles into traditional textile yarns. This technique was investigated *intensively from the 1970s to 1990s. The main advantage of filled polymer yarns is low cost, commercial availability, and the ease of the synthesis process of the yarns.* [7]

Surface CPYs

Surface CPYs are polymer yarns coated with conductive layers. The conductive coatings may consist of metals, conductive polymers, or other conductive materials such as CNTs or CBs. Polymer yarns with metallic coatings constitute one of the most popular products in the current "conductive yarn" market (swicofil, n.d.b; alibaba, n.d.; alibaba.com, n.d.), because these yarns can be conveniently fabricated by a simple metal-deposition treatment to a number of commercial textile yarns. A variety of coating techniques have been suggested and commercially used, including polymer–metal lamination, physical vapor deposition (e.g., sputter deposition), metallic-paint brushing, and electroless plating (Alagirusamy and Das, 2010; Zhang et al., 2011). A disadvantage of the metal-coated yarns is that the metal layer may be peeled off due to washing or other types of mechanical abrasion. This would compromise the yarn conductivity and may lead to a short-circuited connection for the yarns woven into a textile. [8]

[7] *ivi,* p. 23-35.

[8] *ivi,* p. 36-39.

Optical fibers

'Smart' textiles are an interesting class of electronics and photonics textiles. A new class of smart textiles is composed of integrated fibre optic sensors and networks. Optical fibres are compatible with textile structures, they are similar to textile fibers and can be ideally processed like standard textile yarns.
In its basic form, an optical fiber (fig. 3.8) is a hair-thin, highly transparent strand of glass comprised of three parts:

(1) the core that carries information in the form of light signals;
(2) the cladding which surrounds the core trapping the light within it;
(3) the durable, protective outer coating. Encoded into light signals, information travels through the fiber where it is decoded locally or thousands of miles away. [9]

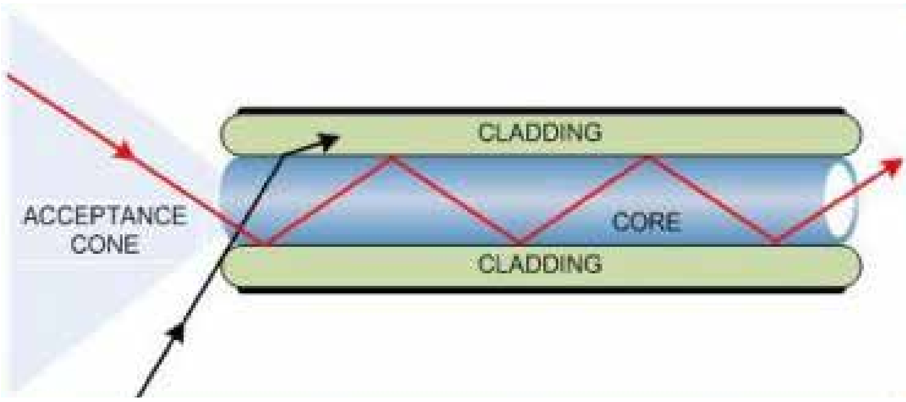


Figure 3.8
Optical fiber
general scheme.

Optical fiber (or "fiber optic") refers to the medium and the technology associated with the transmission of information as light pulses along a glass or plastic strand or fiber. Optical fiber carries much more information than conventional copper wire and is in general not subject to electromagnetic interference and the need to retransmit signals. The optomechanical properties of the fibres *are the major characteristics considered in smart textile applications. The selected fibres have to have the properties of flexibility and small bending loss. There are many types of fibres on the market, from single-mode to multimode fibres, and from all-silica to all-polymer fibres, with a variety of combinations of material properties and core and cladding geometry.*

Optical fibres are currently being used in textile structures for several different applications. For example, using optical fibres as sensors to measure strain and temperature in composite structures, or creating textile-based displays based on fabrics made of optical fibres and classic yarns (fig. 3.9). The screen matrix is created during weaving, using the texture of the fabric. Integrated into the system is a small electronics interface that controls the LEDs that light groups of fibres. [10]

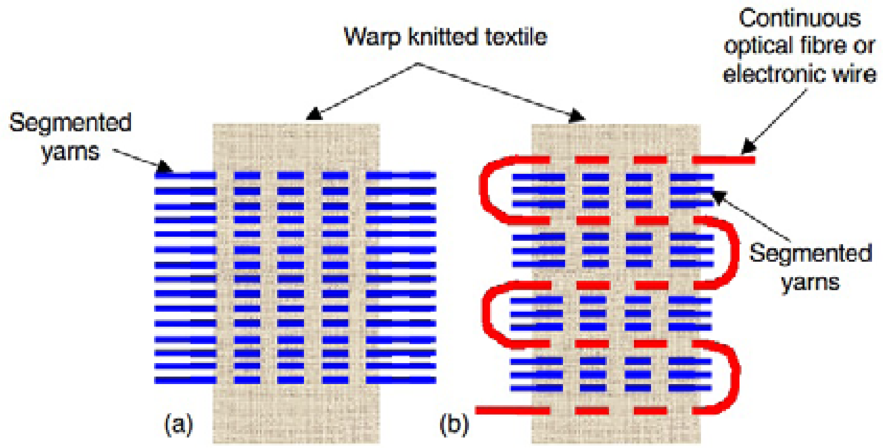


Figure 3.9 Schematic diagrams of (a) segmented yarns and (b) continuous optical fibre, taking a serpentine shape. [10]

[9] X.M. Tao, Wearable Electronics and Photonics, Woodhead Publishing Ltd, 2005, p. 105.

[10] *ivi,* p. 165.

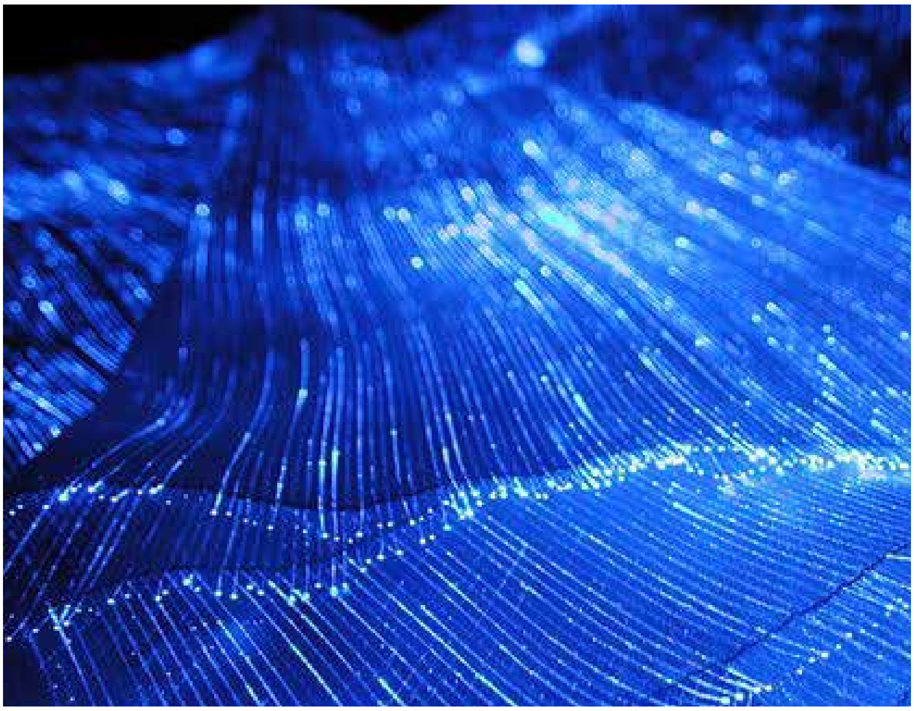


Figure 3.10
Optical fibres embedded in a piece of fabric.

3.5 Summary

With strong growth expected in electronic textiles, it is essential that conductive elements meet not only environmental considerations, but also aesthetic and functional properties.
Electrically conducting fibres should be easily connected to other components and should be highly conductive with an insulated sleeve. They should be resistant to processing and, if required, be machine washable and robust to tumble drying. They should resist damage through fatigue, a major cause of fibre damage (Miraftab, 2009). Ideally, the fibres would also be dyeable. Another factor is the elastic recovery of fibres, although in many cases poor recovery of a fibre can be offset by the choice of fibre geometry within a yarn (e.g., spiral paths) and the inclusion of elastomeric yarns. These requirements are almost certainly unachievable in the near future but could be considered long-term

aims. It is recognized that the recycling of textiles is an important factor and the introduction of electronics will present some challenges. Kohler and Som (2013) have pointed out that electronic textiles may result in adverse side effects during the life cycle of products. Conversely, the introduction of radio frequency identification devices into textile structures would aid identification of constituent fibre types and, after removal, lead to more accurate and efficient recycling procedures. [11]

[11] Tilak Dias, op. cit., p. 14-15.

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Tilak Dias, Electronic Textiles, Smart Fabrics and Wearable Technology, Woodhead Publishing, 2015.

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www.textileworld.com

www.textronic.com

Chapter 4 | Conductive inks

By definition, a conductive ink is an ink that conducts electricity. Such conductive inks usually consist of metallic particles in a medium which allows them to be printed.
They can be used to dissipate static energy and protect from electromagnetic fields alongside other attributes such as antiallergic and anti-bacterial properties. Conductive inks remained fairly stable for decades, only in recent years there have been improvements, as well as innovative new inks to meet the challenges offered by printed electronics making electronic functions possible. Printed electronics is the term that defines the use of traditional graphic printing methods to manufacture circuits on media such as polymer films, paper, textiles, and other materials. The promise of low-cost, high-volume, high-throughput production of electronic components or devices that are lightweight, small, thin, flexible, inexpensive and disposable has spurred the recent growth in development of printed electronics technology.
One of the biggest issues challenging its development was the lack of materials, particularly conductive inks that could meet the necessary electronic requirements in a thin-film. Conductive silver inks for circuit boards and membrane switches printed in a thick layer via the screen process had been available for many years; but the new printed electronics would require similar conductivity in a much thinner film to meet the requirements of the potential applications cost effectively. Since silver metallic inks were used for those formulations, it was a logical development that silver metallic inks with improved formulations would be the next step. Several smaller niche companies began offering new silver inks to address the emerging market, while larger specialty companies began research and development in the field. As the printed electronics began to expand, the landscape began to change. Additional suppliers entered the market with alternative

products and some larger companies began to absorb the smaller niche start-ups.
Today, many suppliers who have served the traditional electronics market are now expanding their product portfolio to include improved thin-film silver inks; some companies have developed other metallic inks, such as copper, as a cost-effective alternative to rising silver prices; others have gone in a totally different direction exploring organic and composite inks for greater functionality, lower cost and a more environmentally-friendly solution. [1]

4.1 Difference between graphic art inks and conductive inks

In simple terms, graphic arts inks are a mixture of pigments (which provides color) suspended in a vehicle/varnish (resin, which provides specific characteristics) along with additives to enable it to transfer to a substrate. This third component, additives, provide special properties that cannot be achieved by the pigment and varnish alone. Materials such as waxes, surfactants and driers are all additives. A more significant additives are oils and solvents, which provide the flow properties and serve as the vehicle which carries the ink through the printing process. Soy and linseed oils are examples of oils; these are used for paste inks which are used in lithography. Solvents are petroleum-based products, but in many cases these are being replaced today by aqueous solutions. Solvents and aqueous solutions are used in flexography, gravure, screen and inkjet printing. After printing,

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[1] Pira International Ltd, *Conductive inks*, iSmithers Rapra Publishing (2012-02-21), p. 7.

the ink is dried to form an ink film. The vehicle and additives leave, only the color remains. A conductive ink is very similar, however, rather than a pigment to provide color, it has conductive powders or flakes, made from silver or carbon as materials. Metallic flakes were an improvement over powders because particles with elongated geometries like metallic flakes increased conductivity. This is because longer metallic paths through the flakes and fewer passes across the resistive junctions between the percolated particles produce less total resistance to the current flowing through the material. These printable conductors or conductive inks have been used for decades in the manufacture of wafer-based pV solar cells, windshield defrosters, medical test strips, and membrane touch switches. [2]

A typical ink recipe is given in table 4.1.

Table 4.1 Graphic arts inks compared to conductive inks.

Source: Pira International

Graphic arts ink	Conductive ink
Pigment for color	Conductive material
Resin/varnish in which pigment is suspended	Retaining matrix
Additives	Additives
Dried by thermal of infrared driers	Require sintering/curing after printing

4.2 Types of conductive inks

Conductive inks can be coarsely divided into two categories depending whether they contain a polymeric binder or not.

[2] *ivi*, p. 31.

1) In the first case: *conductive particles are dispersed in an organic solvent using a stabilizing agent. After being deposited onto the substrate, a sintering step at high temperature (>500°C) is required to form the final conductive component [3], which process is not adequate for flexible substrates nor textiles [4].*

2) In the second case: *a polymeric binder is solubilized in an organic solvent to form the medium. Then, the conductive particles are dispersed in that medium. After being deposited onto the substrate, film formation occurs at low temperature (<120°C) and some flexibility of the final conductive component is given by the polymeric binder. This approach is more adequate for printing on textiles.*

General conductive ink recipe

Most of the commercial conductive inks are solvent-based inks composed of fine conductive particles dispersed in an organic solvent containing a conductive or dielectric binder. A typical conductive ink recipe is given in table 4.2.

Table 4.2 Typical ink recipe.

Source: Gwent group website.

Constituents	wt %
Conductive phase	27-70
Polymeric binder	9-3
Organic solvents	64-27

The volume fraction of conductive particles is rather high and depends on their shapes and dimensions. It has to be maintained

[3] I. Jung, Y. H. Jo, I. Kim, H. M. Lee, J. Electron. Mater. 2012, 41, 115.

[4] A. Chiolerio, M. Cotto, P. Pandolfi, P. Martino, V. Camarchia, M. Pirola, G. Ghione, Microelectron. Eng. 2012, 97, 8.

above the minimum volume fraction required for inter-particle connectivity. As more and more conductive fillers are added to the polymer matrix, a filler network begins to form that allows the composite to transition from insulator to conductor. This transition named "percolation threshold" corresponds to the critical volume fraction of filler needed to obtain the first percolating path throughout the polymer matrix [5].
Dupont, Toyo ink or Sunchemical are currently the main actors for conductive inks development. The conductive particles can be metallic (copper, silver, gold…), conductive carbon particles or conductive polymers (table 4.3). [6]

Table 4.3
Comparison of resistivity of various conductive materials.

Source: Vorbeck Materials

Surface resistivity ohm/sq	Material
10^{16}	Plastics
10^{14}	
10^{12}	Antistatic
10^{10}	
10^{8}	Static Dissipative
10^{6}	
10^{4}	Conductive composites Carbon-based inks
10^{2}	
10^{0}	graphene
10^{-2}	
10^{-4}	metals
10^{-6}	

Note: Electrical resistivity is a measure of how strongly a material opposes the flow of electric current. A low resistivity indicates a material that readily allows the movement of electrical charge. The international unit of electrical resistivity is the ohm.

[5] D. Stauffer, A. Aharony, Introduction to Percolation Theory, Taylor & Francis, 1994.

[6] E. Thommerel, J. C. Valmalette, J. Musso, S. Villain, J. R. Gavarri, D. Spada, Mater. Sci. Eng. A 2002, 328, 67.

Sintering step required

4.2.1 Nanoparticle Silver Inks

The small size of the particles increases the exposed surface area of the silver. This accomplished several things: less silver materials needed to be used to achieve the same conductivity, thus a thinner film could be printed and the inks could be sintered at a lower temperature, which enabled the use of flexible substrates.
Many of the companies who had supplied conductive inks to the industry expanded their portfolio with nanoparticle formulations. Unfortunately, the cost of silver has escalated recently, in part due to diminishing silver supplies and the increased demand from China, India, Russia and eastern Europe. Furthermore, it is not only the rising cost, but the wide fluctuations in prices that are causing problems. Those costs are not likely to drop, thus the emerging printed electronics industry is increasingly looking for alternatives for conductive printing inks.

4.2.2 Nanoparticle Copper Inks

Although nanoparticle silver inks enabled the new printed electronics, the escalating price of silver has caused some concern. The logical choice for an alternative was copper, which has 90% of the conductivity of silver, but is approximately 10% of the cost. Formulating copper inks has been a challenge because of the tendency of the metal to form oxides on the surface and the necessity of a special environment to manufacture copper inks.

However, nanoparticles solved the problem and companies found innovative technology to solve the former, such as the use of the pulse Forge tools to sinter the inks. This process is done in milliseconds, thus it controls the tendency of the copper to oxidize.
In the past few years, five companies (Applied Nanotechology, Cima nanotechnology, Hitachi Chemical, Intrinsiq Materials, and NovaCentrix) have introduced copper inks to the marketplace. There are likely to be more. [7]

Copper Oxide Ink

One of the challenges in developing a copper inks is coping with the formation of copper oxide, which is an insulator. Copper readily oxidizes in air, and as a result the synthesis and processing of copper inks for conductors has been expensive. A possible solution, introduced by novaCentrix, is a copper oxide ink, which consists of copper oxide (Cuo) and a reducer. When processed in the company's pulseForge system, the film undergoes a chemical reduction to render a highly conductive copper film. Since both the ink synthesis and the processing are scalable, a good, inexpensive, printed conductive pattern is now a reality.
Why copper oxide rather than pure copper?
The answer is that a reducible metal oxide ink approach has several advantages over a pure metal ink. Foremost perhaps is that copper oxide is inherently cheap. Nanoparticles of copper oxide are an order of magnitude cheaper than current nano-copper

[7] Pira International Ltd, op. cit., p. 4.

sources and even more than an order of magnitude cheaper than nano-silver. Furthermore, copper oxide particles are easier to disperse because they have more surface charge than copper particles. In addition, the dispersions are more stable. The density of copper oxide is only 6.31 g/cc, that is 30% less dense than copper and 40% less dense than silver, meaning that it also doesn't settle as readily in the dispersion over time. Moreover, sintering in solution or plating of various printing components is minimized as the surface energy of copper oxide is much less than copper. Finally, working with an oxide means that one doesn't need to worry about the particles oxidizing. Similar to nano-silver inks, the copper oxide inks need to be sintered after printing. [8]

4.2.3 Silicon Inks

One of the areas which are receiving increasing attention is printing silicon. Such a process would combine the proven performance advantages of silicon with the lower cost additive manufacturing processes, such as printing or aerosol deposition. Silicon is the most widely used material in the electronics industry. It is also the material of choice for thin-film transistors and thin-film photovoltaic cells. However, the current manufacturing method is not only expensive, but involves harsh environments. One of these environments is high temperature would preclude the use of flexible substrates, particularly polymers, which is where the electronics industry is moving. Using a silicon ink in an additive printing process offers a solution to many of these

[8] *ivi,* p. 24.

issues. Furthermore, since so much of the electronics industry (in terms of equipment and facilities) are built around silicon, replacing the silicon with silicon inks, rather than a new untested material, would reduce the need for new capital expenditure, at least for the short term.

Several companies have introduced silicon inks in the past several years, and it is an area where there is likely to growth. There are several other companies such as Epson who are also working on silicon-ink technology in Japan. It is likely that the engine of the new printed electronics will print transistors on flexible substrates that can be one tenth to one hundredth of the cost of those in simple silicon chips.

No sintering step required

4.2.4 Conductive Polymers

Conductive polymers are another category of conductive inks under development. For printed electronics to be able to take advantage of the benefits of high volume printing methods, all of the components of the device would need to be fabricated. Organic or conductive polymers are the materials that are being developed to do that. The use of electro-conductive polymers is growing rapidly in many fields of application from antistatic coatings to through-hole plating in printed circuit boards and new displays. If these materials can be improved to offer enough conductivity, it might take minutes or seconds to make a chip, rather than the days needed now for silicon technology. Polymers are traditionally employed as insulators in electronics. However, there is a *special class of polymers, the intrinsically conductive polymers, that have conductivity levels between those of semiconductors and metals (up to 10 - 10 S/cm). The combination of metallic and polymeric properties offers significant potential in numerous applications, for example in lighting and oLED displays.* [9]

4.2.5 Carbon-based Inks

One of the most significant breakthroughs in the conductive/semi-conductive ink is the introduction of carbon-nanotube-based inks. Carbon nanotubes (Cnts) have become a hot topic offering potential as a breakthrough material for the 21 st century. The traditional electronics manufacturing process is poised for a paradigm shift away from expensive photolithography toward inkjet technology, and carbon nanotubes are enabling this paradigm shift. Cnts high conductivity and nanoscale size enables the production of new inks that create the needed conductive paths at much smaller feature sizes than is currently possible. Depending on their chemical structure, Cnts can be used as an alternative to organic or inorganic semiconductors as well as conductors, but the cost is currently the greatest restraint. The structure of Cnts results in unique optical and electrical properties, remarkable strength and flexibility; high thermal and chemical stability. In addition, when dispersed into a vehicle to formulate an ink, Cnts can be printed via inkjet.
Following are some of the benefits of carbon nanotubes:
• Flexible and durable printing;

[9] *ivi,* p. 26-27.

• Easy scalability;
• Simplified manufacturing eliminates masking steps;
• Allows for high speed manufacturing processes;
• Nanoscale size can deliver next generation circuit features.

Until recently, the coexistence of semiconducting and metallic Cnts after synthesis and the difficulty in separating them have presented significant limitations for the usage of carbon nanotubes in electronic applications. Several separation methods have been discovered over the last years and some companies are now offering Cnt-based inks, and transparent conductive films using those inks. The immediate application for these inks is in a printed conductive film as a replacement for ITO (Indium Tin Oxide), which is expensive, brittle and tends to crack. Cnt-based films offer an improved alternative, particularly as the electronics industry moves towards flexible substrates for many devices.
Future development of Cnt-based inks will enable them to become serious contenders in many printed electronics applications including biological sensors, transistors, field emitters and integrated circuits with demand for mass production, high speed and efficiency.

Graphene Inks

Although only isolated a few years ago, graphene (a single layer of carbon atoms tightly packed in a honeycomb structure) is generating interest in the material science community because of its combination of outstanding mechanical, structural, electronic, and other properties, Moreover, it offers bright opportunities to fashion circuit components from graphene for use in computing, *digital displays, and other types of electronic technologies. However, while the potential was appealing, the reality was elusive. The challenge with graphene was separating the individual layers of the graphite, which has been described as a three-dimensional crystal built from graphene layers. Researchers and companies approached in many different ways to have a good result. One significant fact that the research provided, was that the material was very stable, even at room temperature. Graphene is readily dispersible in a variety of solvents. The company Vorbeck materials has introduced graphene ink formulations for gravure, flexo and screen printing. Furthermore, this conductive ink requires no sintering; standard drying/curing/fusing equipment can be used. It cures at lower than 80°C, so it can print on temperature-sensitive, substrates such as paper, paperboard, and label stock.*

Currently, silver inks are more conductive than the graphene inks, but also more expensive and need some sort of treatment process to complete the conductivity of the inks after printing. Graphene ink requires no heat treatment and is more conductive than other carbon-based alternatives to silver inks. [10]

4.3 Printing and coating processes

Because organic electronics can be processed from solution, there are a number of existing Roll-to-roll (R2R) methods suitable for processing them on a larger scale. Roughly two kinds of deposition methods have proven useful in the preparation

[10] *ivi,* p. 24-26.

of organic electronics: ***non-contact coating techniques*** *and* ***contact printing techniques.*** *Printing allows two-dimensional patterning, whereas coating at best allows for one dimensional patterning and is mostly used for layer deposition over large areas. The promise of low-cost, high-volume, high-throughput production of electronic components or devices that are lightweight, small, thin, flexible, inexpensive and disposable has spurred the recent growth in development of printed electronics technology. There is still much discussion in the industry as to what printing process is best suited for printed electronics. Before examining each of the printing processes individually, there are general considerations that impact the choice of printing process used. The first consideration is economics, both capital expenditures and operating expenses. Capital expenditures would mean equipment costs and integration costs; operating expenses are usually a function of throughput. The next consideration would be the capability to print the product/device. This includes issues such as ink lay down (thickness), lateral resolution, registration and surface uniformity. The final consideration would be the suitability for printing on the substrate of choice. There are significant differences between the printing technologies and no one process seems to be a clear favorite for printing electronics. Rather, similar to graphic arts printing, the end-use application, or in the case of printed electronics the device or component of the device significantly impacts which process would be best suited in that particular circumstance. In many cases, a combination of several different printing processes would provide the solution.* [11]

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[11] Stergios Logothetidis, *Handbook of Flexible Organic Electronics Materials*, Manufacturing and Applications, Woodhead Publishing (2014), p. 172-173.

Non-contact techniques

4.3.1 Spray coating

Similar to ink-jet printing, spray coating is also a noncontact technique where the layer is deposited through a spurt of ink droplets, but there is no digital control of the deposited pattern in this type. Masking can be used to deposit a two-dimensional pattern, but the edge definition is low, and recovery of the ink deposited on the mask can be tricky. Another option is to use a laser after spray coating to etch the desired pattern.
Compared to traditional printing techniques the layer thickness can in most cases be tightly controlled. Coating methods are also suitable for a broad range of viscosities and are less sensible with respect to surface wetting. [12]

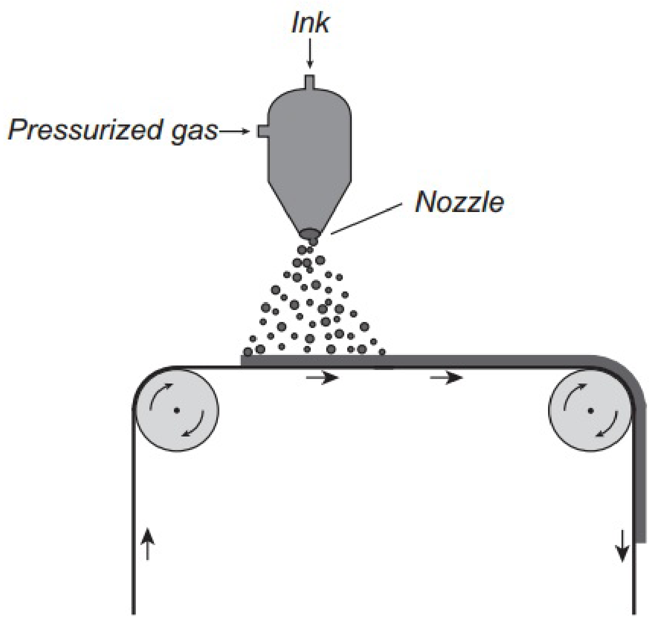

Figure 4.1
Illustration of spry coating, [12]

[12] *ivi,* p. 180-181.

4.3.2 Inkjet Printing

Contrary to traditional printing techniques, ink-jet printing does not transfer the printing pattern through contact. Ink-jet printing is a fully digital non impact method that utilizes tiny droplets of highly fluid ink that are given an electric charge. Inkjet delivers consistent drop volume and accurate drop placement, which is important in printing electronics, because of the size of the circuitry. This printing process can also provide the layer-to-layer registration needed for printing electronics. However, compared to flexography and gravure, which in traditional graphics printing can reach 1,000 to 3,000 feet per minute, and even in printed electronics can reach 400-500 feet per minute, inkjet is a relatively low throughput process. On the other hand, because inkjet is a digital process it images the design directly onto the substrate. This eliminates flexo plate and gravure cylinder costs and reduces makeready times. Because of the newer nanoparticle inks, ink-film thickness will be no longer an issue. These inks enable higher conductivity in thin films at lower processing temperatures. The main drawback lies within the ink formulation (density, surface tension, viscosity, boiling point, etc.), which needs to be adjusted to fit a number of parameters including nozzle size, printing surface and materials. [13]

The viscosity must be low enough in order to allow the exit channel of the nozzle to be refilled at high frequency. The surface tension must be adequate to favor drop formation. Typical inkjet inks have a viscosity around 10 mPa.s and a surface tension around 35 mN m-1. In addition, another major concern in ink

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[13] Pira International Ltd, op. cit., p. 38.

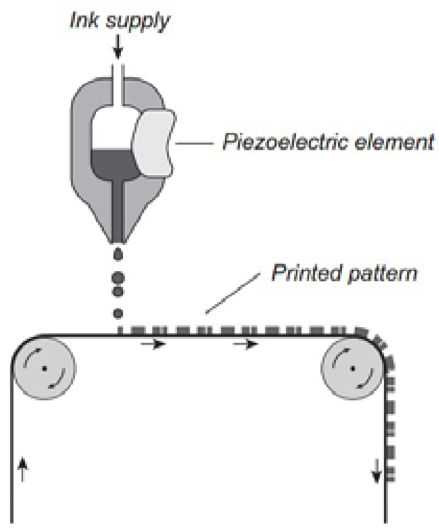
formulation is to avoid nozzle clogging when using suspensions with particles. Clogging can also occur when ink dries inside the nozzle, especially with water-based inks or with polymers which film-form at room temperature. In addition, aggregation phenomenon should be avoided: the maximum particle size must be lower than one to ten micrometers, depending on the nozzle size. Note that sedimentation without aggregation should be acceptable as far as the sediment flows back in suspension after shaking. [14]

One of the challenges of inkjet has been the ability to deposit overlapping drops so that the device printed has continuous features and in special cases it is possible to work in 3D by printing multiple layers.

The throughput for inkjet is continually improving. Some of the inkjet manufacturers involved in the area of printed electronics include: Conductive Inkjet technology, FUJIFIlmDimatix, Hp, Imaging technology International, litrex, Xaar and Xennia. [15]

Figure 4.2
Schematic illustration of piezo-based drop-on-demand ink-jet printing.

Source: Stergios Logothetidis, Handbook of flexible organic electronics, p. 179.



[14] S. Magdassi, *The Chemistry Of Inkjet Inks*, WORLD SCIENTIFIC, 2009. p. 178-179.

[15] Pira International Ltd, op. cit., p. 38.

4.3.3 Aerosol Jet Deposition System

While inkjet printing is used today, other improved methods have been developed, such as the optomec maskless mesoscale materials Deposition (m3D) aerosol Jet System.

The aerosol Jet technology, commercialized by Optomec, was originally developed under a Darpa contract. The system was designed to fill a neglected middle ground in microelectronic fabrication. Then-known manufacturing techniques could create very small electronic features, for example by vapor deposition, with screen printing used for large ones. However, there was no technology capable of satisfactorily creating crucial micron-sized (10-100 µm) production of interconnects, components, and devices. In addition, as electronic devices continue to shrink, the physical limits of screen printing were being approached.

While not a traditional printing method, Aerosol Jet Spray Deposition is an additive manufacturing process, so it brings benefits that cannot be realized by means of the subtractive methods currently used. Some of the advantages of additive manufacturing processes include direct CaD-driven, design-to-device processing, which eliminates expensive hard-tooling, masks, and vertical/horizontal integration. Thus there are fewer overall manufacturing steps. These advantages contribute to greater design and manufacturing flexibility; time compression and better manufacturing agility; lower cost; and a greener technology.

While inkjet printing has become fairly widespread for research and development purposes, as well as pilot projects in thin-film printed electronics, it does have limitations, particularly in light of some of the newer inks being developed. The optomec aerosol spray deposition system reduces many of these limitations. Inkjet printing works well with low-density inks, while the aerosol *spray system allows a wide range of vehicles, dispersants, additives and metal loadings. These include both organic solvent-based and waterbased conductive metallic inks. There have been definite challenges with clogging of inkjet nozzles; there are no closing issues with the spray system. In addition, inkjet delivers single drops of ink in a random fashion, while the aerosol spray deposition system delivers a continuous feed of inks in a tightly focused direction.*

Aerosol Jet system can be equipped with multinozzle deposition heads and high performance atomizers to meet production requirements. The company claims the system would provide solutions for RFID antennas, fuel cells, strain gauges, printed structures, printed transistors, embedded structures, molded interconnected devices and already has partnerships with companies in several areas. Optomec provides the print platform and sometimes the automation component, while working with material partners and domain experts. [16]

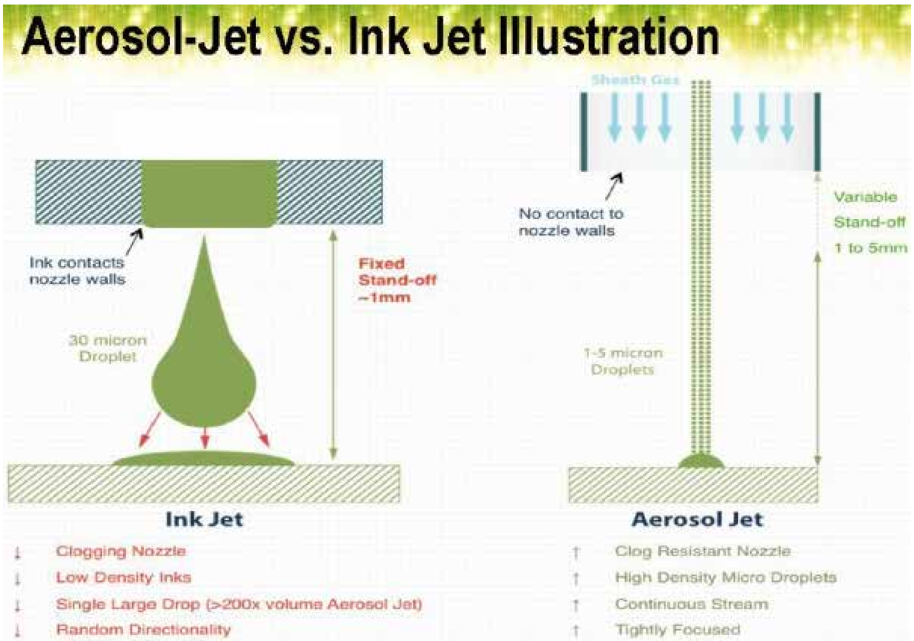
[16] Pira International Ltd, op. cit., p. 28-29.

Figure 4.3
Aerosol spray jet technology versus inkjet.

Source: Optomec

Figure 4.4
Diagram of Optomec aerosol spray deposition system.

Source: Optomec



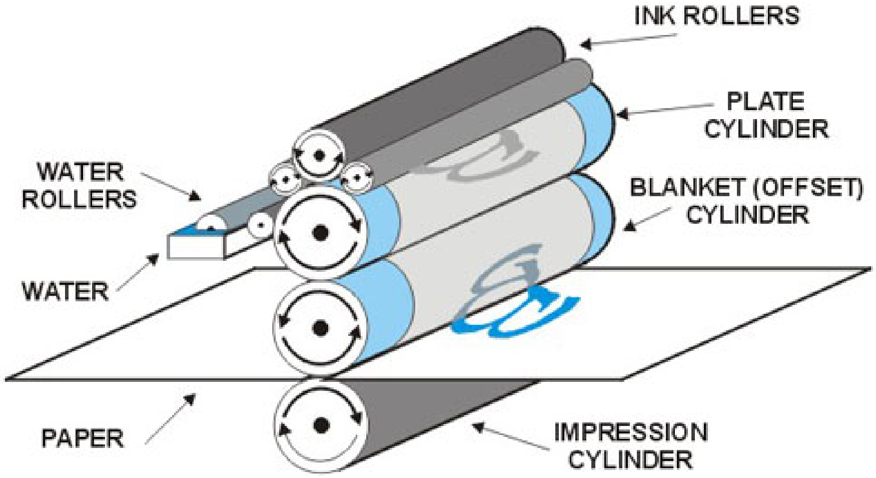
Contact techniques

4.3.4 Offset Lithography

Offset Lithography has traditionally been the dominant printing process in the graphics arts industry. It derives its name because it is not a direct printing process. One of the advantages of the offset litho process being able to lay a thin coat of ink or coating on a substrate for fine printing is one of the factors that make it a poor choice for printing electronics. Functional inks/coatings require a thicker layer to ensure the needed conductivity for the applications. Usually multiple passes through the press are necessary to achieve the needed functionality for printed electronics. Offset litho is a high throughput and high resolution process, but at present it is not widely used for printing electronics. [17]

Figure 4.5
Illustration of Offset Lithography.

Source: web



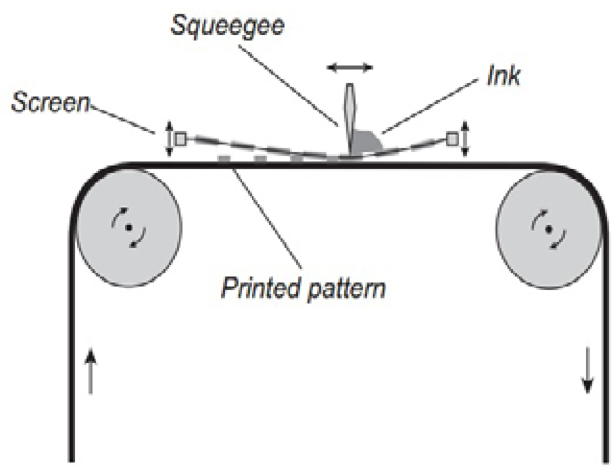
[17] *ivi,* p. 37-38.

4.3.5 Screen Printing

Screen Printing although originally called silk screen printing, today, stainless steel or polyester is used to make the screen rather than silk. It has been used for decades for printed and etched circuit boards in electronic equipment, electromagnetic interference (EMI) shielding and membrane switches. Basically, the process consists of an ink or paste being pushed through a stencil attached or embedded in a mesh that is stretched over a printing frame. There is no intermediate transfer vehicle, so the ink's consistency or viscosity is not limited. Screen printing is a relatively low throughput process. It has so far mainly been used to print electrodes because it gives a thick layer ensuring high conductivity. Until recently, this was a moot point because there was no other choice to achieve the thick ink layer required for the necessary conductivity in electronic applications. However, the introduction of nanoparticle inks have enabled increased functionality in thinner films opening the doors to use of other analog and digital processes that have higher throughputs. [18]

Figure 4.6
Illustration of the flatbed screen-printing principle.

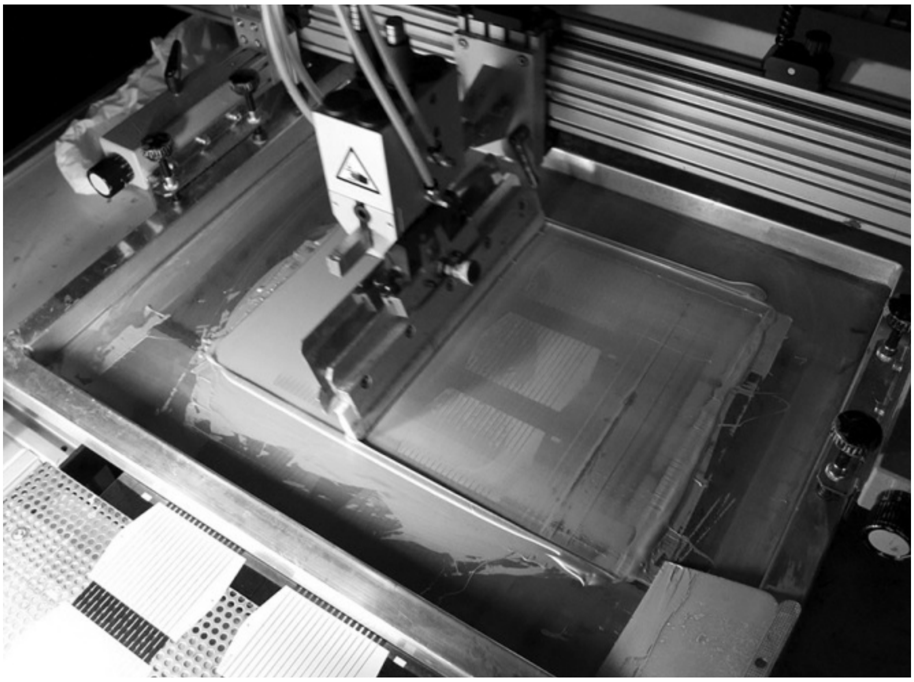
Source: Stergios Logothetidis, Handbook of flexible organic electronics, p. 173.



[18] *ivi,* p. 38-39.

Figure 4.7
Flatbed screen printing of silver top electrodes.

Source: Stergios Logothetidis, Handbook of flexible organic electronics, p. 174.



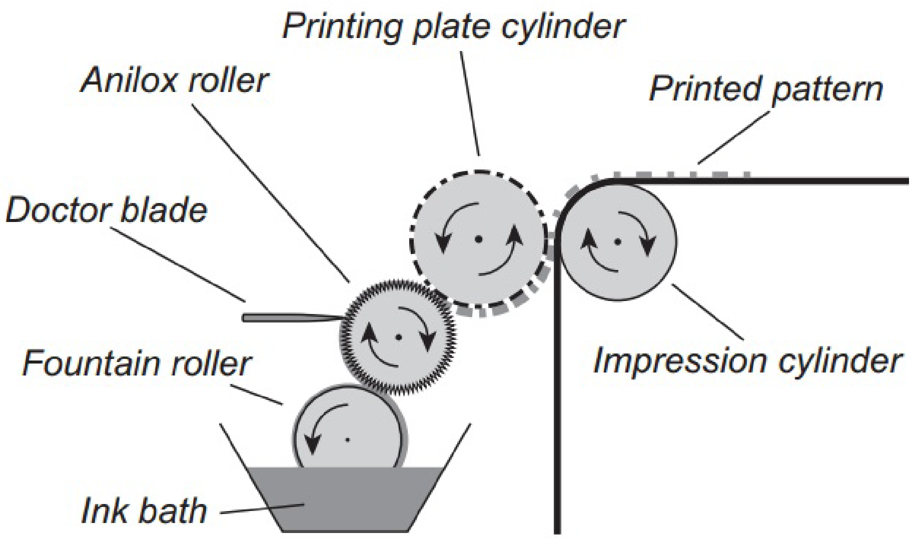
4.3.6 Flexoprinting

Flexography is a direct printing process, which uses relief plates made of rubber or photopolymer and anilox rolls for inking metered by a cambered doctor blade system. Although today it is a high-quality printing process, it began as a “rubber stamp” process for corrugated boxes. Its main advantage has always been its ability to print on a variety of substrates. While its quality is close to gravure, because it uses plates, the set-up costs are much lower than the engraved gravure cylinder. Initially, it did not seem that flexography would be able to lay down a thick enough ink film to meet conductivity requirements for functional materials. However, with the improvements in conductive inks, which now make use of nanoparticles, which are easier to sinter at low temperatures increasing conductivity, flexo is quite capable of printing electronic devices with the necessary conductivity.

The resolution in high quality flexography today is approximately 20 μm. Since it is widely used in packaging, it is a natural fit for Radio Frequency Identification (RFID) antennas or complete tags and other smart packaging applications. It is used to print on uneven substrates, since its inception was printing corrugated boxes. Flexography is a highvolume printing process capable of printing anywhere from 750 to 1200 feet per minute.
Flexography is currently used to print RFID antennas on labels. Flexo will continue to be used for printing RFID antennas and there is interest in using it for EMI shielding. Although much of the work is being done under non-disclosure agreements, flexo is being used to print batteries, organic circuits, photovoltaics and low-cost lighting. [19]

Figure 4.8
Illustration of the flexoprinting principle.

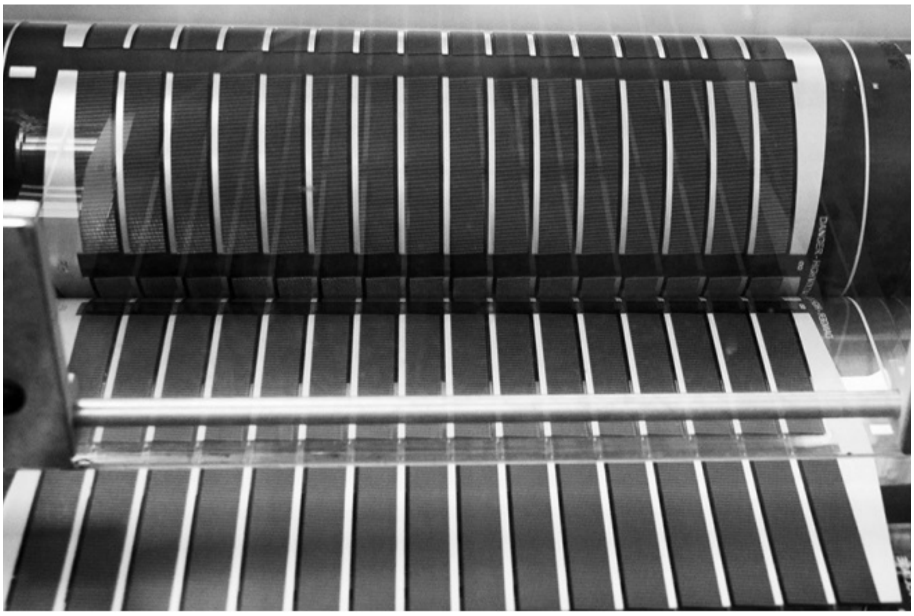
Source: Stergios Logothetidis, Handbook of flexible organic electronics, p. 176.



[19] *ivi,* p. 39.

Figure 4.9
The printing cylinder with the relief carrying the ink during printing, (in this case a silver paste).

Source: Stergios Logothetidis, Handbook of flexible organic electronics, p. 176.



4.3.7 Gravure Printing

Gravure printing is a direct printing process, widely used to print large volumes of magazines and catalogues.
Opposed to flexoprinting, the ink in gravure printing is transferred from carved micro cavities and not from a relief. It uses engraved cylinders for inking and this enables the image quality to remain consistent through long runs. The engraved cylinders are very expensive, which means high set-up costs. There have been some recent innovations such as sleeve technology, to offset this expense. Because of this high set-up cost, gravure does not lend itself to a research and development environment, which, until very recently was what most printed electronics operations were. Gravure is, however, very high speed (1,200-3,000 ft /minute), the highest quality and the most precise of the traditional printing processes. In addition, gravure has traditionally been able to print on a wide variety of substrates, so it is a flexible process.

Gravure is capable of printing the largest range of ink/coating formulations, so it would lend itself to new materials such as functional inks. It is also capable of deposing different amounts of ink in different areas, something none of the other printing process can do. This printing process is highly dependent of ink viscosity, substrate speeds as well as the pressure applied by the impression roller and great care is therefore required in the choosing of process conditions and ink formulation. However, the process is suitable for low-viscosity ink and high printing rates up to 15 m/s can be achieved.
In the printed electronics area, the small printing resolutions needed for printing electronic devices has been a difficult challenge for gravure printing.
The traditional markets for gravure are disappearing, and portions of the markets that still exist are moving to different printing processes. Gravure printers are aggressively seeking alternative growth areas, but for now flexography is a better choice in terms of high volume. [20]

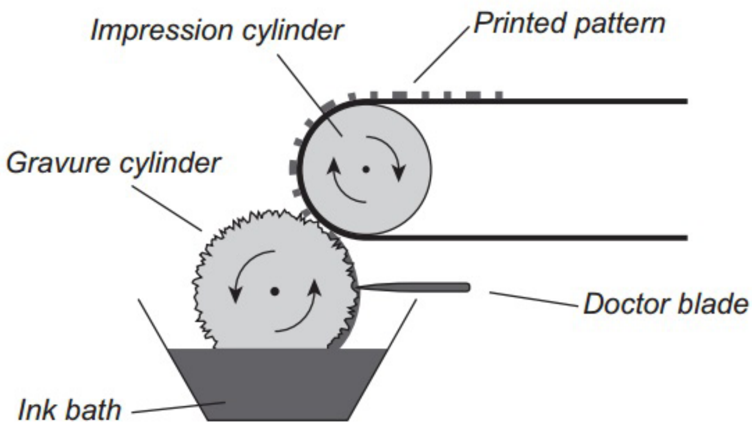


Figure 4.10
Illustration of the gravure-printing principle.

Source: Stergios Logothetidis, Handbook of flexible organic electronics, p. 177.

[20] *ivi,* p. 40.

Table 4.4
Comparison of printing processes for printed electronics.

Source: Pira International

Process	Advantages	Disadvantages
Lithography	High resolution High throughput	Low ink film thickness Ink almost pastelike
Inkjet	High resolution Accurate and precise Good ink film thickness (~0.1 µm) Many suppliers working on materials and processes Ability to create in small volumes	Low throughput
Screen	Thick ink film (100 µm)	Low throughput
Flexography	Good ink film thickness (3-8µm) Good resolution, High speed	Resolution could use improvement.
Gravure	Very high speed, Good ink film thickness (2-5µm)	High cylinder costs

4.4 Printed electronics applications

In addition to the traditional membrane switches and printed circuit boards, radio frequency antennas, batteries, sensors, displays, lighting and novelty items are all experiencing expanded use of printed electronics.

Photovoltaics

Due to the growing demand for renewable energy sources, as well as improvements in technology, the manufacture of solar cells and photovoltaic arrays has advanced dramatically in recent years.

First-generation, wafer-based silicon solar technology is limited by polysilicon feedstock and the high cost of manufacturing.

Second generation thin-film inorganic solar technology is still not cost competitive, and the popular materials used, like cadmium and indium, are toxic, expensive, and not scalable to meet global demand. Third-generation photovoltaic technologies are currently under development; these include organic photovoltaics (OPVs) and dye-sensitized solar cells (DSSC).

However, while future generation Organic Photovoltaic (OPV) technology has the promise to be the low-cost renewable energy solution, there is a more immediate solution available, printable silicon inks. [21]

Display

A second explosive area in the printed electronics sector today is in the display market. As electronics manufacturers are looking

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[21] Pira International Ltd, op. cit., p. 41-42.

for increased functionality in smaller and smaller devices at lower cost, they need innovative solutions and the conductive ink manufacturers are supplying them. There is also a move towards flexible displays, which will require inks that can bend with the substrate without cracking or losing adhesion. Typically the conductivity is lower for conductive polymers than inorganic materials, but they are also more flexible, inexpensive and environmentally friendly in processing and manufacture. [22]

Lighting

OLEDs and lighting are areas where conductive polymer inks offer advantages. OLEDs are expected to become a major component in flat displays, as well as drive a new era in lighting innovation. In these applications, there is a large area of light on a sheet, and the ideal is to have the light to be homogeneous with the same look and temperature over the entire area. High conductivity is not suitable for such homogeneity. [23]

Memory

Logic, i.e. memory and transistors, are slated to represent a large portion (about a third) of the emerging future printed electronics market. An essential part of most electronics, memory is required for identification, tracking status and history, and is used whenever information is stored.

Printed batteries

Thin-film and printed batteries is an application area that offers

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[22] *ivi,* p. 48.

[23] *ivi,* p. 49-50.

great potential for printed electronics, particularly in smaller applications where size, form factor and higher cost of use limit traditional batteries.

Radio Frequency Identification

From automatic toll collection booths to retail stores, managing supply chains, and much more, RFID promises to be a technology that can add great convenience to our lives, while reducing losses and automating processes. An RFID tag consists of an antenna, and a receiver (or transceiver).

Several companies such as GSI Technologies and Toppan Printing are printing RFID antenna, using silver conductive inks in high volumes. PolyIC is the most visible producer of completed printed RFID tags, using roll-to-roll printing with organic (conductive polymer) inks.

Next-generation PCBs/Switches

One of the key markets for silver inks in the past has been in printed circuit boards (PCB) and membrane switches, thus the new nanoparticle silver inks will definitely find a role.

Similar to many electronic areas, a key trend in the PCB industry is miniaturization. The miniaturization of electronic products continues to drive printed circuit board manufacturing toward smaller and more densely packed boards with increased electronic capabilities. A similar area is printed membrane switches, where thick silver screen inks have been in used for many years. As these applications move towards thinner films, it will continue to provide a market for conductive inks. [24]

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[24] *ivi,* p. 50-51.

Sensors

Printed sensors can potentially bring entirely new price points to markets such as smart packaging and point-of-care medical diagnostics; markets where there is a pent-up demand for cheaper sensor products, with printing promising significantly improved economics. Moreover, printing sensor arrays onto flexible substrates brings with it the capability to create novel sensor array products for various applications such as smart textiles.
Flexible sensors are a unique product that only printed electronics can create. It is an area where many of the products are unique. Currently it is the sensing layer that is printed, but potential all the components of a sensor could be printed. [25]

EMI Shielding

Electromagnetic interference (EMI) from unwanted electromagnetic fields can interrupt, obstruct, or degrade the effective performance of electronic devices. Vacuum deposition metals were traditionally used to provide emI shielding, but these are susceptible to corrosion and delamination. In addition, metal screen emI shielding is heavy, rigid, and does not exhibit uniform shielding over a range of frequencies. Alternatives for emI shielding, which are more robust, lightweight and exhibit strong shielding across all wavelengths, are Cnt-based inks applied to films, as well as transparent Sante™ films from Cima nanotech. EMI shields are used in plasma displays.

There is almost no limit to the potential for printed electronics for the future, especially now that there are innovative conductive and semi-conductive inks available. There are many traditional applications which will continue for some time and there are potential uses that are emerging all the time. The emerging techno-

logies will need time to improve and move to scale production, but there is enormous work being done to achieve that goal. [26]

Table 4.5
Current versus future materials for PE applications.

Source: Pira International

Application	Current Material	Future Trend
Photovoltaics	Silver bus bars	Silicon-ink based platforms Conductive films
Bistable displays	Electronic ink	Electronic ink
Displays Touch screens	ITO	CNT-based films Transparent ink films
Flat Panel Displays	ITO	SANTE films. Flat panel displays are the next step after touch screens for the above technologies, a bit further down the road.
LCD backplanes and OLEDs and electrodes	Silver	Silver
Lighting	Emerging	Silver
Memory	Emerging with conductive polymers	Conductive polymers
RFID	Silver antennas, some work with silicon inks and conductive polymers	Movement towards complete printed tags with organic materials and silicon inks; perhaps copper antennas
PCBs/Switches	Silver	Nanoparticle silver
Sensors	Emerging with silver and organics	Organics and silver
EMI Shielding	Metal screens	CNT-based films, SANTE films.

[25] *ivi,* p. 51-52.

[26] *ivi,* p. 53.

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‘electronic inks for the wearable world’ can be found on www.dupont.com

‘stretchable inks for wearable electronics’ can be found on www.dupont.com

Chapter 5 | Analysis of writing instruments

The development of a particular pen for EdM Conductive Ink needs the study and analysis of the main writing instruments from the past to nowadays. In this chapter will be analysed the historical evolution of all those writing instruments which, via a fluid substance, ink, more or less dense depending on the instrument used, leave a sign on a support.
First of all, existing writing tools can be divided between those designed to use by hand, born and evolved since the origins of man, and those intended for automatic use, developed only in the last centuries.
According to the thesis project, thus the specific use scenario and the context of "Do-it-yourself", the analysis mainly focuses on hand writing instruments, not on printing methods.

5.1 The evolution of writing tools

The man, from its origins, has got to use two basic types of instruments which enabled him to write.
They are part of the first type chisels, awls and styles, which will leave a graphic trace through the incision.
In the second there are soft stones, charcoal, ceramic fragments, blood pastels and lapis, which leave a substance on the support that is used. Still nowaday instruments from the latter type, such as pencil and crayons are used.
Finally, another family of tools also belong to the second type: brushes, pens, fountain pens, ballpoint pens, markers, which, however, to leave their mark on the paper, require a substance, ink, more or less dense depending on the instrument used. These are precisely the tools that will be considered, analyzing them in order to meet the requirements of the thesis project.

Paintbrush

One of the first people who used a kind of brush was the Egyptian; the scribes, who were responsible for bringing the story of their civilization, they were able to obtain a crude form of brush enervating the end of a reed to the point to make it soft enough to leave marks with ink on rolls papyrus.
The Chinese were the real inventors of this tool, they extracted it from the bamboo stem, reduced to thin sheets, it took the form of a brush.
Thus, for the past three thousand years, the brush represented from the civilizations of the Far East one of the most used tools for writing, although the marker, its direct descendant, is now much more used by the Japanese.

Quill

In the West, the history of writing is closely related to a completely different category, that of "open toes." The ancestor of all the other tools was the pen, simple cane cut stem to tip, which was practiced a slit through which passed the ink.
From Palestine to the Pillars of Hercules, it was used throughout the Mediterranean: wood at the Arabs, bronze among the Romans. The quill was dipped in the inkwell, a simple jar that contained the black ink and could be coupled to the jar containing red ink.

Quill pen

In the first half of the seventh century is described for the first time bird's feathers that conveniently cut they were used to write. Depending on the type of mark needed different bird feathers were used. For the preparation specially tools were used to trace the incision in the tip axis. The quill rivaled the bird pen, especially goose, which eventually impose itself without reserve, with the exception of the Islamized peoples, who remained faithful to the plant stem, because they refused to write with an animal fragment. The bird quill pen is more flexible, easier to cut, less brittle, and its elasticity allows the pressure of the hand game.

Pencil

Pencils create marks by physical abrasion, leaving behind a trail of solid core material that adheres to a sheet of paper or other surface. They are distinct from pens, which instead disperse a trail of liquid or gel ink that stains the light colour of the paper.

The writing part of the pencil, the mine, is composed of a graphite and clay together, with addition of other elements such as antimony, wax, resin, rubber and the carbon black in the particular dosages depending on the type of product needed. One of these elements, namely antimony, was known to the ancient in the classical era, who knew his property, like that of lead, to draw a gray-wake silvery on the surface.

The first known use of a mine in lead dates from the twelfth century. Towards the end of the sixteenth century, the discovery in England of rich deposits of graphite gave start to a flourishing mining and industrial producer of graphite pencils, very popular material because it could be used to write directly, without any processing. In the second half of the eighteenth century began to produce pencils in an industrial way.

It was founded in 1761 in Stein, near Nuremberg, the A.W. Faber, which produces the famous lapis “Castell”.

Towards the end of the eighteenth century it came the development of a new mixture using a fine plastic clay, soft material, easily malleable and provided of a great cohesion with graphite. Mixing the wet clay to graphite, a body free from all impurities is obtained, with a fine structure, stable and uniform. Furthermore, by adjusting the proportion of components in the mixture, different hardness degrees can obtained.

The metal stylus

The idea to model a metal nib is not recent. The Egyptians had already thought of, like the Romans that wound copper sheets to package tapered quills.

The industrial production of steel nib was born in 1820 in the cradle of the industrial revolution in England. Between 1820 and 1840 it was succeeded by patents, design and production become more and more sophisticated, the elasticity increases due to the splitting of a hard surface with cracks, cuts, perforations; the steel nib becomes a quality instrument, the price of which constantly decreases. Soon the steel nib permanently replaces the quill across Europe, becoming a symbol of the struggle for the democratization of education.

The fountain pen

Later it was thought the possibility of equipping the pen of an ink reserve that would allow to write without interruption and the need to refill frequently the pen.

It can be said that the concern to provide a reserve of ink to the stylus dates back to ancient times, but with few solutions. The desire to escape from incessant movements between paper and inkwell seems to be for many the essential reason for the triumph of the fountain.

In order that a pen write and work well, it is important not only to establish an ink flow between the reservoir and the nib, but above all it is necessary to regularize the flow.

In the fountain pen, the ink is subjected to the action of different

forces. In the rest state, these must cancel, regardless of the position of the instrument: the delicate balance must only break in contact of the nib on the paper.
Three elements must be considered: gravity, capillary action and atmospheric pressure.
Liquids are attracted to smaller spaces: the fissure that divides in two the pen tip is a capillary which allows to write from long time. The Waterman genius lies not in having apparently discovered this principle, but in having applied to power of the pen.
The tube dimensions vary according to the hand pressure, and then the relative divergence of the nib and of the duct, thus modulating the ink flow. In a fountain pen, the nib participates therefore to two capillary effects: as the quill and the quill pens, what happens through the contact between the ink and the support, and together with the contact, the one presiding over his own power. In order to avoid an excess of leaking ink, consequent to pressure variations, the most good feed ducts is provided with slits or tongues intended to collect this inappropriate influx. Such ink is the first to be used, and the slots are emptied before resorting to the tank. All supply conduits work with the same principle adopted by Waterman, and in most cases are located under the nib. Throughout all these ducts they were shaped and milled into cylindrical Ebonite rods, then they were overcome from synthetic resins that were injection molded. Their convexity fits perfectly to the concavity of the nib.
The capillary action of ink attraction towards the tip is constant.
As for the filling systems, from the late nineteenth century to nowadays, we have opposed two conceptions: the ink containment directly into the body of the fountain pen, or in a separate tank located in the body itself.

The ballpoint pen

It was reported that, one day, a Hungarian gentleman named Laszlo Biro, observing children playing on the sand with some balls, he realized that those rudimentary spheres left a concave portion visible on the sand.

It is said that the same man, avid hunter, same day he was making himself some shot cartridges in his cluttered study, the man would fall on a stained paper of ink some dots, which rolled in ink and left a mark of color on the paper.

Whatever the truth of the facts, Birò had an intuition that he realized: insert ink into a container and let it spread on paper by a sphere. The first inks used were too liquid and processing of raw ballpoint pens was too craftsmanship: the pen stained relentlessly and was too expensive too. Soon Birò sold the patent to the young Italian Marcel Bich, who sensed that Biro had committed a double error: on one hand, the total lack of “engineering”; on the other, the inaccessible price. The advantages that this system of writing offered (convenience, smoothness, durability) must be accompanied by cost-effective solution. In this way they could all benefit from a revolutionary and functional product.

The solution would be the application, for its production, of economies of scale. Thus the Société BIC was born in 1951.

Since 1951 were produced and sold more than 50 billion ballpoint pens BIC, whose manufacture has evolved hand in hand with the production systems and new materials used in industry.

The working principle of a ballpoint pen is based on the physical principles of capillarity, gravity and rolling friction.

When the sphere is in contact with the paper it rolls on it; by capillarity, from reservoir tube it is sucked ink, that flowing along the conduits, it is collected by the sphere which acts as a suction pump, and by it is distributed on the paper; during writing pauses

the ball itself works as a valve which prevents the ink leakage.
In the first ballpoint pens, as the ink was distributed on the paper, it was generated, between the back of the ball and the reservoir, a partial vacuum in consequence of which the power supply was interrupted; this difficulty was overcome by drilling a small hole at the top end of the tube, or simply leaving open the reservoir tube, thus that on the ink could act the external atmospheric pressure.
For the proper working of this type of pens it required an ink that can flow out to the ball by capillary action without going out of from the hole or opening vent.
Currently the beads used are made of steel or tungsten carbide, and they have a diameter of 1 millimeter.

The Marker

The marker is considered the direct descendant of the brush.
A marker pen, fineliner, marking pen, felt-tip marker, felt-tip pen, flow, marker or texta (in Australia) or sketch pen (in India), is a pen which has its own ink-source, and a tip made of porous, pressed fibers such as felt.
A permanent marker consists of a container (glass, aluminum or plastic) and a core of an absorbent material. This filling serves as a carrier for the ink. The upper part of the marker contains the nib that was made in earlier time of a hard felt material, and a cap to prevent the marker from drying out.

Rapidograph

The rapidograph is a technical pen, a specialized instrument used mainly for technical drawings. It’s available on the market in a wide range of tips, generally from 0.1 mm up to 2 mm of thickness. Technical pens use either a refillable ink reservoir (Isograph version) or a replaceable ink cartridge.

Roller ball pen

Roller ball pens are pens which use ball point writing mechanisms with water-based liquid or gelled ink, as opposed to the oil-based viscous inks found in ballpoint pens. These less viscous inks, which tend to saturate more deeply and more widely into paper than other types of ink, give roller ball pens their distinctive writing qualities. The writing point is a tiny ball, usually 0.5 or 0.7 mm in diameter, that transfers the ink from the reservoir onto the paper as the pen moves.

5.2 Analysis of the main working principles among hand writing instruments that use an ink to mark the substrate

The development of a particular pen for EdM Conductive Ink needed the study and analysis of the main writing instruments from the past to nowadays.

Hand writing instruments can be basically divided for the working principle to lay down the ink. The working principle is mainly drived by the ink viscosity and the substrate for the end-use.

All these aspects are shown in the following analysis. According to this project the hand writing instruments can be categorized in four different working principles:

1. Gravity and capillary action
2. Gravity and mechanical (metal ball) action
3. Felt-tip ink absorbing action
4. Flow control by pressure

The first three working principles are the most common and they mainly refer to different nibs. The point 4 is more focused on how the ink comes out from the writing instrument, thus in the same category the nib can be different according to end-uses. In this case the ink is more viscous than normal inks, like paint.
This is the reason why the category focuses on “flow control by pressure“, it doesn’t work well without pressure.

1. Gravity and capillary action
This category include: pen, quill pens, metal pen, fountain pen (fig. 5.1) and rapidograph.
Excluding quill and the quill pen as too rudimentary, the remaining tools would be appropriate to be use nowadays with common inks. These pens draw the ink from the reservoir through a feed to the nib and deposits it on paper via a combination of gravity and capillary action as working principle.

2. Gravity and mechanical (metal ball) action
Ballpoint pen and rollerball pen use this working principle. They dispense ink by rolling a small metal sphere (fig. 5.2), usually 0.7–1.2 mm. The ink dries almost immediately on contact with paper.

3. Felt-tip ink absorbing action
A felt-tip pen, marker pen, fineliner, or sketch pen (fig. 5.3), is a pen which has its own ink-source, and a tip made of porous, pressed fibers such as felt. A core of an absorbent material serves as a carrier for the ink.

4. Flow control by pressure
The main reason for using this principle is about the high ink

viscosity, like paint. In this category, the tip can be just an hole, or have a mechanical action according to end-uses such us correction pen tip and rollerball tip. The ink flow is controlled by hand pressure (fig. 5.4).

Figure 5.1
Fountain pen, gravity and capillary action as working principle. (top left)

Figure 5.2
Ballpoint pen, gravity and mechanical action as working principle. (top right)

Figure 5.3
Felt-tip pen, ink absorbing action as working principle. (bottom left)

Figure 5.4
Paint tube, flow control by pressure as working principle. (bottom right)

The study and analysis of the working principles among the main writing instruments from the past to nowadays, it gave useful indications and inspirations to define design solutions for the development of the pen prototype for EdM conductive ink.

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Chapter 6 | The substrate: textiles

In the thesis project there are three main actors: the conductive ink, a tool for using the ink and a substrate to lay down it. Each one plays an important role. In this case, the thesis aim and the end-use scenery concern the conductive ink deposition on textiles. Starting from this point, there is the need to know and identify the fine differences among fibers, fabrics, finishes, coloration/printing methods and the global textile market sectors.

Consumers often describe textile products by fiber names, such as cotton T-shirt, wool sweater, or nylon parka.
Fibers are the basic units used to produce most fabrics. Understanding fibers and their performance will help to understand fabrics, textile products, and their performance. Fibers have been used to make fabric for thousands of years. All fibers were natural and produced by plants and animal until 1885, when the first manufactured fiber was produced. These fibers continue to be used and valued today, but most are less important now. Today many more fibers have been invented. There fibers are manufactured from natural and synthetic chemicals (man-made fibers). [1]
In the recent years, intense research taken place in development of new fibers for innovative fabrics. Growth areas for fiber development include: nanotechnology, high performance, multifunctional, smart and technical applications.
The quest in the 21st century is now to create fibers that are both functional and sustainable, along with smart fibres that can be adapted precisely to the changing needs of today's users. [2]

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[1] Sara J. Kadolph, *Textiles: basics, Pearson, 2013, p. 22.*

[2] R. Sinclair, Textiles and Fashion, Materials design and Technology, Elsevier Science, Woodhead publishing in textiles, 2014, *p.24.*

6.1 Types of textile fibres

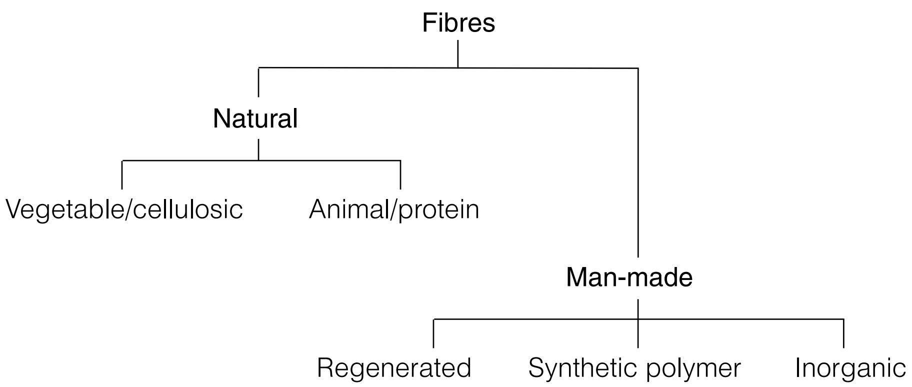
Fibres are the foundation for all textile products and can either be natural (natural fibres) or man-made (manufactured or man-made rengenerated). A piece of a fabric contains a huge number of fibres. Individual types of fibres can be used on their own or combined with other types of fibres to enhance the quality of the end-product. [3]

A fiber is defined as any substance, natural or manufactured, with a high length-to-with ratio with suitable characteristics for processing into fabric; the smallest component, hairlike in nature, that can be removed from a fabric. Consumers often describe textile products by fiber names, such as cotton T-shirt, wool sweater, or nylon parka. Fibers contribute absorbency, stretch, warmth, strength, and many other properties to products. [4]

There are three basic types of fibre groups:

- Natural fibres
- Regenerated fibres
- Synthetic fibres

Figure 6.1
Types of textile fibres
[3]



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[3] R. Sinclair, op. cit., p. 3.

[4] Sara J. Kadolph, op. cit., *p. 4.*

Natural fibres

Natural fibres are those that are found in nature as fibres. Theay are produced in fiber form by plants, animals, or insects.

Natural fibres can be divided into two main types:

- Animal or protein fibres
- Vegetable or cellulosic fibres

Animal or protein fibres

Table 6.1 Natural fibres, protein (animal) fibres [6]

Sheep's wool	wool	
Specialist wools/hair	Cashmere Mohair (from the Angora goat) Vicuna Camel Llama Alpaca Angora (from the Angora rabbit)	
Silk	Tussah silk	Cultivated from 'wild' silkworms
	Cultivated silk	Farmed silkworms (sericulture)
	Organic silk	Farmed from silkworms which are allowed to emerge from the coco-on before processing

Vegetable or cellulosic fibres

Table 6.2 Natural fibres, cellulosic (vegetable) fibres [6]

Cellulosics	Seed	Cotton Kapok
Specialist cellulosics	Bast (from the stem)	Flax Hemp Jute Ramie
	Leaf	Manila Sisal
	Fruit	Banana Coir Pineapple

Man-made fibres

Regenerated and synthetic fibres are collectively known as man-made or manufactured fibres.

Regenerated fibres are made from natural polymers that are not useable in their original form but can be regenerated to create useful fibres.

Synthetic fibres are made by polymerising smaller molecules into larger ones in an industrial process. [5]

Manufactured, or man-made, fibres can be classified as:

• Regenerated

• Synthetics

• Inorganic (glass, carbon, ceramic, metallic)

Regenerated cellulosics

Table 6.3 Man-made regenerated fibres. [6]

Rayon (viscose and Cuprammonium) Acetate Lyocell Triacetate

Synthetics

Table 6.4 Man-made synthetic fibres. [6]

General use synthetics	Acrylic Nylon (polyamide) Olefin Polyester Rubber Spandex PLA (polylactide or polylactic acid)
Specialist synthetics	Aramid Modacylic Saran

[5] R. Sinclair, op. cit., p. 4-5.

[6] A. Briggs-Goode, K. Townsend, *Textile Design, Principles, Advances, and Applications*, Woodhead Publishing, 2011, p. 6-7.

Blend fibres

Individual types of fibres can be used on their own or combined with other types of fibres to enhance the quality of the end-product. In this way, the three basic types of fibre (natural, regenerated, synthetic fibres) can be blended, in order to *give a particular mix of properties that best fit how the product will ultimately be used.*
The process for combining fibres is known as blending.
There are several reasons why different fibres may be blended or mixed (Bunsell, 2009; Erberle, 2004):

- *To compensate for weaker attributes or properties of one type of fibre*
- *To improve the performance of the resulting yarn or fabric*
- *To improve or provide a different appearance*
- *To improve the efficiency of processing, especially of spinning, weaving and knitting*
- *To reduce costs* [7]

Blend fibres contribute along the smart fibres, to the changing needs of today's users. The market is expanding and it is used in various industries like agriculture, clothing, construction, health care, transportation, packaging, sports, environmental protection, protective wear, and many more.

[7] R. Sinclair, op. cit., p. 3-4.

6.2 Fibres to fabrics

All natural fabrics begin life as fibres. These fibres, are spun into yarns, which in turn is constructed into fabric. [8]

Yarn

A yarn has been defined as a product of substantial length with a relatively small cross-section, consisting of fibres and/or filaments with or without twist'. [9]
Consumers may refer to yarn as string or thread, but yarn is the broader term and the one used in the global textile complex.
Yarns, or thread are usually knitted or woven together to make fabric, and may be dyed before or after the process. [10]
Fabric producers' yarn choice affects fabric hand, appearance, drape, durability, comfort, and other areas of performance. [11]
Yarns can be categorised in various ways, basic yarn types are:

- *Monofilament*
- *Multifilament*
- *Staple or spun*

As their name suggests, monofilament yarns contain a single filament. More commonly, many filaments are twisted together to form multifilament yarns. Staple or spun yarns consist of staple fibres combined by spinning into a long, continuous strand of yarn.

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[8] Hallett, Clive, *Fabric for fashion, the complete guide : natural and man-made fibers,* Laurence King Publishing, 2014, p. 13.

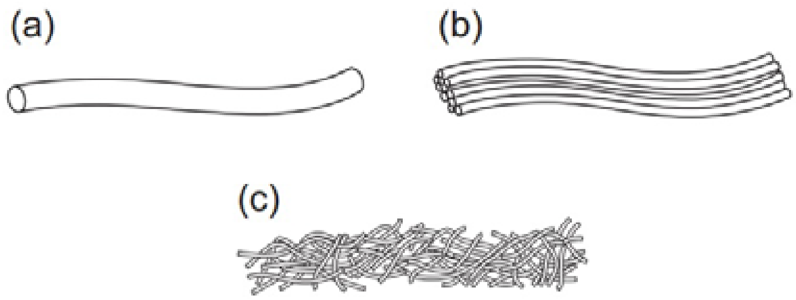
[9] R. Sinclair, op. cit., p. 8.

[10] Sara J. Kadolph, op. cit., *p. 4.*

[11] *ivi, p. 118.*

These types of yarn are illustrated in figure 6.2. *[12]*

Figure 6.2
Types of yarn:
a) monofilament
b) multifilament
c) staple/spun.



Fabric

A fabric is defined as a manufactured assembly of fibres and/or yarns that has substantial surface area in relation to its thickness, and sufficient cohesion to give the assembly useful mechanical strength. Consumers refer to fabric as cloth or material, but fabric or piece goods is used in the global textile complex.
There are many ways of combining yarns to create a fabric. Some of the most important are:
- *Weaving*
- *Knitting*
- *Nonwoven*

Weaving

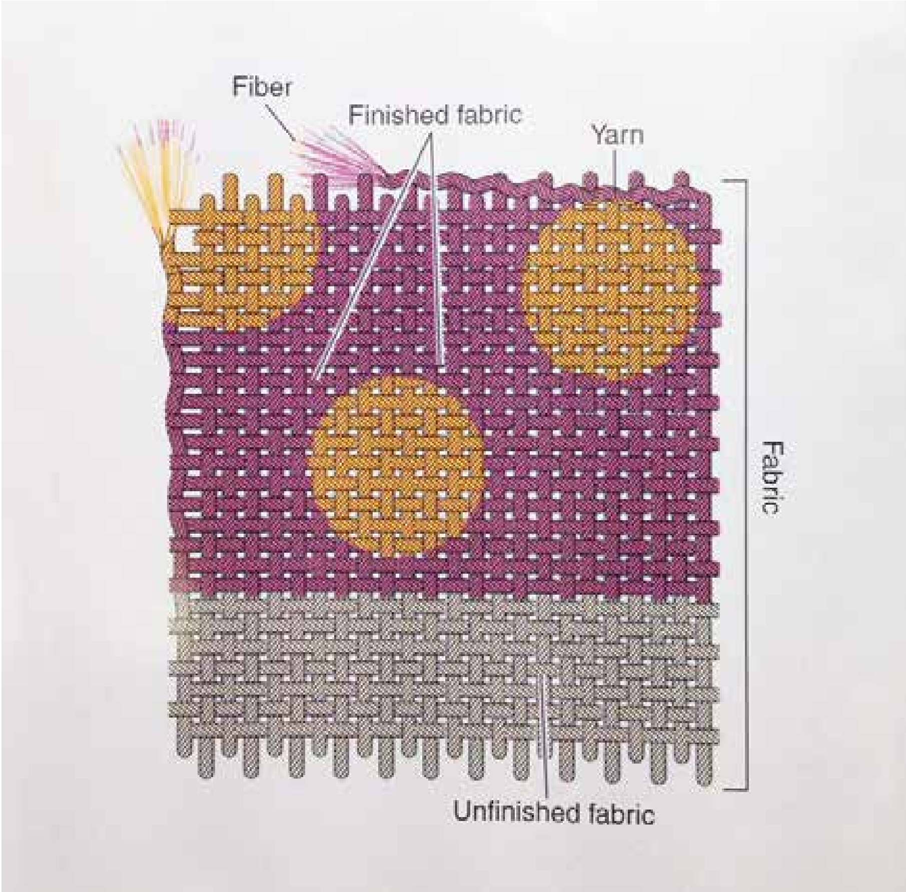
Weaving is the process of interwaving two sets of threads, the warps (vertical) and the wefts (horizontal), on a weaving loom. Three basic weave types, plain, twill and satin, form the majority of woven fabrics. There are also several alternative weaving techniques that create more complex fabrics. *[13]*
An illustration of woven fabric is shown in figure 6.3.

[12] R. Sinclair, op. cit., p. 8-9.

[13] Hallett, Clive, *op. cit.,* p. 16.

Figure 6.3
Woven fabric. The components of a fabric: fiber, yarn, structure and finish.

Source:
Sara J. Kadolph, op. cit., p.4.



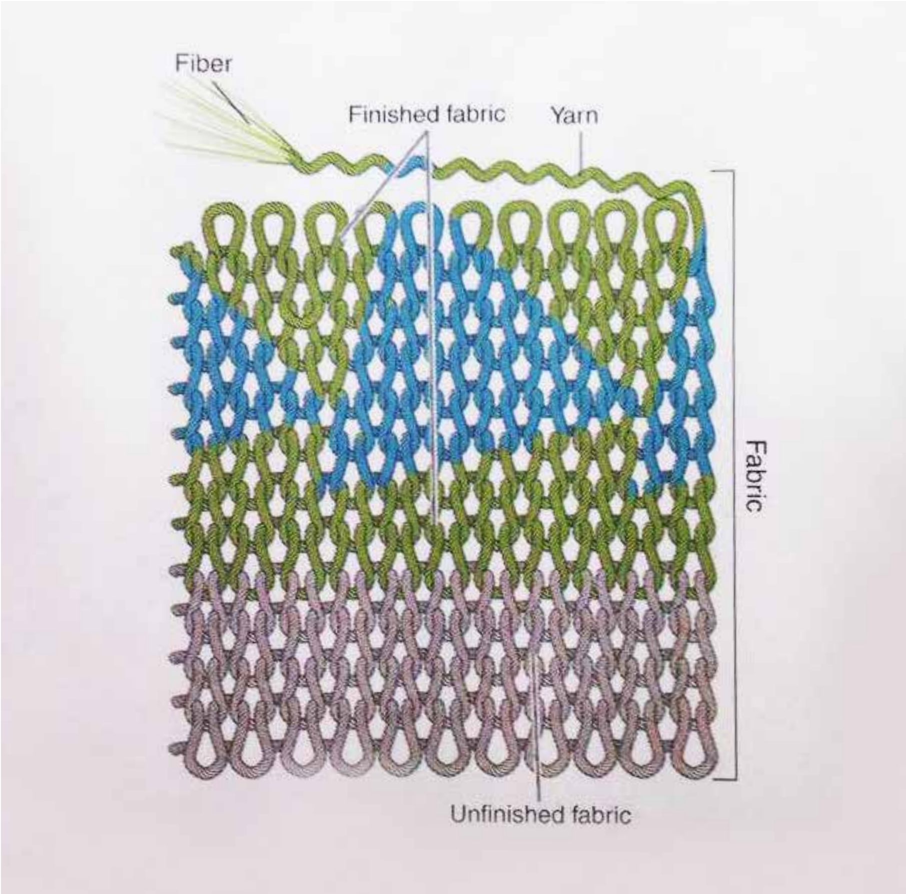
Knitting

Knitted fabric is constructed from yarn by means of a series of interlinked loops. This can be achieved by hand using individual needles, by using hand-operated machines, known as hand-frame knitting, or by power machine, simply called knitting machine. Knitting can refer to two areas of clothing. Sweaters-knits are garments that are partially or totally constructed on a knitting machine or by hand knitting. Jerseywear is a range of various garments, including T-shirts and polo shirts that are cut and made from fabric that has been knitted. Integral knitting using advanced technology is also known as jerseywear, and is used for seamless men's underwear and women's brasseries. The term knitwear refers to any fabric that has been knitted, regardless of how fine it is. [14]

An illustration of knitted fabric is shown in figure 6.4.

Figure 6.4
Knitted fabric. The components of a fabric: fiber, yarn, structure and finish.

Source: Sara J. Kadolph, op. cit., p.4.



Nonwoven

Some fabrics are made directly from fibers. Nonwovens are made from fibrous webs and bonded to form a stable fabric. They are more flexible than paper. The nonwoven process is simple, quick and inexespensive: select the fibers, create a web from them, and bond the web together to make the fabric. Any fiber can be used in the web. Nonwoven properties result from the fiber arrangement in the web, fiber content and binder type. Nonwovens have many technical, apparel and interior applications. [15]

[14] Hallett, Clive, *op. cit.,* p. 22.

[15] Sara J. Kadolph, op. cit., *p. 194.*

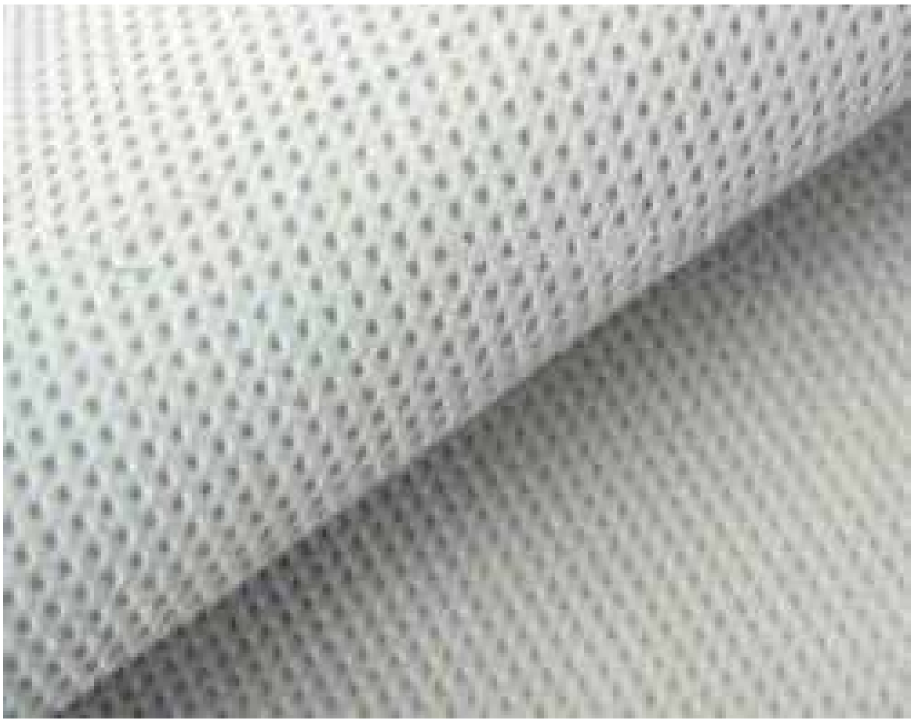


Figure 6.5
Nonwoven fabric.

Source: Web

6.3 Fabric finishing

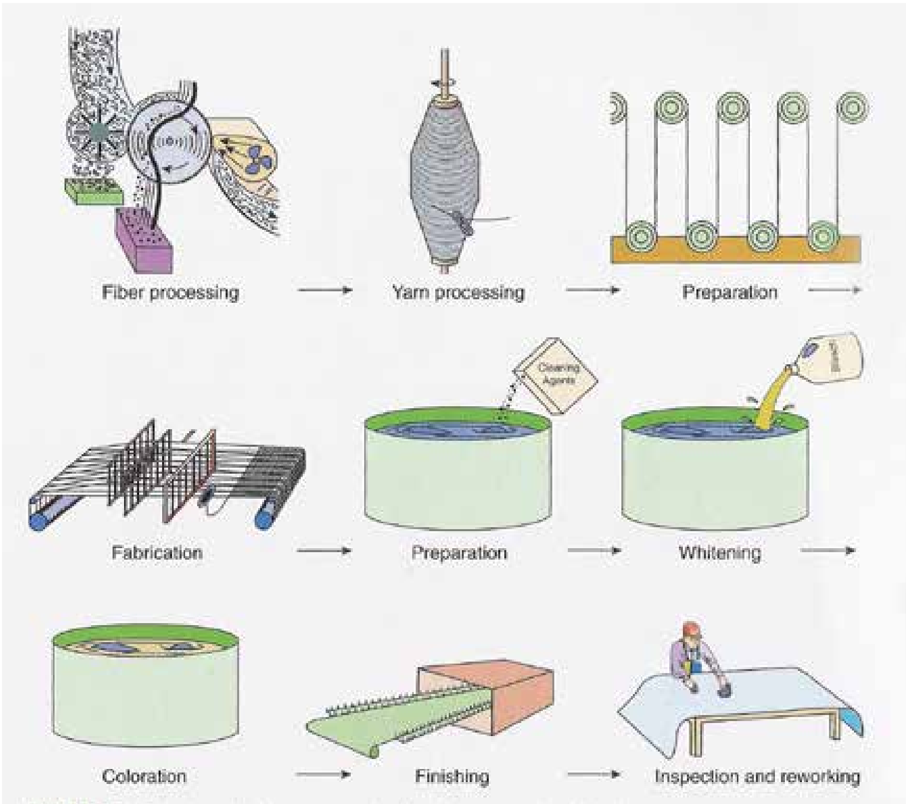
A finish is a process done to fiber, yarn or fabric to change its appearance, hand, or performance. Fabric finishing is the set of different processing steps that textiles undergo before being made up into garments or home furnishings: preparation, dyeing and coloring, printing, physical/mechanical finishing, and chemical finishing. [16]

Almost all fabrics receive some finishing, but it increases production time and product cost. Fabrics start out as gray goods and are converted into finished goods. A finish's life span results from the type of finish and process used and the fabric's fiber content. Most fabrics undergo several routine finishes to prepare them for coloration, aesthetic and special-purpose finishes. Routine finishes convert fabric into attractive, serviceable ad marketable products.

Aesthetic finishes change fabric appearance and hand and may change a fabric's name. These finishes are applied design or surface design. Some are additive finishes, others are substractive finishes.
Special-purpose finishes use chemicals to enhance product performance. For some finishes, improved performance in one area means a loss of performance in another. [17]

Figure 6.6
Typical production sequence for fabrics for apparel and interiors.

Source:
Sara J. Kadolph, op. cit., p.210.



Fabrics must be properly prepared before they are dyed and/or printed, in order to ensure that dye uptake is uniform, the desired colors are achieved, and the colors are fast. [18]

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[16] R. Sinclair, op. cit., p. 459.

[17] Sara J. Kadolph, op. cit., *p. 231.*

[18] R. Sinclair, op. cit., p. 459.

Dyeing

Color is a significant factor in textiles. Colorants include dyes and pigments that differ in their application to textiles and characteristics. The goal of coloration, the process of adding color, is in appealing, level, fast color at a reasonable price, with good performance and minimal environmental impact. Color can be applyed to fiber, yarn, fabric or product. The stage of coloration is based on product design and requirements related to colorant, cost, quality and end use. Dyeing can be done at any stage, while printing is most often done to fabric or products. [19]

Printing

Printing adds colour to the surface of specific areas of textiles. Printed fabrics have a definite face and back. Printing provides options for different colorways. The textile printing industries are typically categorized as two markets: industrial textile printing and soft signage printing. The industrial textile printing market includes apparel, home furnishing, and technical textiles; the soft signage textile printing market focuses on graphic advertisements printed on textile substrates such as banners, corporate flags, etc. Industrial textile printing has shown annual growth rates of over 1% for some time, driven by the acceleration of fashion cycles and continuous growth of the world population, and today produces over 20 billion linear meters per year (Osiris, 2008). Apparel and home furnishing textiles account for over 54 and 38%, respectively, of the market share in printed textile production, with technical textiles making up the remainder 8%.

All fabrics to be printed need to be clean and free from impurities. Many printing problems result from improper fabric preparation.

Although the contributions of traditional methods such as block printing and engraved copper printing to the textile design fields *have been significant, they are barely used in the textile printing industry today, having been replaced by newer and more reliable technologies such as automatic flat-bed screen printing and rotary screen printing. According to a worldwide survey by Stork, more than 90% of printed textiles are produced by screen printing technologies, which include table, flat-bed, and rotary printing. Transfer printing accounts for 6% and digital inkjet printing for slightly over 1% (see Table 6.5) (Stork, 2002).*

Table 6.5 Printing textiles processes.

Source: Sara J. Kadolph, op. cit., p.242.

Direct	Discharge	Screen	Others
Roller*	Discharge	Flat	Digital
Warp		Rotary*	Heat transfer

*Major printing processes.

The choice of printing method must take into account several factors that are critical in today's competitive global textile printing market, including:

- *short-run productions,*
- *sustainable printing conditions,*
- *quick response time, improper fabric preparation,*
- *customized printing products,*
- *new design possibilities.*

In some cases, the choice of the printing method depends on the purchaser of the design, and in other cases it is up to the designer to develop the print designs with a particular printing technology in mind. Direct printing is the most common technique, but a number of special printing styles can be used to provide different effects, not only visual but also tactile, when desired. [20]

[19] Sara J. Kadolph, op. cit., *p. 251.*

[20] R. Sinclair, op. cit., p. 506-507.

Table 6.6
Comparison and summary of printing methods.

Source: Sara J. Kadolph, op. cit., p.243.

Name	Stage	Advantages	Disadvantages	Identification
Roller print	Print on fabric	Multiple colors possible; less expensive; versatile: color, pattern, size; duplex prints possible	Number of colors limited; expensive; out-of-register prints; size limited by roller size	Up to 16 color patterns; variable repeat size; second most common method
Warp print	Print on yarn	Soft edge to pattern; unique look	Expensive process; slow process	Pattern more distinct when unraveled; minor process
Discharge print	Discharge paste on dyed fabric	Cost dependent on design	Tender fabric possible; patterns with few colors and dark ground	Ground color on back in patterned areas; usually white or one to two colors with dark ground
Screen print	Print on fabric or product	Fine detail with many colors; inexpensive; quick response; hand or commercial process; imitates other techniques	Change of fabric hand; separate screen for each color; out-of-register prints	Most common method; flat or rotary types; used for fabric and product
Digital print	Print on fabric and carpet	Inexpensive; quick response; quick color changes; mass customization possible; unique designs possible	Currently used for carpet; very fine detail limits; fastness and hand concerns; slow process; color matching issues	Most common method of printing carpet; widely used in textile design and sample development; sharp print on face; little, if any, on fabric back
Heat-transfer print	Print paper, transfer to fabric or product	Quick response; minimal downtime; detailed designs possible; inexpensive; low capital and space needs	Disposal of waste paper; limited dye classes; mostly on synthetic fibers; dye migration during storage possible	Sharp print on face; little, if any, on fabric back

6.4 Textile market

Today, exciting potential is offered by leaps in technology with natural fibres, man-made artificial regenerates and refined synthetics. They offer exciting options for an increasingly complex range of consumer demands. Sophisticated developments in man-made textiles offer a look quite different to traditional, natural materials, and do not work against them but alongside them instead. Combinations of microfibres (the new generation of ultra-fine synthetics), with regenerated yarns, silks, cottons and linens provide new looks and performance potential.
The chart below (fig. 6.7) shows recent figures for global textile fibre demand, illustrating the current worldwide dominance of low-cost synthetic fibres. In the natural and bio-based fibre sectors, cotton is the most popoular choice. [21]

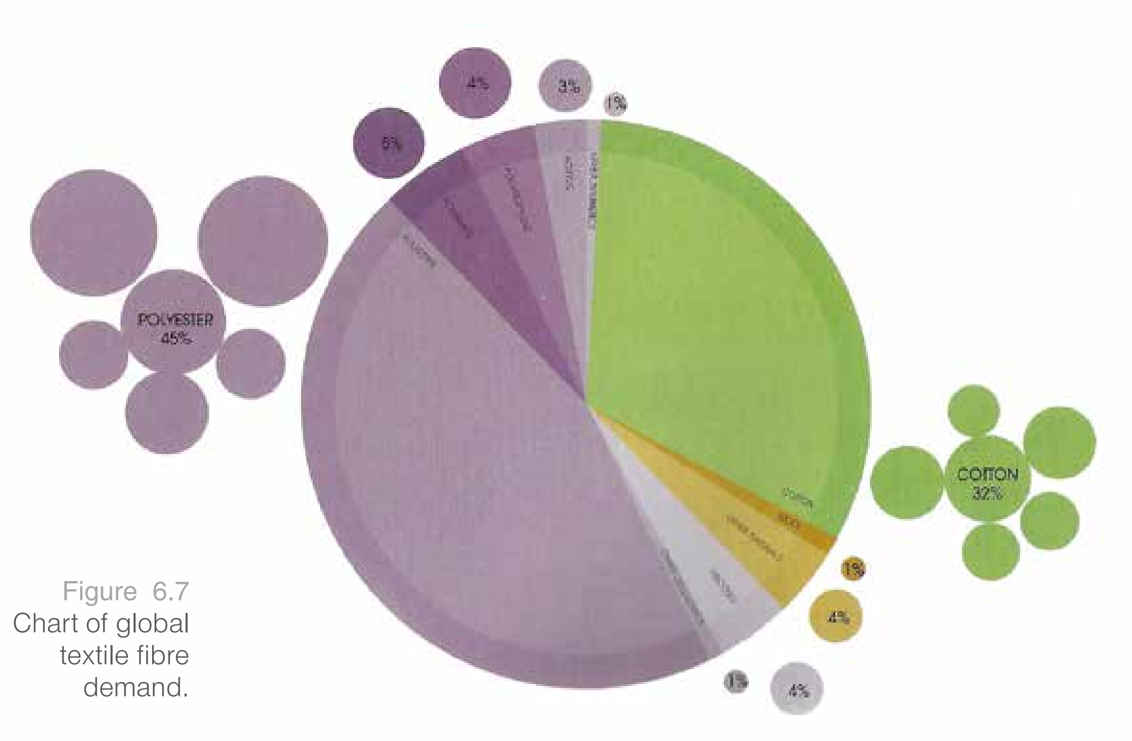


Figure 6.7
Chart of global textile fibre demand.

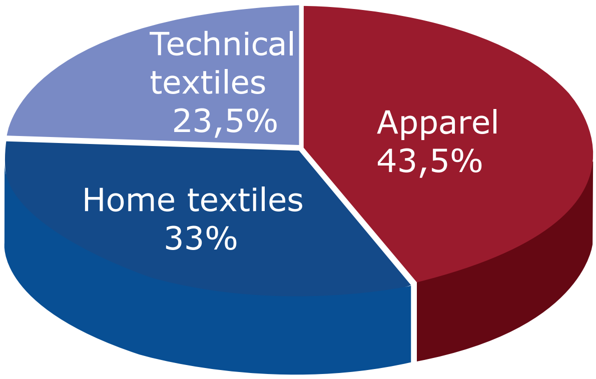
Source: The Fiber year, Oerlikon, 2010.

[21] Hallett, Clive, *op. cit.*, p. 8.

*The manufacture of textile can be divided into three segments: **Apparel** (clothing and fashion accessories like bags and shoes made from flexible materials), **Home textile** (upholstered furniture, carpets and towels), **Industrial/ Technical Textile** (toothbrushes, bandages, seat belts, conveyor belts and roadbed underlays). The ratio of Global textile production of these segments is shown in the following chart (fig. 6.8).*

Figure 6.8
Ratio of global textile production.

Source: http://www.teonline.com/industry-overview.html



*In the recent years, intense research and development have taken place in technical textiles and innovative apparel fabrics. Technical textile is high performance textile that is based on special functionality. Its market is expanding and it is used in various industries like agriculture, clothing, construction, health care, transportation, packaging, sports, environmental protection, protective wear, and many more. Apart from three segments seen above, an emerging Global Market for **Smart Fabrics and Interactive Textiles (SFIT)** is growing significantly. These textiles provide interactive properties such as electrical conductivity, ballistic resistance and biological protection. Electrically heated seat kits which have been a major commercial success is a fine example of this type of textile.*

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[22] 'Global textile market' can be found under http://www.teonline.com/industry-overview.html (2016)

Global smart textile market size was USD 350.3 million in 2013. Decreasing manufacturing costs of electronic components as well as fabrics along with miniaturization of electronics is expected to drive the smart fabric market over the forecast period. The rise in demand can be attributed to the introduction of conductive materials and advanced fibers that are used to manufacture such fibers. Nanotechnology has helped in the creation of such smart fabric at microscopic level. The chart below (fig. 6.9) displays Europe smart textile market by end-use, forecast of growing from 2012 to 2020.

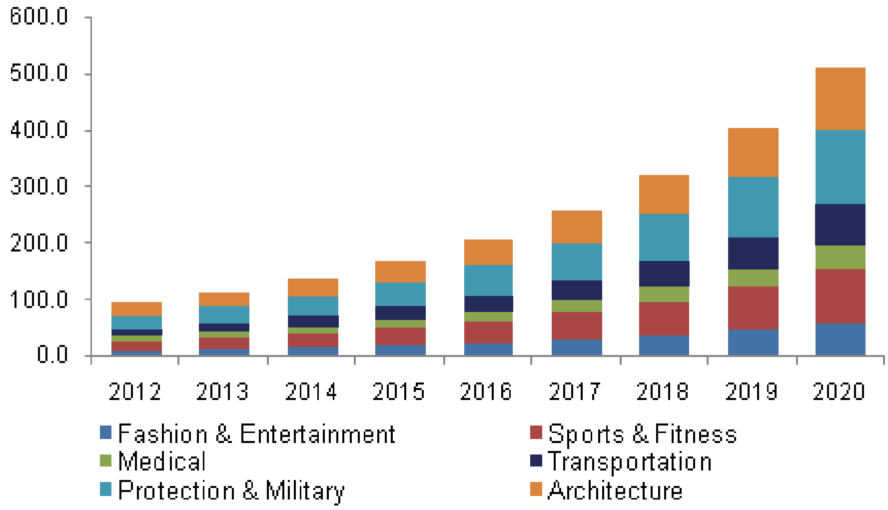

Figure 6.9
Europe smart textile market by end-use, 2012 – 2020 (USD Million).

Source: http://www.teonline.com/industry-overview.html

Although **Smart Fabrics and Interactive Textiles (SFIT)** is an emerging Global Market, the aim of the thesis project make possible the integration of this new segment with the existents. In this way these markets can work together and create new interesting partnerships. The following part will explain in detail the end-use opportunies.

[23] ‘Global smart textile market’ can be found under http://www.grandviewresearch.com/industry-analysis/smart-textiles-industry (2016)

6.5 Textile selection for the thesis project

The main approaches to have conductive fabrics are essentially two:

- in the process of making fabrics (weaving, knitting conductive fibres), thus creating special textiles;
- making the fabric conductive after the process, thus from everyday textiles.

This thesis, focuses on the second one, applying a conductive ink on common fabrics. In this way, as introduced before, across the different end-uses of intelligent textiles and meeting the thesis objective, the fabrics can be divided simply in two groups:

- Wearable textiles
- Home textiles

In order to make clear the following textiles selection, below are shown the main key factors for the thesis project.

Objective	Work on the Ecole des Mines Conductive Ink, in order to make it printable on textile through a pen.
End-use scenary	Make the fabric conductive after the process by using a pen, let the users free to do-it-yourself on everyday textiles.
Users	There is no need to be a technician, suitable for everyone.

The textile selection is divived in two approaches:

1. Textiles selection related to the **end-use scenery** of the thesis project, thus focused on a range of everyday textiles available in the stores to everyone.

Table 6.7
Main textile areas and end-use categories for the thesis project.

Apparel	Home textiles
T-shirts Pants and shorts Sweaters and cardigans Sportwear Coat and jacket Lab coat Dress	Upholstered furniture Carpets Towels Bedding and pillows Toys Window covering Outdoor covering

From the two main areas, each one has different categories of usage and for both were identifyed the most common fabrics (sometimes recurring across the areas).

2. Starting from the previous selection, this time drived by the **experimental approach**, thus focused on the interaction betwe-en the conductive ink and fabrics. A precise selection based on the type of fiber and the join process (yarn to fabric) (table 6.8), in order to achieve a pointed feedback for the tested samples and understand the general behaviour ink/textiles in broader terms.

Table 6.8
Selection based on the type of fiber and the join process (yarn to fabric)

Type of fiber		Yarn to fabric		
Natural	Man-made	Weaving	Knitting	Nonwoven

The main fiber properties considered for textiles selection are: density, hand, flexibility, elongation, absorbency.

References

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‘Global textile market‘ can be found under
http://www.teonline.com/industry-overview.html (2016)

‘Global smart textile market’ can be found under
http://www.grandviewresearch.com/industry-analysis/smart-textiles-industry (2016)

Chapter 7 | Testing phase 1 in the laboratory

The aim of the experimental phase is about working on the formulation of the conductive ink developed by Ecole des Mines of Saint Etienne, in order to make it printable on textile through a pen.
In the following chapter will be introduced the first part of the testing phase in preparation for the second one, about optimizing the ink performance.

The work mainly focuses on taking confidence with the ink formulation and understanding the general behaviour from the interaction with fabrics. It starts from an adjustament of the viscosity and an increase of the conductive filler within the ink recipe, to manage the composite blend. Following step is about lay down on textiles the conductive ink through free-standing and then writing instruments. Afterwards it will be measured the resistance on the samples and analized all of them with a microscope.

7.1 Introduction to the main actors

In the thesis project there are three main actors:

- **Conductive ink**
- **Textiles**
- **Writing instruments**

Each one plays an important role.

Conductive ink

Table 7.1
Details of conductive ink ingredients.

Source: Amélie Noel thesis

The components of the conductive ink, based on few layer graphene and mixed with polymeric latex, they are described in detail below (table 7.1).

Composite blend		
Ingredients	Description	Particle size (L:ø)
Filler Few Layered Graphene (FLG)	Graphene is a two-dimensional monolayer of carbon atoms closely packed in a honeycomb lattice. The term Nanosize Multilayered Graphene (NMG) is chosen to describe FLG with a small lateral dimension (< 400 nm). **Advantages:** low cost, good el. conductivity **Disadvantages:** carbon particles are hardly stable in water suspensions	lateral size 50 to 300 nm
Binder Natural rubber latex (commercial)	A latex is a colloidal suspension in water of particles. Polymer latexes can be used to create a segregated network by forcing the conductive particles into interstitial spaces between the polymer particles during drying.	Ø 80 to 2000 nm
Binder Acrylate latex (man-made)		Ø 300 - 650 nm
Surfactant SDBS	Surfactants are defined as amphiphilic molecules, meaning that they contain both hydrophobic tails and hydrophilic heads. Surfactant molecules can adsorb on interfaces, and can thus stabilize hydrophobic particles suspended in water media.	

In addition

A **thickener** could be added to adjust the viscosity in order to deposit the right amount of ink in a single layer. For instance, polyacrylic Acid is commonly used as thickener for latexes.

Textiles

Table 7.2
Data of textile samples used for the testing phase.

A scheme of fabric samples used for the first testing phase is shown below (table 7.2). This group of textiles are from the laboratory of Ecole des Mines, Saint Etienne.

Textile samples	Type of fiber		Yarn to fabric			Treatment	
	Natural	Man-made	Weaving	Knitting	Nonwoven	Finishing	Coating
1		x	x				polimer layer
2	x		x				
3	x		x				
4		x			x		
5		x			x		
6	x		x				
7	x			x			
8	x			x			
9	x		x				
10	x		x				
11		x	x				

Writing instruments

In addition to the free-standing on fabric by a metal paddle, below are shown the tools used for laying down the conductive ink in the first testing phase in the laboratory:

- Fountain pen
- Correction pen
- Felt-tip pen
- Syringe

Figure 7.1
Fountain pen
Source: web
(top left)

Figure 7.2
Correction pen
Source: web
(top right)

Figure 7.3
Felt-tip pen
Source: web
(bottom left)

Figure 7.4
Fountain pen
Source: web
(bottom right)

7.2 Make the composite blend following the ink recipe

The testing phase started making the composite blend following the recipe. The ingredients are: graphene initial suspension, latex and thickener. The most important ingredient is the graphene suspension which give conductivity, thus the first step concerned the amount of filler in the graphene solution and thus in the composite blend. The recipe of Ecole des Mines to make the composite blend is shown below (table 7.3).

Table 7.3
The recipe to make the composite blend.

Source: Amélie Noel thesis

	Non Concentrated	Concentrated	
	0	5 times	10 times
Filler Few Layered Graphene solution (FLG)	60 - 100 ml	30 - 50 ml	6 - 10 ml
Binder Natural polymer latex commercial (60% solid content)	1 ml		
Binder Polymer latex man-made (20% solid content)	3-4ml		

– **Viscosity** **+**

There are two ways to achieve a good ratio of graphene content:

- Large amount of graphene solution without concentration
- Concentration several times (5x, 10x or more)

Figure 7.5
Concentration process, heating and stirring the graphene solution to evaporate water.

The **concentration process** evaporate the water from the solution leaving a more concetrated amount of graphene platelets. In this way the final blend should be more conductive, but increasing too much the amount of graphene the final ink structure could be unstable.

First step needed to concentrate the graphene suspension. It was taken 200mL suspension (graphene concentration 2g/L) in a becher and evaporated it on a heater under magnetic stirring. Water was evaporeted until it reached 20mL suspension (concentration 10 times higher than the initial one: 20g/L).

An important requirement of this project demand conductivicty after only one cycle of deposition. The feedback about the attempts to lay down the ink on textile before to start the internship, addressed this testing phase to go on through the maximum concentration of graphene (10x) without considering the lower concentrations.
Starting from 200ml suspension graphene in a becher it was followed the same process explained before, reaching 20ml of

concentrated solution. Afterwards, following the Ecole des Mines recipe, the amount of graphene in the composite blend was modulate in a range from 6 to 10ml.

7.3 Looking for conductivity on fabric

From the first attempts it was used the concentrated graphene solution (10x), it was made and blended with the latex and a little amount of thickener. The first formulation started with 6 ml of filler, adjusting the quantity from 6 to 10mL for the following. The **first ink formulation** is shown below.

6ml concentrated graphene solution + 1ml commercial latex + 0,8g thickener

Figure 7.6
(a) concentrated graphene solution,
(b) commercial latex,
(c) thickener,
(d)composite blend.

A digital analytical balance is shown below (fig. 7.7), it was used in the laboratory to measure the components in a precise manner, to make the composite blend.

Figure 7.7
Digital analytical balance with 1 mg readability.

Laboratory, Ecole des Mines, Saint Etienne.

EdM conductive ink was applied on fabrics (fig. 7.8) by using a metal paddle in a free-standing way. For the first attempts it was used a hair dryer (fig. 7.9) for drying the conductive ink.

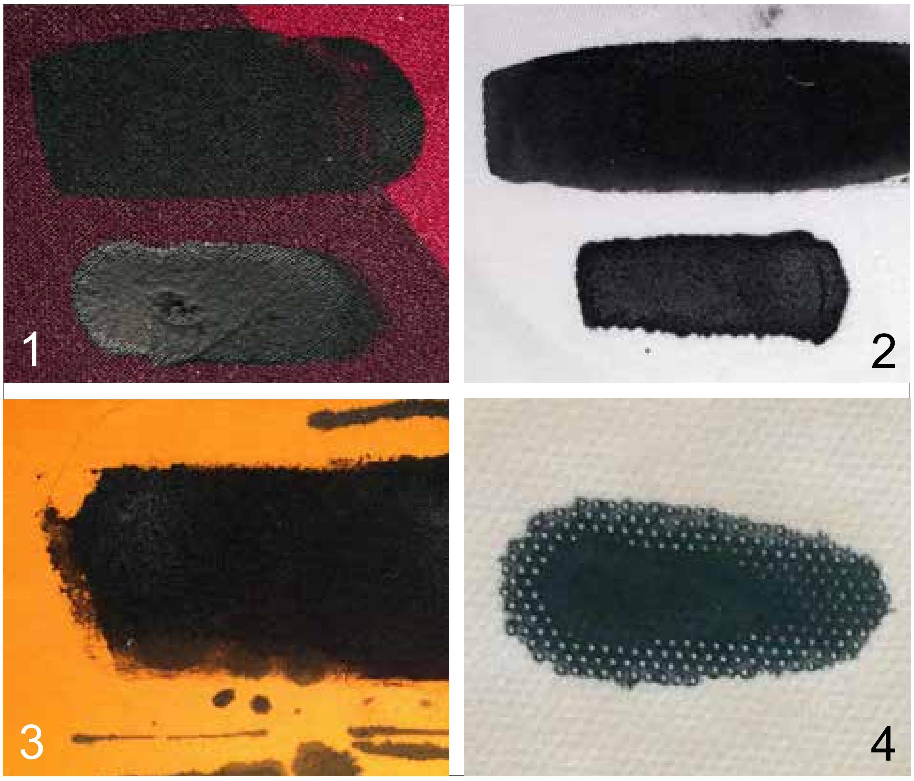


Figure 7.8
First fabric samples after conductive ink drying, free laying by a metal paddle, mark wideness 15-20 mm for samples n.1,2,4, 40 mm for sample n.3.

Figure 7.9
Hair dryer used for ink drying on fabrics.

Laboratory, Ecole des Mines, Saint Etienne.

After the ink drying was measured the electrical resistance by using a multimeter (fig. 7.11).

The first attempts were > 100 Mohms.
The layer is considered conductive if the measured resistance is < 100 Mohms.

Figure 7.10
Fabric sample n.1 in a ring clamp for textiles.

Laboratory, Ecole des Mines, Saint Etienne.

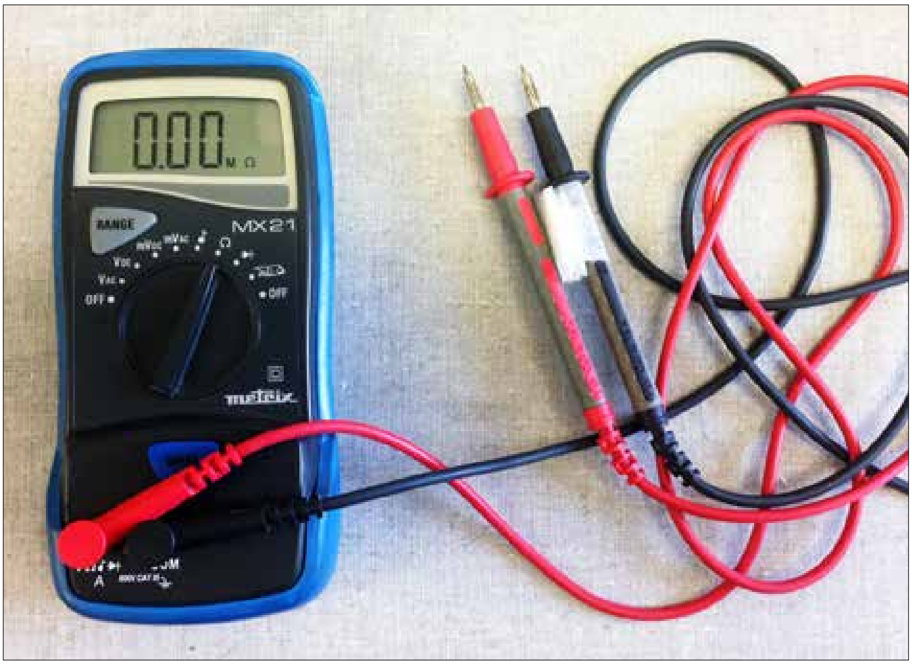


Figure 7.11
Multimeter used for measuring the electrical resistance.

Laboratory, Ecole des Mines, Saint Etienne.

Starting from 6ml of concentrated graphene solution, in the second attempt it was added more quantity reaching the maximum range of 10ml. **EdM ink formulation** is shown below.

10ml concentrated graphene solution + 1ml commercial latex + 0,8g thickener

Then it was mixed like the first formulation, layed down the composite blend on the same four different fabrics and dryed by a hair dryer. The result was the same obtained in the previous attempts, **no conductivity.**

Resistance > 100 Mohms.
The layer is considered conductive if the measured resistance is < 100 Mohms.

In order to understand weather the not conductive result was attributable to the ink formulation, the textiles used, or both of them, the ink was layed down by free standing in a silicon form and then dried in the oven (fig. 7.12). The recipe for free standing in silicone form doesn't need viscosity, thus no thickener was needed in the composite blend. The result showed conductivity.

10ml concentrated graphene solution + 1ml commercial latex

Resistance < 100 Mohms.
The layer is considered conductive if the measured resistance is < 100 Mohms.

Once verified the conductivity of the ink layed down by free standing in silicone form, the ink was applyed the on textile adjusting the viscosity with the thickener. The ink formulation needs thickener for an ideal deposition on textiles. The textile used, fabric sample n.5 (fig. 7.13), it is thicker and tighter weave than the previous four fabrics, it showed conductivity after drying.

Figure 7.12 (on the left) Heating silicon forms in the oven.

Laboratory, Ecole des Mines, Saint Etienne.

Figure 7.13 (on the right) Drying the ink by using an hair dryer.

Laboratory, Ecole des Mines, Saint Etienne.

The samples from free standing in the silicone form and textile sample 5, few days later the conductivity measurement, they lost their conductivity. It was decided to try the latex made by Ecole des Mines (man-made latex) instead of the commercial latex used before, in order to see whether there was some change by following the same method. Thus the new ink formulation was layed down by free standing in the silicone form **showing conductivity after drying**. The new composite blend is shown below.

10ml concentrated graphene + 4ml man-made latex

In parallel the previous samples that lost conductivity, fabric sample n.5 and the samples from the silicone form, they was dipped in water in some bechers in order to make them free from surfactants that sometimes go up on the surface during the film formation (fig 7.14). After drying in the oven, the samples recovered conductivity.

Note

There is a negative point to report:
During the water treatment the ink film went out from the fabric sample n.5, a synthetic textile.
This synthetic textile has a non-wetting treatment on it and it's specific for printing. The ink to be fixed to the textile needs to stick on the fabric, otherwise even after soft washing it leaves the substrate showing incompatibility.

Hypothesis

The surfactants exudation is the cause of losing conductivity.

Figure 7.14
From left to the right: samples from the silicone form and beside textile sample 5 dipped in water in some bechers.

This observation has brought to think a compromise to build a good film of conductive ink on the surface and at the same time going inside the fibres enough to make it fixed and stable.

The samples from the silicone form using man-made latex in the recipe showed conductivity, thus the feedback said that the formulation worked well and at the same time the observation about the synthetic fabric, sample n.5, it brought to set the experimental phase closer to natural fibers.

7.4 Focus on wearable textiles

Once found conductivity from the composite blend, the next step was about achieving conductivity on textiles even stretchable. Some textile was chosen from the laboratory, two of them with a little elasticity and a woven cotton fabric. Starting from the previous ink formulation the testing phase went on more focus on werable technology.

Figure 7.14 From left to the right: fabric samples n. 6-7-8.

The conductive ink was layed down on the new textiles and after drying they showed conductivity. Below there is the composite blend from the previous ink formulation, in addition a little thickener for using on textiles.

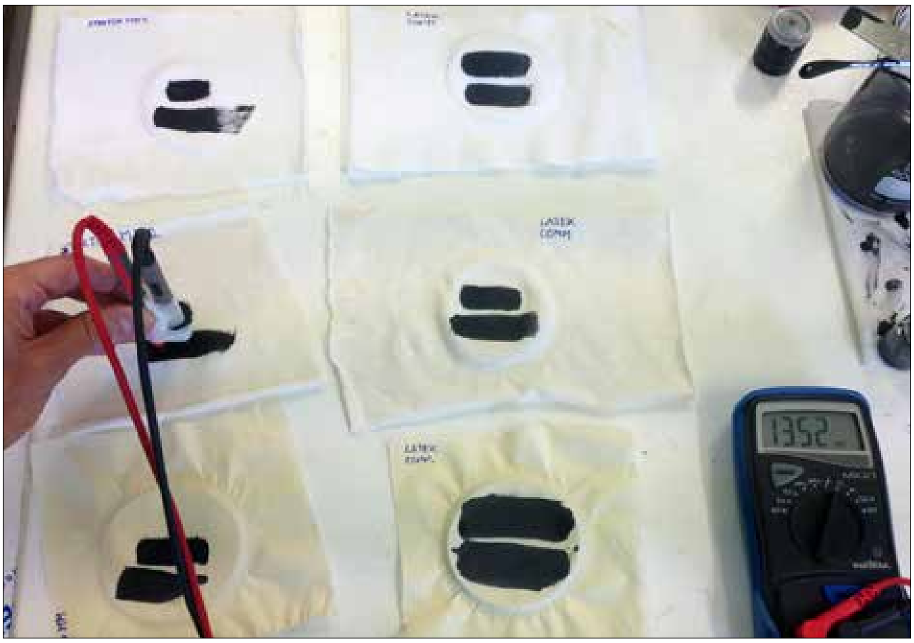
10ml concentrated graphene + 4ml man-made latex + 1g thickener

Once found conductivity even on stretchable fabrics, It was decided to compare both latexes, man-made and commercial, in order to decide which one choose for going on. During the first testing phase they were used in different conditions, such as different amount of concentrated graphene in the final blend, different textile samples and at least different drying method.

It was made the same formulation used in the last attempt by using the commercial latex this time instead of the man-made, paying particular attention to follow every single step done previously. At least it was layed down the conductive ink on the same textiles, samples n. 6-7-8 (fig. 7.15), they were dryed in the oven and then measured the electrical resistance. As the man-made latex samples **the result showed conductivity**.

> Resistance < 100 Mohms.
> The layer is considered conductive if the measured resistance is < 100 Mohms.

Figure 7.15
Measuring textile samples n.6-7- 8, comparison of man-made and commercial latex in the composite blend.



After the measurement with the multimeter the fabric samples were analyse by a galvanometer, a more precise machine used for measuring the electrical conductivity. For the test, samples n.6,7,8, (fig. 7.16) both formulations with man-made (MM) and commercial latex (COM), were cut in small pieces and after the measurment it was filled out a table of ten values for every sample, in order to calculate the average level (table 7.4).

Table 7.4
Measuring fabric samples 6,7,8 by a galvanometer, comparison of man-made and commercial latex.

Fabric samples		Measurements										
		1	2	3	4	5	6	7	8	9	10	U (V)
6	MM	2.7	0.4	1.6	0.6	1	1	0.5	1.2	5.6	0.2 edge	1.5
	COM	2	2.5	2	9.5	3	4.3	3.5	2	2.9	1.7	3.3
7	MM	1.6	1.2	0.8	1	1.5	1.9	1.3	0.8	1.2	1.3	1.3
	COM	0.5	0.2	1	0.2	0.3	0.2	0.03	0.08	0.02	0.03	0.3
8	MM	0.4	0.2	0.2	0.2	0.3	0.5	0.6	0.8	1.7	0.4 edge	0.5
	COM	0.2	0.01	0.03	0.01	0.01	0.03	0.02	0.01	0.01	0.06	0.04

Figure 7.16
From left to the right: fabric samples 6,7,8. comparison between man-made and commercial latex .

The electrical conductivity was measured using a four-point probe setup (with gold contacts and 3.48 mm of distance (s) between each probe) equipped with a galvanometer (Keithley 2400). The equipment used is shown in the picture 7.17.

Figure 7.17
Four-probe galvanometer equipment (Keithley 2400).

A galvanometer is used to inject the measurement current in the end pair of leads. The second lead pair is used to measure the potential drop across the device. Assuming that the leads resistance is smaller, four-point probe is more accurate than two point's measurements. For each specimen, ten measurements are done on each side of the nanocomposites films. Each measurement allows the calculation of the resistivity though the following equation:

$$\rho = \frac{\pi}{\ln(2)} t \left(\frac{U}{I} \right) f_1 f_2 \qquad \text{Equation 1}$$

where t, f1 and f2 represent respectively the thickness of the sample and two form factors depending of the shape and thickness of the specimens. The form factor f1 depends of the thickness of the sample. The form factor f2 depends of the shape of the samples.

$$= \frac{1}{\rho} \qquad \text{Equation 2}$$

Imput parameter: $I = 15\ \mu A$

The results will be shown in the paragraph 7.8, Outcome of the testing phase 1.

7.5 Use of writing instruments for laying down the conductive ink

Once achieved a conductive ink formulation, stable and conductive even on stretchable textiles, the following step was more focused on laying down the ink by writing instrument on fabrics.
After the first tests of free-standing on textiles with a metal paddle only to lay down the ink and verify the conductivity, there was the need to make the system repeatable in an easy and conventional way. In addition the advantage to use a writing instrument make possible to lay down the conductive ink in narrow lines for different end uses. Ecole des Mines had already used two type of writing instruments to lay down the conductive ink: **fountain pen** and **correction pen** (fig. 7.18, 7.19).

Figure 7.18
Correction pen for using with EdM conductive ink in the testing phase. (on the left)

Figure 7.19
Fountain pen for using with EdM conductive ink in the testing phase (on the right)

Feedback of use fountain pen and correction pen by Ecole des Mines

Fountain pen: this kind of pen uses a very liquid ink. EdM Conductive ink to build a good film on fabric needs a viscous formulation, thus it doesn't come out from the tip of the fountain pen.

Correction pen: like fountain pen, correction pen uses a very liquid ink. Thus EdM Conductive ink remains trapped into the nib drying inside the pen.

In parallel with the testing phase in the laboratory the research carried on about different principles to lay down inks, from the history of writing instruments. This analysis was very useful to go on the attempts to lay down EdM Conductive ink by writing instruments in the laboratory.
For the first attempts **felt tip marker** and a special kind of **fountain pen (parallel pen)** were tryed, but they didn't show good results. The first one is suitable for writing on textiles and work by absorbing action, it doesn't fit a viscous ink because it remains trapped into the nib drying inside the pen. The latter in spite of the special nib, wider than common fountain pen, it shows the same issue seen for the fountain pen. The writing instruments used for the first attempts are shown below (fig. 7.20, 7.21).

Figure 7.20
Felt tip marker for using with EdM conductive ink in the testing phase. (on the left)

Figure 7.21
Parallel pen for using with EdM conductive ink in the testing phase. (on the right)

The focus went on the **correction pen**, it has been adjusted for EdM conductive ink, removing the spring and the piston from the tip, leaving the ink goes out freely through the hole. The principle worked well, pushing the ink by hand pressure, playing at the same time with the ink viscosity. Thus EdM conductive ink was layed down many times in long paths on two pieces of cotton (fig. 7.22 - 7.23), fabric sample 10.

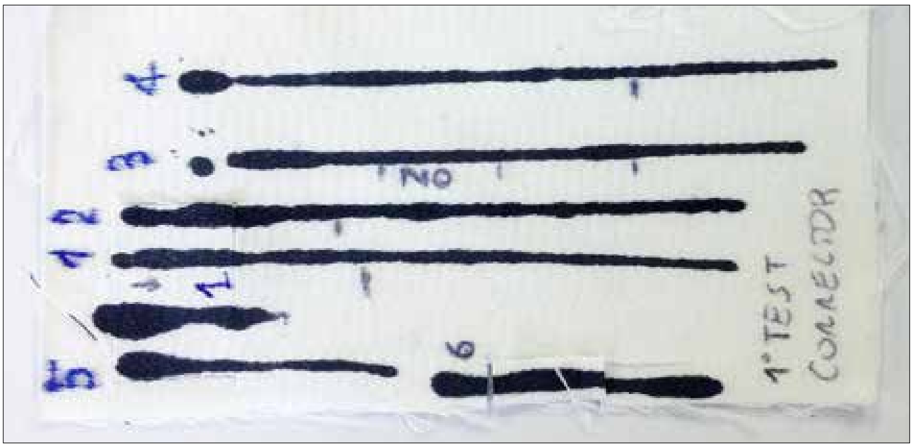


Figure 7.22
Cotton fabric sample 10, ink lines, first test.

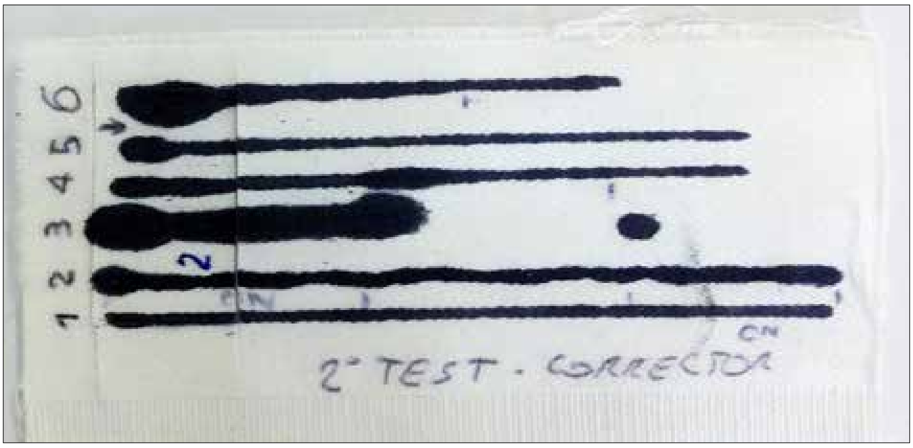


Figure 7.23
Cotton fabric sample 10, ink lines, second test.

After drying It was measured the resistance along the lines to verify whether the paths were conductive for all the lenght or not. **The measurement was not continuos**, probably the line size not regular and the ink laying down not homogeneous didn't favour an ideal ink deposition on fabric, filler aggregation in some parts and filler loss in others.

After the first deposition it was layed down an other ink layer only on lines n.2 from both samples to measure how the resistance value changes. From the first sample the conductivity increased, while the second one from not conductive became conductive.

The cotton samples were dipped in a becher of water (fig. 7.24) for a while, as it has been done previously in the testing phase with an other sample, in order to make them free from surfactants that sometimes go up on the surface during the film formation. After soft washing the ink was still stable on fabric and after drying still conductive.

Figure 7.24
Cotton fabric samples 1-2, soft washing in bechers.

After that feedback the same ink formulation it has been applyed by using the **correction pen** on two different synthetic textiles, one of them with a polymer layer on it (fig. 7.25). Two lines were layed down and then measured the resistance after drying.

Figure 7.25
From left to the right: a synthetic fabric (sample n.11) and a synthetic fabric with a polymer layer on it (sample n.1).

Figure 7.26
From left to the right: soft washing in bechers of a synthetic fabric (sample n.1) and a synthetic fabric with a polymer layer on it (sample n.11).

As it was done previously in the testing phase with an other sample, the synthetic textiles was dipped in a becher of water (fig. 7.26) for a while. **The ink film left the fabrics surface resulting not compatible with these textiles.** This response addressed the following testing part more focused on natural fibers also in line with the use as apparel in wearable technology.

7.6 An alternative approach to have conductive textile by using the conductive ink

The feedback from the first part of the testing brought to consider 2 ways to have a conductive textile by using the EdM conductive ink in order to prevent the high absorption of the ink from the fabric. The first one provided the use of viscous ink as it was used in the previous attempts for the testing phase. The latter was focused on liquid ink, standing a primer on the fabric before to lay down the ink. In this way the ink is not absorbed from the fibers because it sticks on the primer leaving all the ink uniformly on the surface, without loss of filler. In addition a liquid ink work better with common writing instruments or printing machines.

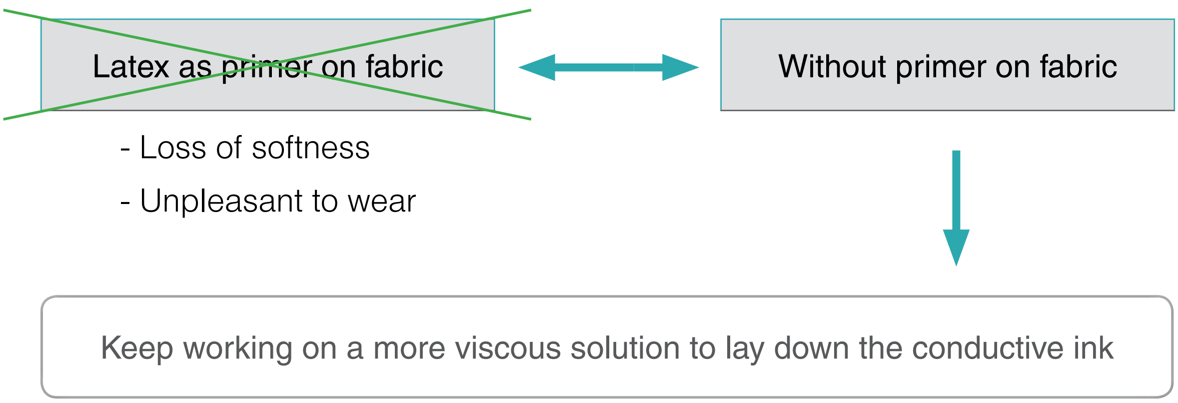
The two methods introduced before about making conductive textiles by using the conductive ink are described below.

:

Table 7.5 Comparing the two ways of having conductive textiles by using the conductive ink.

Without primer on fabric	Latex as primer on fabric
Lay down the composite blend with thickener on fabric without latex as primer on it.	Latex layer brushed as a primer on the textile surface, then layed down the composite blend without thickener.
viscous solution concentrated graphene sol + latex + thickener	liquid solution concentrated graphene sol + latex

A cotton sample was taken and brushed some latex on the surface, then layed down 2 lines of conductive ink, one with thickener and beside an other without. After drying they showed conductivity. The decision to brush latex on the surface as a primer and then lay down only the blend without thickener It was a try to verify whether it could be an alternative instead of using viscous blend direct on the fabric surface, which it has more issues to manage. In spite of the advantages explained before about having a liquid ink, the idea to use the latex as primer on fabric was given up after seeing how the fabric lost softness becoming more rigid and unpleasent to wear.

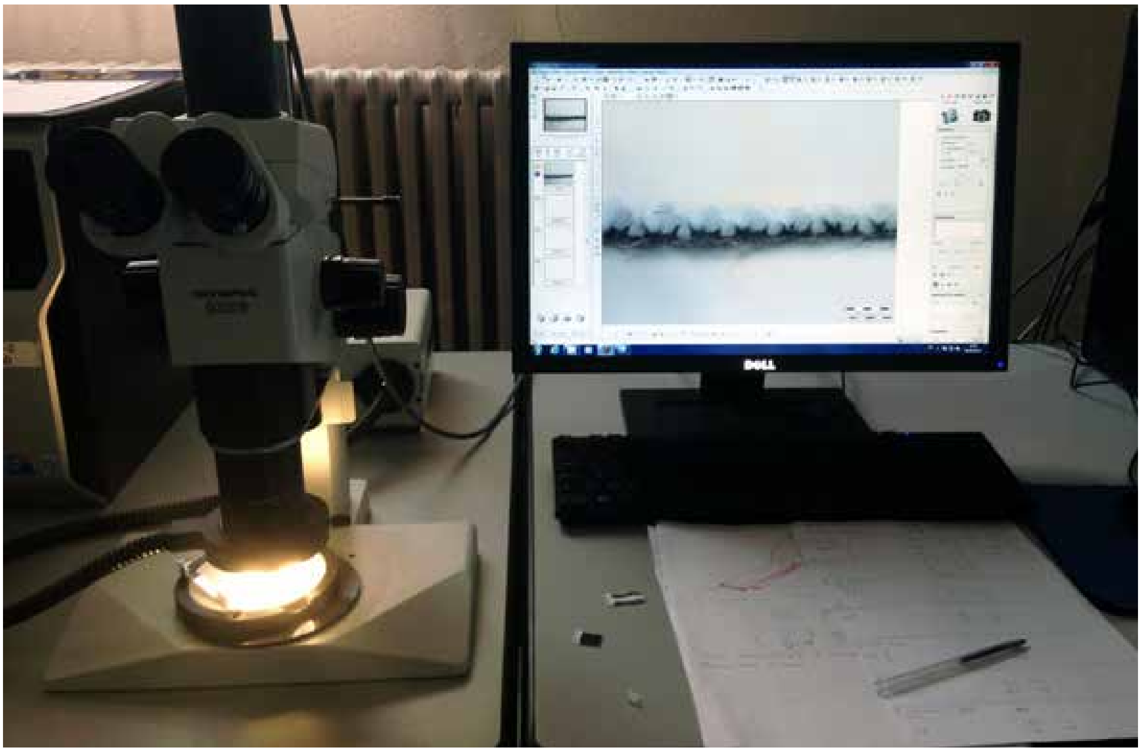


7.7 Microscope analysis of the fabric samples

Finally, long time has been spent in the microscope room analysing the textile samples used in order to understand better the behaviour of the conductive ink on the fibers.
Seeing how the ink sticks on the fabric and how the film looks could give a good feedback to manage at best the following part, otimizing the ink performance.
The analysis was done by using an optical microscope set with two lens (0.5x / 2x) and changing the magnification during the analysis. The test was set in two ways: collecting data pictures of the planar view and cross section.
The picture below displays the use of an optical microscope to analyse the fabric samples (fig. 7.27).

Figure 7.27 Optical microscope, analysis of fabric samples.

Laboratory, Ecole des Mines, Saint Etienne.



The following pictures show the set of two different fabric samples under cross section analysis with the optical microscope (fig. 7.28 - 7.29). The pictures obtained by the microscope will be shown in the next pages.

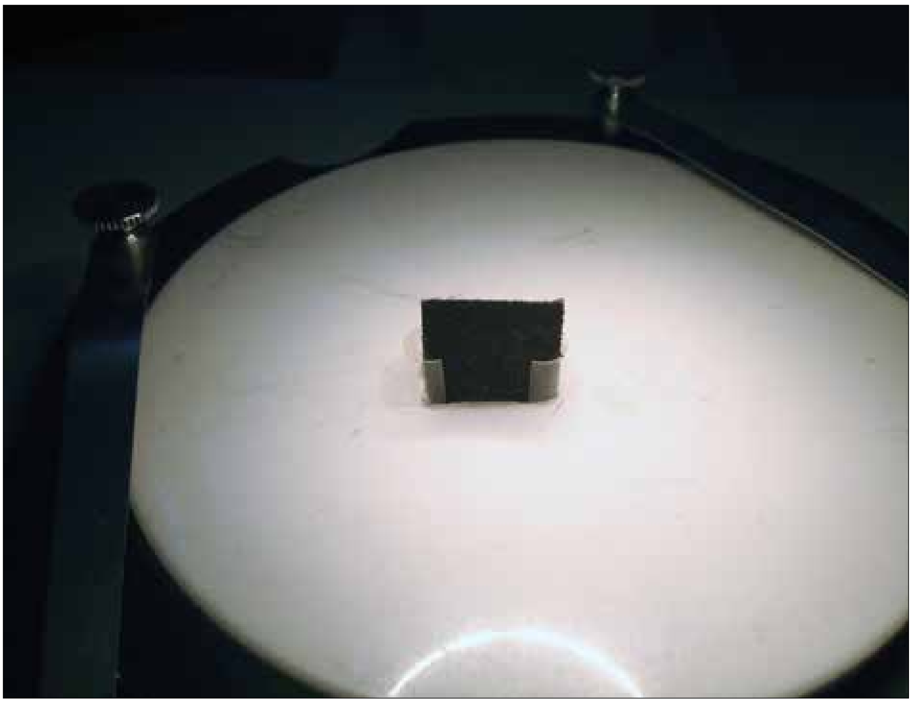


Figure 7.28
Cross section analysis, sample n.9, square mark by free-standing.

Laboratory, Ecole des Mines, Saint Etienne.

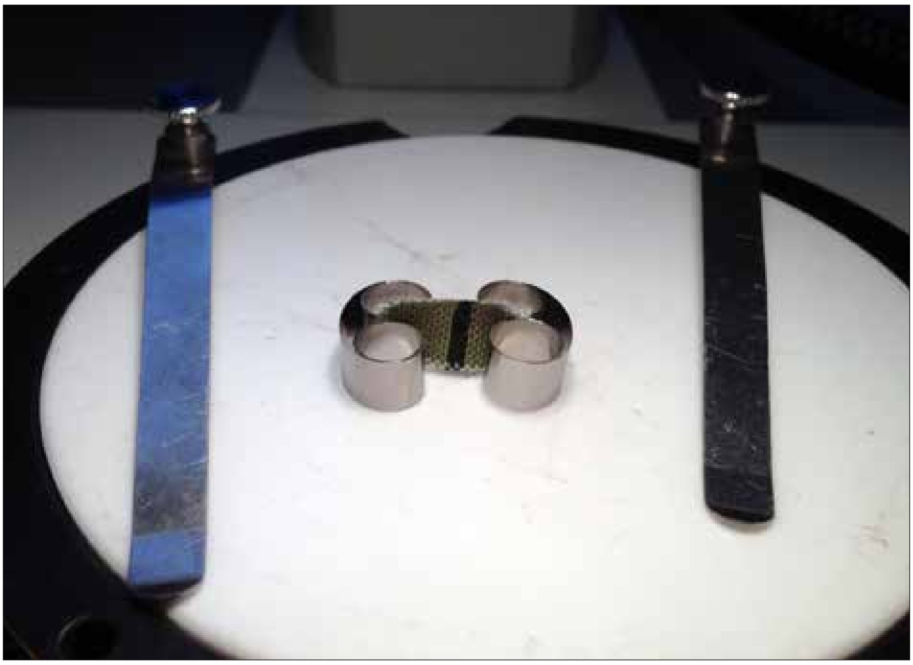
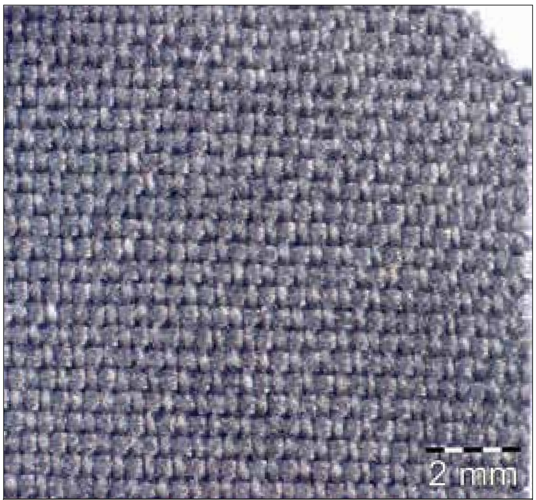


Figure 7.29
Cross section analysis, sample n.11. narrow line by correction pen.

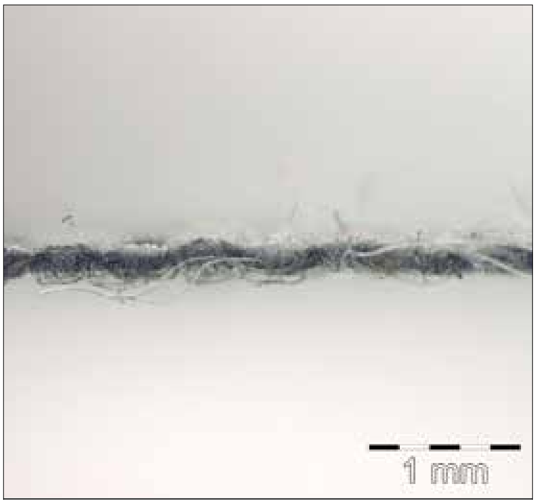
Laboratory, Ecole des Mines, Saint Etienne.

Planar view	Cross section
Lens parametres	
0,5x	2x

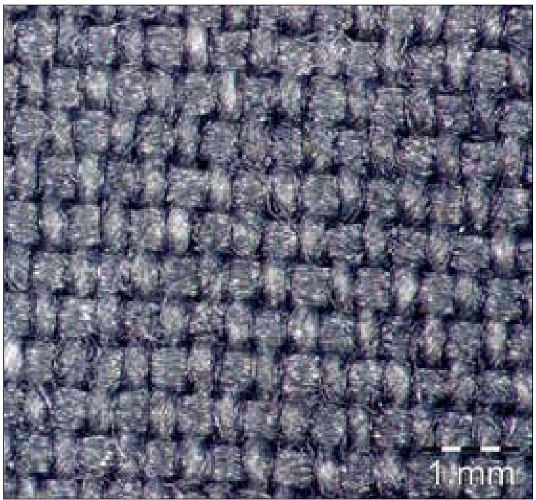
Fabric sample n.6



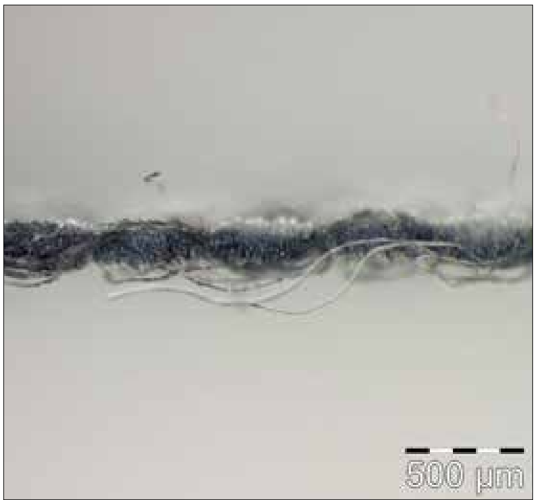
8 magnification



25 magnification



16 magnification

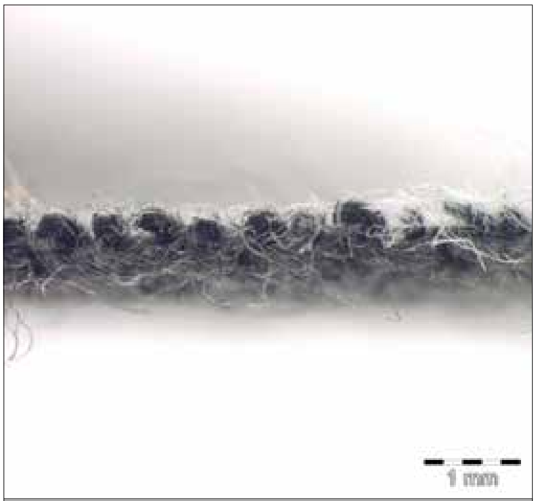


40 magnification

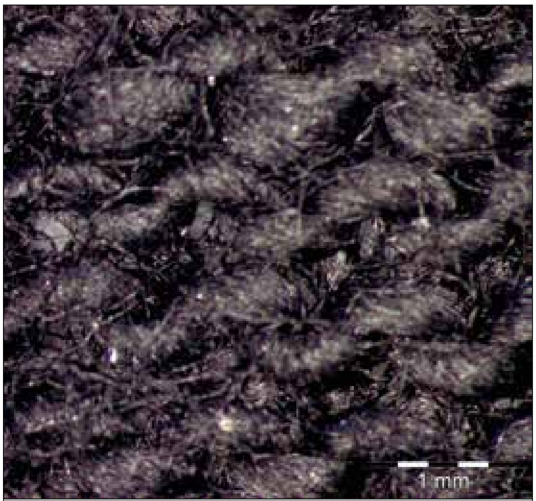
Planar view	Cross section
Lens parametres	
0,5x	2x

Fabric sample n.7

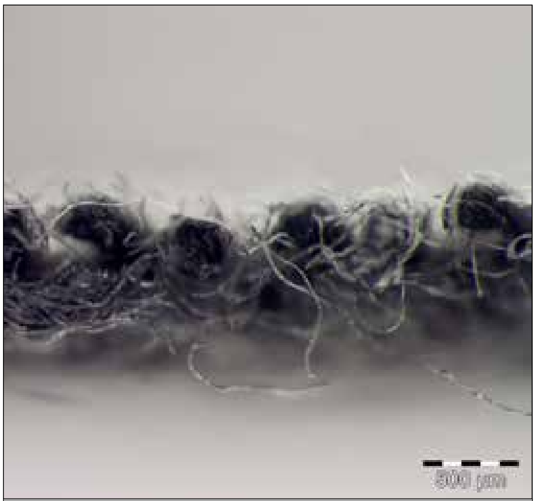
8 magnification



16 magnification



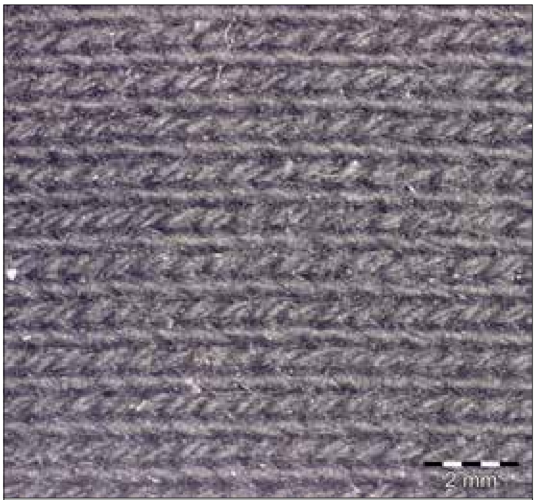
25 magnification



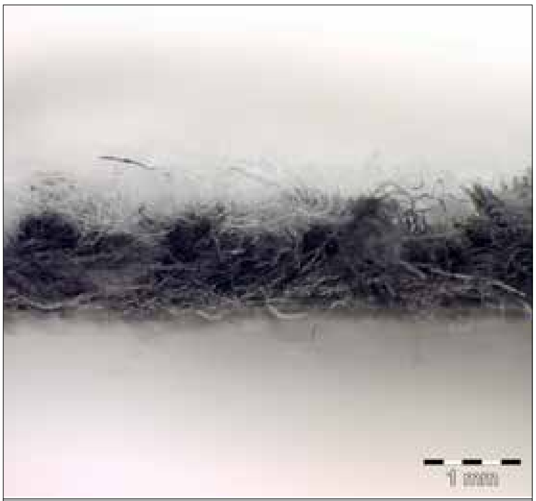
32 magnification

Planar view	Cross section
Lens parametres	
0,5x	2x

Fabric sample n.8

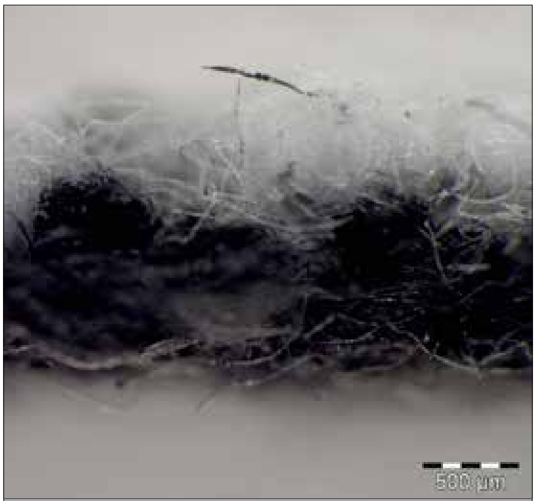


8 magnification



16 magnification

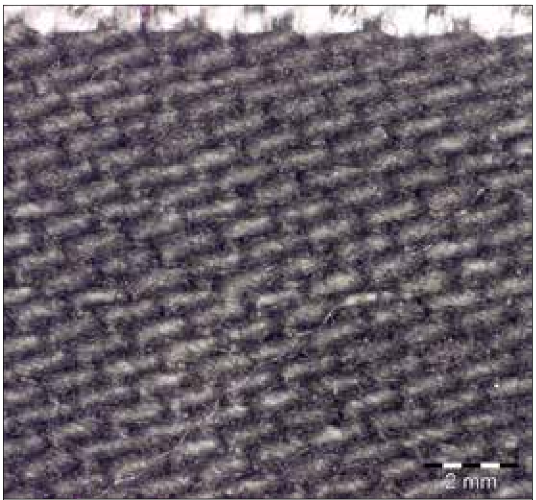
16 magnification



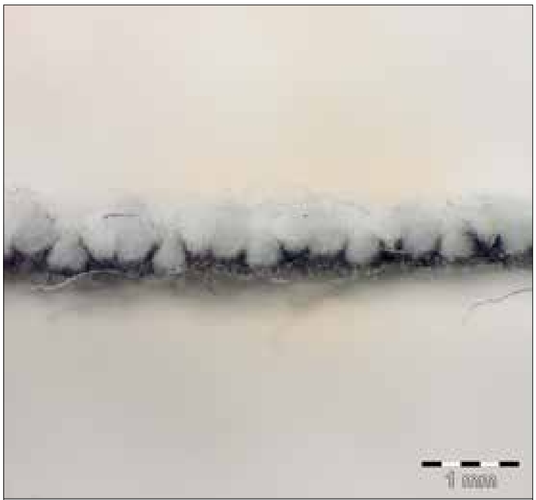
32 magnification

Planar view	Cross section
Lens parametres	
0,5x	2x

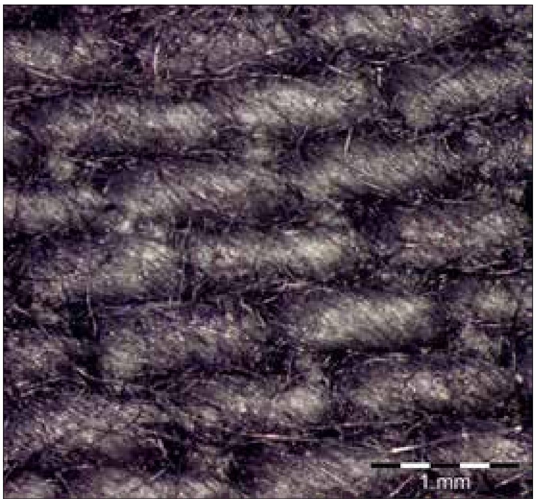
Fabric sample n.9 (Amélie Noel's sample)



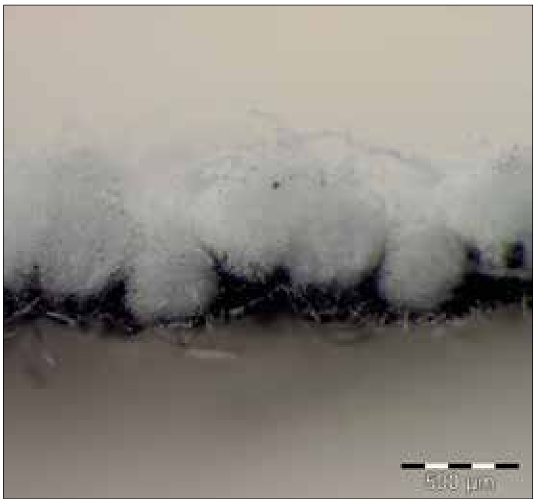
8 magnification



16 magnification



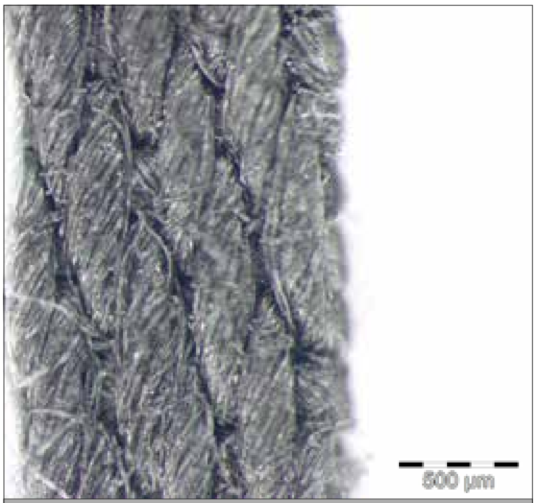
25 magnification



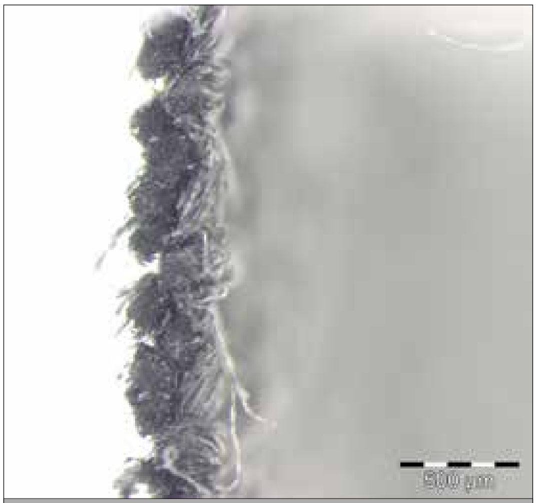
40 magnification

Planar view	Cross section
Lens parametres	
2x	2x

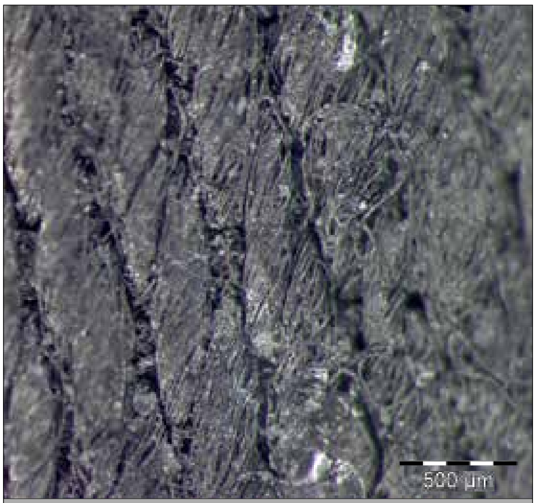
Fabric sample n.10, lines 1-2, ink layed down by using a correction pen.



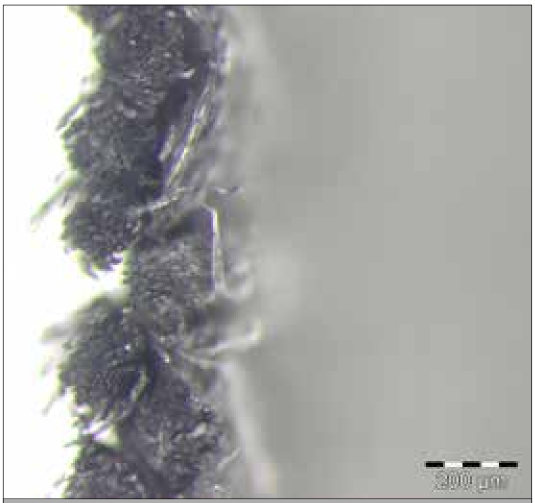
Magnification 40



Magnification 40



Magnification 40



Magnification 80

7.8 Outcome of the testing phase 1

After the testing phase 1, many points have been achieved working on EdM conductive ink.

It has been found a good ink formulation after many attempts starting from the basic recipe. Adjusting the viscosity and an increasing the filler within the ink recipe, the composite blend has shown conductivity on fabric.

The attempts on different fabrics have shown good stability and conductivity even after soft washing on most of the textiles used. The analysis at the optical microscope has pointed out how the ink sticks on fabrics showing good interaction between the film of EdM conductive ink and the fibers.

EdM conductive ink has been layed down on some textiles with a little elasticity and softness as requirements, thus closer to wearable technology. The measurement has shown conductivity even during fabric stretching.

EdM conductive ink has been layed down by using some conventional writing instruments, having a good result with a correction pen after some adjustaments. The focus was about laying down EdM conductive ink in narrow lines according to the aim of the project. The lines have exhibited conductivity after only one cycle (lay down/dry).

The following part displays a **comparison of the values measured on the fabric samples**, with two different equipments, multimeter and galvanometer.

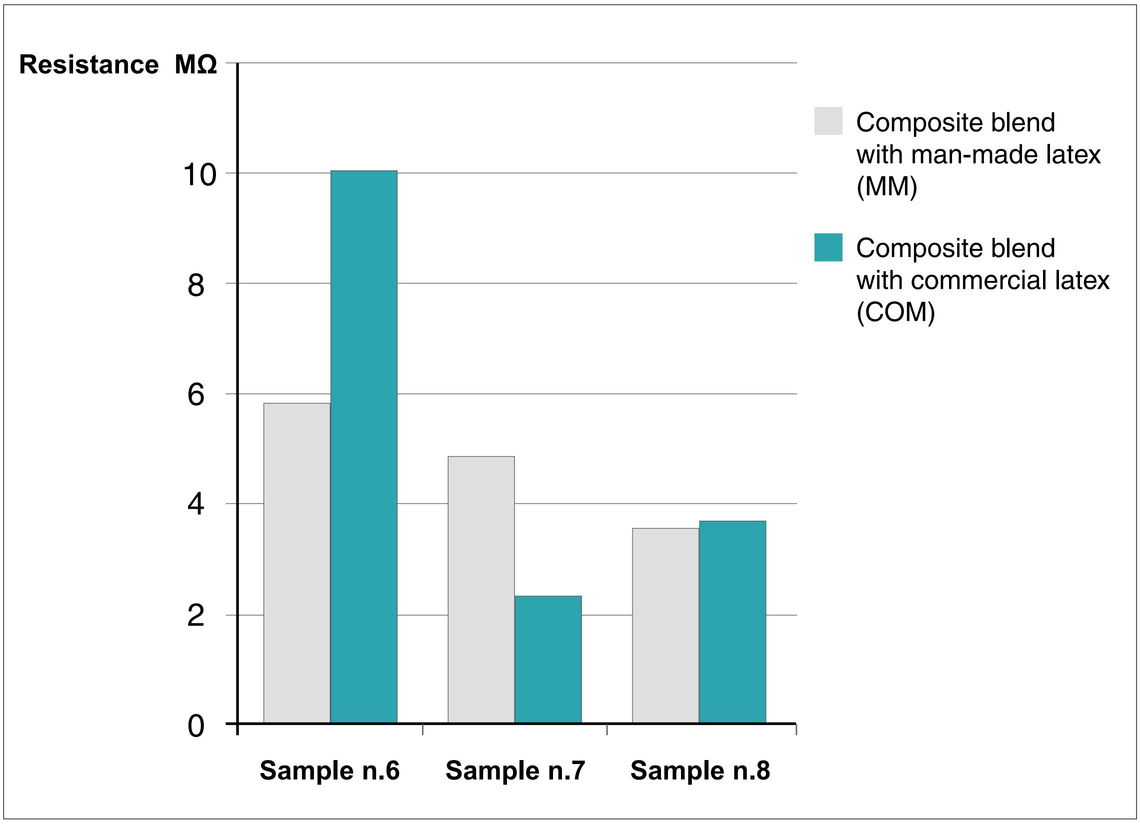


Figure 7.30
The chart above shows the average value of the measured resistance on fabric samples n.6,7,8, by using a multimeter.

Table 7.5
The table displays the calculated resistivity and conductivity on fabric samples n.6,7,8, by using a four-probe galvanometer equipment (Keithley 2400).

Textile samples		Resistivity (Ωm)	Conductivity (Sm^-01)
6	MM	135	7,35E-03
	COM	299	3,34E-03
7	MM	392	2,55E-03
	COM	90	1,10E-02
8	MM	151	6,62E-03
	COM	15	6,62E-02

Chapter 8 | Testing phase 2 in the laboratory

In the second part of the experimental phase the work focuses more on use scenario visualize for the conductive ink, trying to optimize the ink performance. From free deposition on textile, essential for understanding the interaction between conductive ink and textiles, to the use of a stencil and a pen prototype to lay down the conductive ink. From a generic list of textiles in the first part, to a precise selection in the second one, in order to achieve a pointed feedback and understand the behaviour of the conductive ink on textiles in broader terms.

8.1 Introduction to the main actors

Starting from the same ink formulation achieved in the first part of testing, the focus went on more on the textiles selection and the methods to lay down the conductive ink.

- **Textiles**
- **Methods to lay down the conductive ink**

Textiles

From a group of textiles without fiber reference, in the first testing part, the second one focused on a range of everyday textiles selected among home textiles and apparel, based on the type of fiber and the join process (yarn to fabric).
The main fiber properties considered for textiles selection are: **density, hand, flexibility, elongation, absorbency.**
From the two main areas of textiles (table 8.1), each one has different categories of usage and for both were identifyed the most common fabrics, sometimes recurring across the areas.

Table 8.1
Main textile areas and end-use categories for the thesis project.

Apparel	Home textiles
T-shirts Pants and shorts Sweaters and cardigans Sportwear Coat and jacket Lab coat Dress	Upholstered furniture Carpets Towels Bedding and pillows Toys Window covering Outdoor covering

Among the chosen fabrics, it was done an additional selection based on results of the water drop test. Thus from a wider range of “candidates” only five samples have been chosen through a water drop test (fig. 8.1), those that showed a low/medium grade of absorbency.

Starting from the previous eleven fabric samples in the first testing phase, the following are shown below (table 8.2).

Table 8.2
Data of fabric samples used for the second testing phase.

Fabric samples	Type of fiber		Yarn to fabric			Treatment	
	Natural	Man-made	Weaving	Knitting	Nonwoven	Finishing	Coating
12	Cotton 97%	Elastine 3%	x				
13		Polyester 100%		x			
14	Cotton 45%	Polyester 52% Elastine 3%	x				
15	Cotton 100%		x				
16	Wool 100%		x				

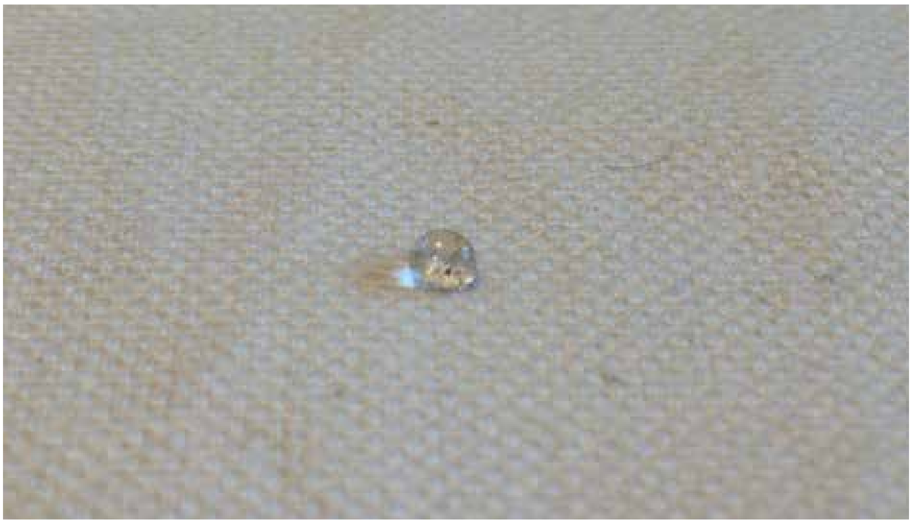


Figure 8.1
Water drop test, fabric sample n.15.

Methods to lay down the conductive ink.

Moving from free-standing on fabric by a metal paddle and conventional writing tools in the first testing part, to the use of stencils and the pen prototype (fig. 8.2) to lay down EdM conductive ink in the second part.

- Stencil
- Pen prototype

Figure 8.2
Provisional pen prototype used to lay down EdM conductive ink in the testing phase 2.

8.2 Approach to the testing phase 2

In the first testing phase in Ecole des Mines, EdM conductive ink has been layed down mainly in two different shapes:

• **Square mark**
• **Narrow lines**

The first one was done through free-standing by a metal paddle, about the narrow lines some writing tolls were used.
The first shape was a useful starting point to verify the conductivity on textiles, while narrow lines was a step to get close on the end-use scenario to play with EdM conductive ink.

In the following testing phase it will be used the same set, but instead of the metal paddle and the writing tools used previously, this time by using two different methods:

1. Stencil
2. Pen prototype

Using a stencil, the conductive ink should theoretically achieve the ideal deposition on fabric, showing a better conductivity without loss during lay down process.
After that, by using the designed pen prototype, it can be compared the conductivity achieved with the stencil.

1. stencil

The stencil can be considered a kind of homemade screen printing, a little closer to printing method than conventional writing tools. Some examples are shown below, from a competitor, Bare Conductive (fig. 8.3 - 8.4).

Figure 8.3
It showes a stencil (homemade screen printing) used to apply a conductive ink on paper.

Source:
Bare Conductive website

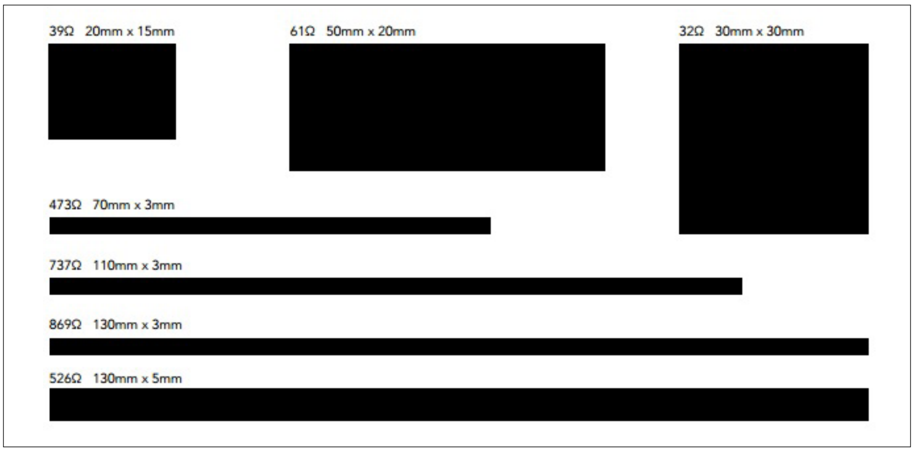


Figure 8.4
Resistance samples visual, It showes the difference in resistivity based on the ratio of lenght/width.

Source:
Bare Conductive website

Note

Electric Paint presents a wholly unique way of exploring electrical resistance. In general, the resistance of a sample of conductive material is defined by the dimensions of the sample being tested, and resistance is inversely proportional to cross sectional area (i.e. given a set length and depth, a wider sample will have less resistance than a thin one). Thus, the resistance can be defined *by the ratio of length/width.* [1]

Figure 8.5
Scheme of the stencil for laying down EdM conductive ink in the second testing phase.

The previous part from Bare Conductive website pointed out that the change in resistivity is based on shape, size and thickness of the mark. Starting from that note, it was set the stencil, following size and shape of the marks from Bare Conductive, for having a good comparison. Following pictures show an illustration of the stencil (fig. 8.5) and the shape and size of the marks on a fabric sample in detail (fig. 8.6).

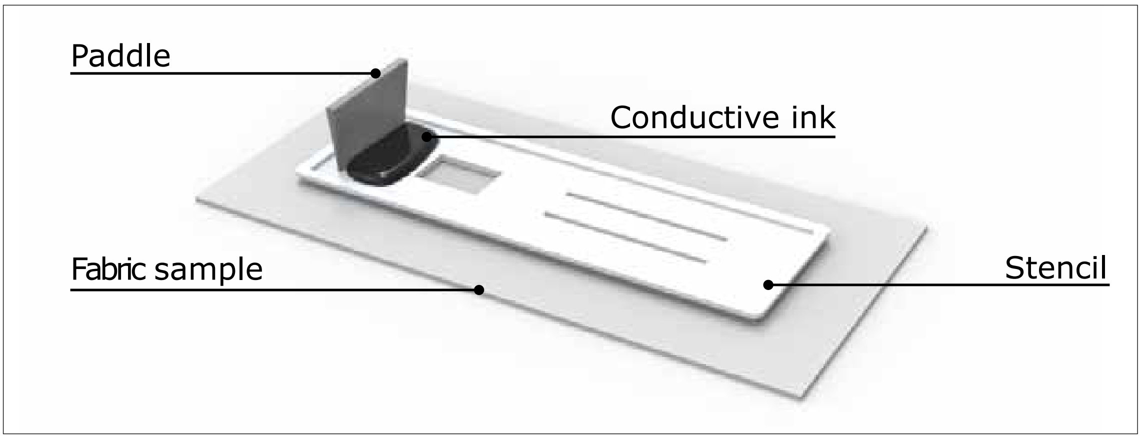
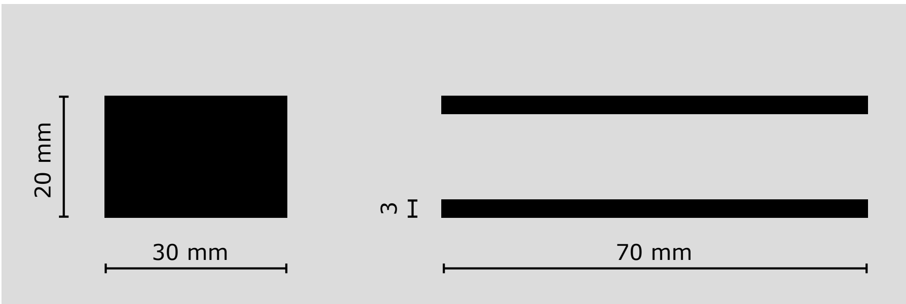


Figure 8.6
illustration of a fabric sample after lay down process, the planar view shows two different shapes: a **square mark** and two **narrow parallel lines**.



In preparation for connecting battery and led, two parallel narrow lines were set as positive and negative pole. Finally, the thickness of the stencil is about 2 mm.

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[1] http://www.bareconductive.com/wp-content/uplads/2015/01/ElectricPaint_ApplicationNotes.pdf

An illustration of the fabric samples by using the stencil to lay down EdM conductive ink is shown below (fig. 8.7).

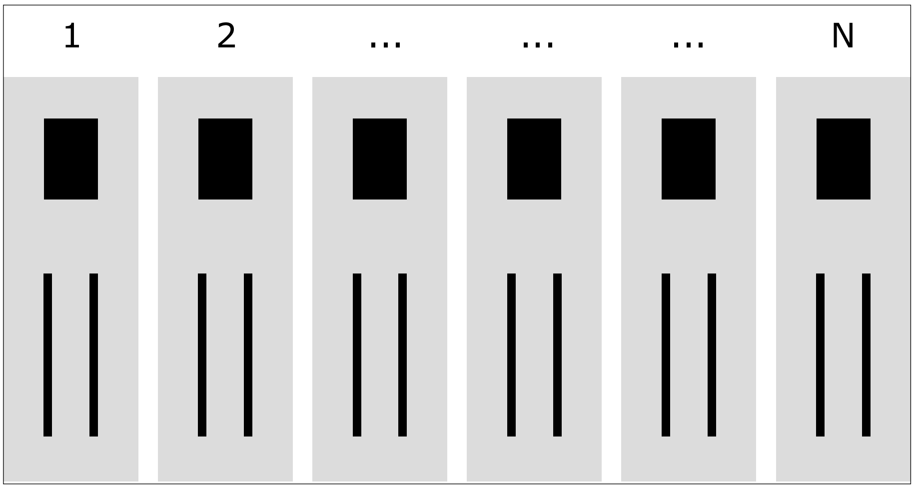


Figure 8.7
The illustration shows a planar view of fabric samples with conductive film on them.

2. Pen prototype

By using the designed prototype pen will be layed down EdM conductive ink on the same type of textiles previously used with the stencil (homemade screen printing). In this case the ink goes out from the nib of the prototype (freehand writing instrument).

For the testing phase the prototype will lay down the ink only in lines (fig. 8.8), having the same size from the previous through the stencil, in order to compare the conductivity between both the methods. Finally, some demonstrations will be made, joining devices through the conductive paths.

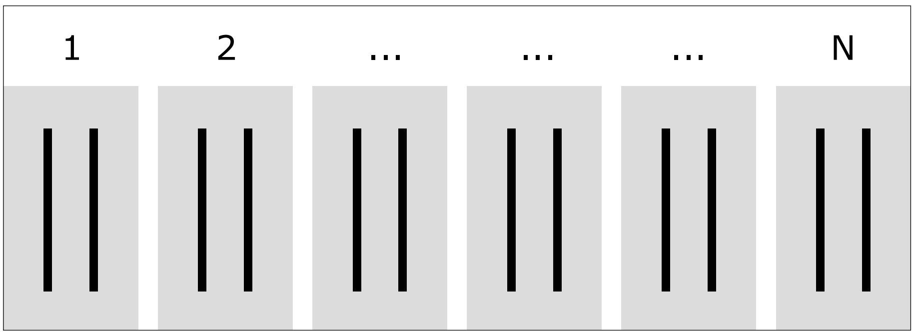


Figure 8.8
The illustration shows a planar view of fabric samples with conductive lines on them, layed down by using the designed prototype.

8.3 Laying down EdM conductive ink by a stencil

The second testing phase started making the composite blend, EdM conductive ink, following the conductive recipe, which has been achieved during the testing phase 1.

10ml concentrated graphene solution + 1ml commercial latex + 1g thickener

After that, EdM conductive ink was layed down in simple square marks by using a stencil on few cotton fabrics, only to verify the resistivity grade, in order to start testing the selected textiles. Thus once measured the resistance by a multimeter, an other formulation was done, increasing a little the amount of graphene, trying to improve the conductivity.

11ml concentrated graphene solution + 1ml commercial latex + 1g thickener

Once verifyed the conductivity of EdM conductive ink on a piece of fabric, it was layed down on the selected fabric samples in simple square marks and then in parallel narrow lines by using the stencil (fig. 8.9).

In order to compare in the same way the resistance of the new fabric samples with the three main textiles used in the previous testing phase in Ecole des Mines, It was layed down the same ink formulation on textile n. 6,7,8, by using the stencil (fig. 8.10).

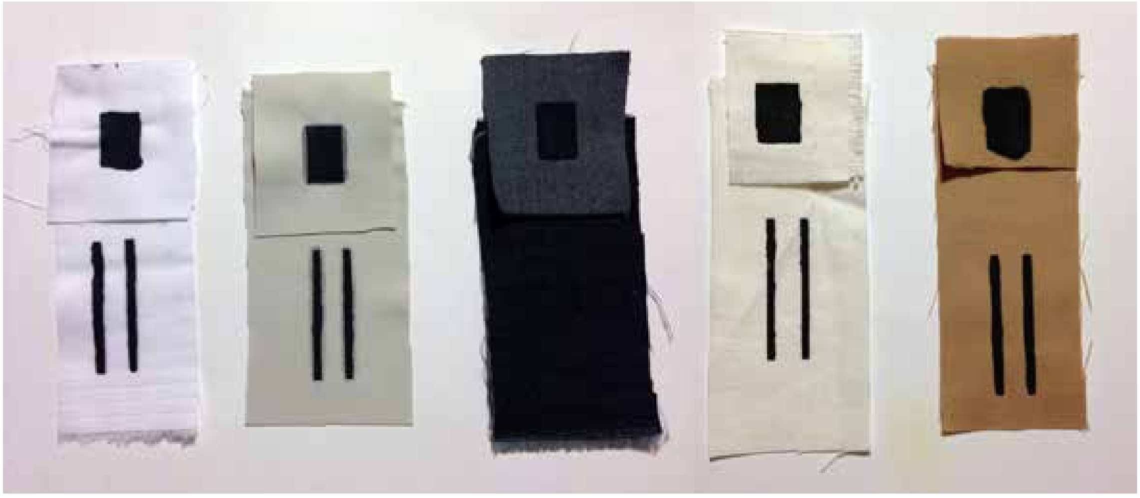


Figure 8.9
From left to the right: sample n.12 elastic cotton, sample n.13 jersey polyester, sample n.14 denim jeans, sample n.15 cotton, sample n.16 wool.

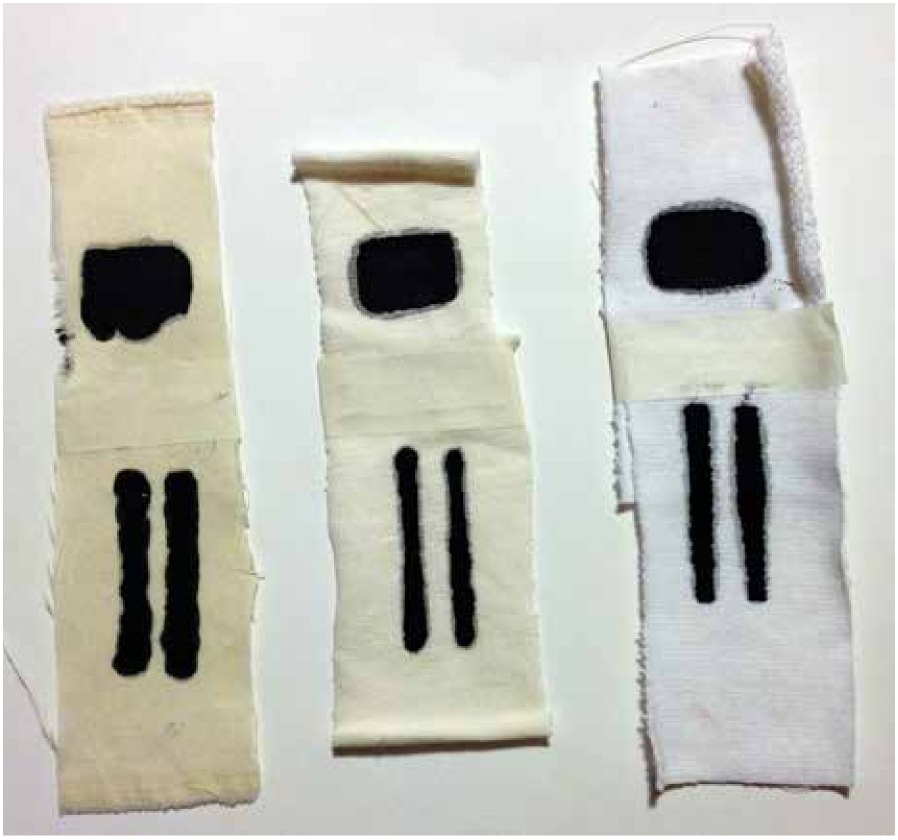


Figure 8.10
From left to the right: sample 6, sample 7, sample 8, textiles from the laboratory of Ecole des Mines, Saint Etienne

The use of a stencil to lay down the conductive ink make the film homogeneous and continuos even for narrow lines. The electrical resistance measured on the fabric samples was less than what it was achieved by free-standing in Ecole des Mines, comparing the values by a multimeter (fig. 8.11). In the testing phase 2, the electrical resistance was about 10 times less then the values achieved in the first testing phase.

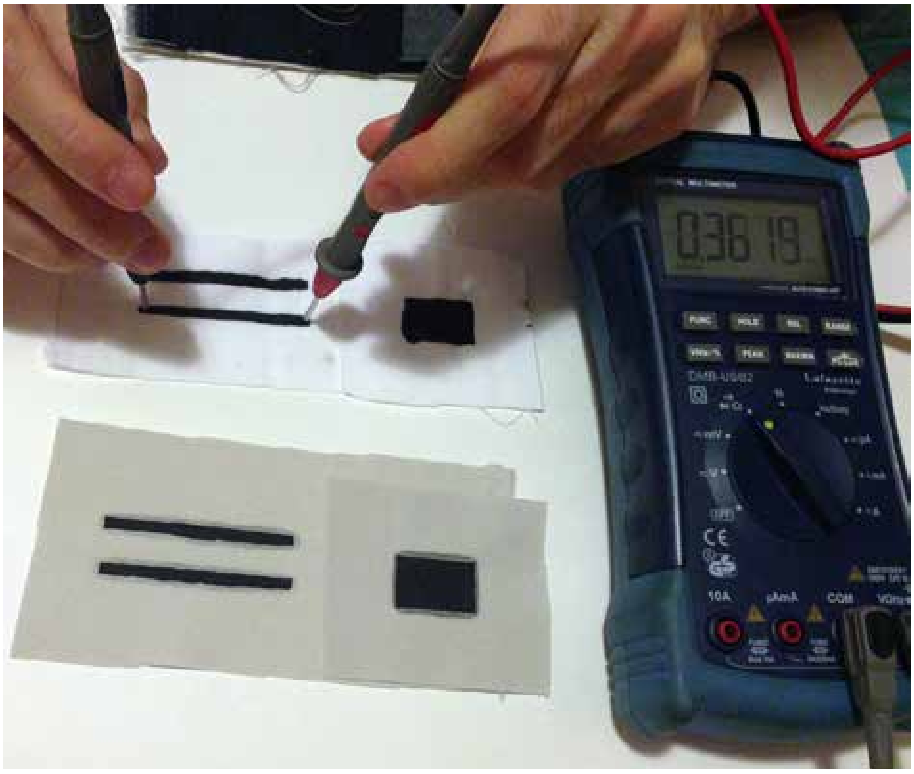


Figure 8.11 Measurement by using a multimeter, fabric sample n.12 elastic cotton, the resistance value is about 0.36 Mohms.

Anyway the measured values weren't still enough for some basic demonstrations such us light opening from LEDs. Thus In preparation for demonstrations the amount of graphene solution was increased from the original recipe, in order to improve the conductivity. The new composite blend is shown below.

21ml concentrated graphene solution + 1ml commercial latex + 1g thickener

The new composite blend was layed down by a stencil in parallel lines as shown previously. The electrical resistance measured on cotton sample n.15 is shown below (fig. 8.12).

Note

The resistance decreased from 0,3 Mohms (300 Kohms) to 0,03 Mohms (30 Kohms), ten times less.

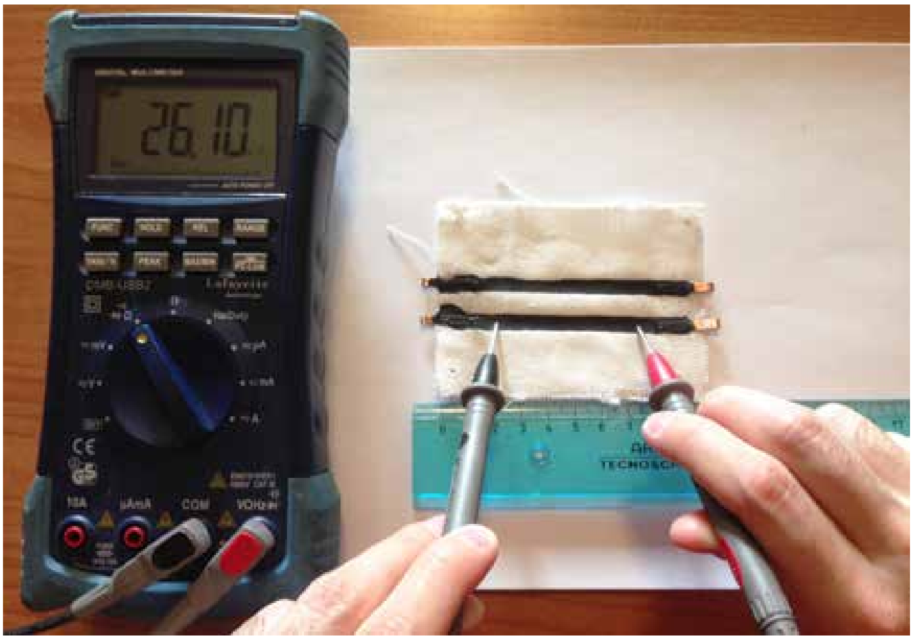


Figure 8.12 Measurement by using a multimeter, fabric sample n.15 100% cotton, the resistance value is about 0.03 Mohms.

8.4 Laying down EdM conductive ink by the designed pen prototype

Among the fabric samples tested previously only two were chose for going on the testing phase by using the pen prototype: an elastic cotton (sample n.12) and 100 % cotton (sample n.15).
They were the most relevant from the response of the test by stencil and for the use scenario of the project. Thus EdM conductive ink was laid down in lines by the pen prototype.
The following picture displays the electrical resistance measured on two fabric samples (fig. 8.13).

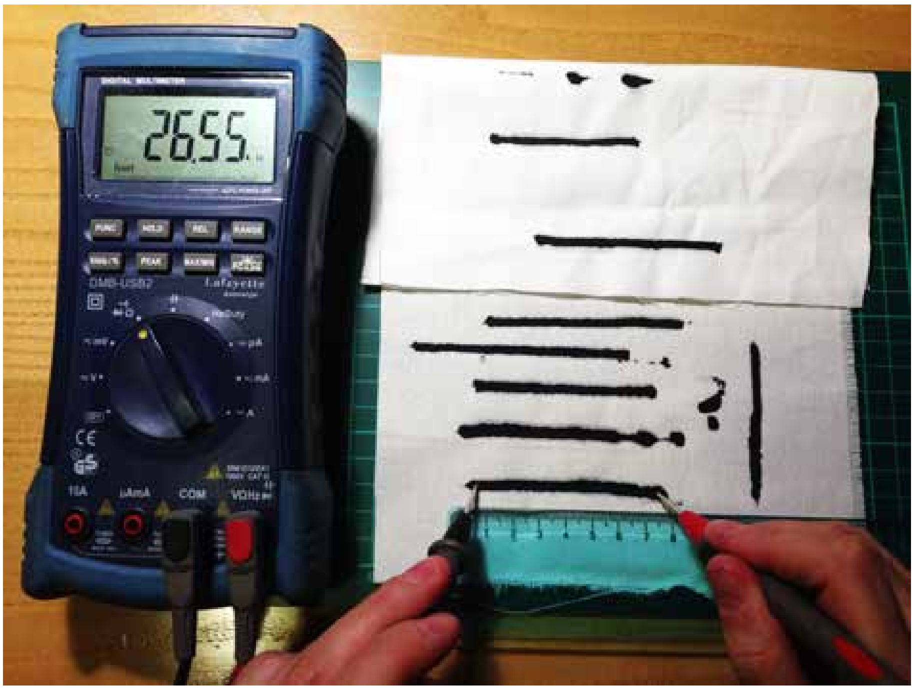


Figure 8.13
Measurement by using a multimeter, fabric sample n.15 100% cotton, the resistance value is about 0.03 Mohms,

Note

The electrical resistance measured on cotton sample n.15 by a multimeter shows comparable results with the previous obtained by stencil, about 0,03 Mohms.
After that, the resistance of the other sample was measured, elastic cotton sample n.12. The value was ten times higher than 100% cotton sample n.15, about 0,3 Mohms.

The sample n.12, beeing an elastic cotton, it was observed how the resistance behaves stretching the fabric. Stretching pretty much the fabric, about 10% elongation, the resistance increased as it's shown in the following pictures.
In the first picture (fig. 8.14) the fabric is not stretched, thus the sample is measured in "resting position". The second one displays a change in resistance due to the stretching of the fabric (fig. 8.15). The stretching was done in homogeneous

manner along the mark lenght. The path size in “resting position” is about 70x4 mm lenght/wide.

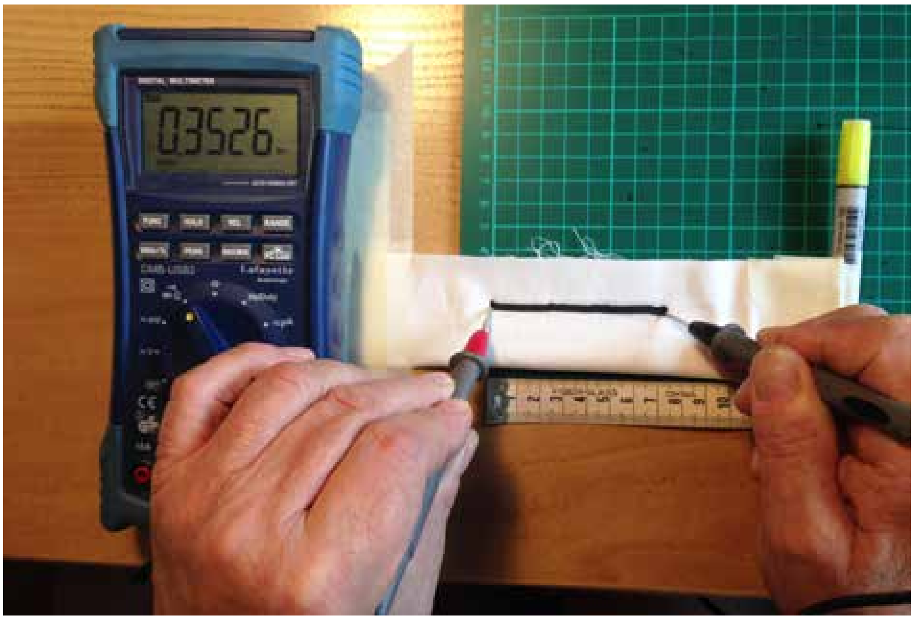


Figure 8.14 Measurement by using a multimeter, fabric sample n.12 elastic cotton, the resistance value in “resting position“ is about 0.3 Mohms.

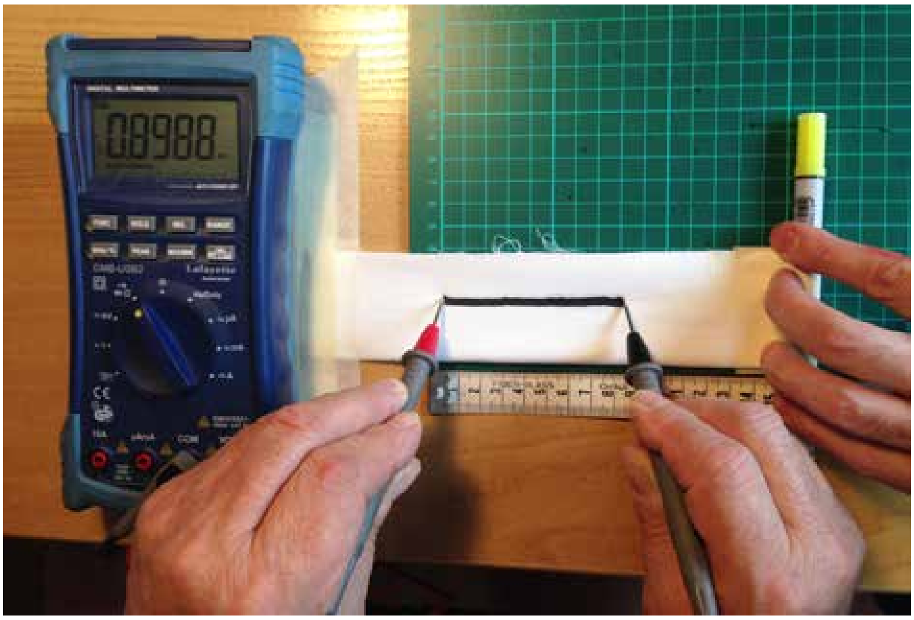


Figure 8.15 Measurement by using a multimeter, fabric sample n.12 elastic cotton, the resistance value during stretching is about 0.9 Mohms.

Note

Stretching pretty much the fabric n.12, about 10% elongation, the resistance increased from 0,3 to 0,9 Mohms.

8.5 Demonstrations

The last step of testing EdM conductive ink on textiles was about connecting devices to a power supply on fabric through the conductive ink paths, in order to verify the workability.
One of the easier way was about joining LED to a battery using EdM conductive ink in replacement of classical copper wires.
As it was done in the previous point 8.4, among the fabric samples tested previously only two were chosen for going on, the most "attractive" for the thesis purpose:

• Elastic cotton (sample n.12)
• 100 % cotton (sample n.15)

The first attempts were done on sample n.12, an elastic cotton (97% cotton fiber, 3% elastane). The composite blend used for the first attempts is shown below.

11ml concentrated graphene solution + 1ml commercial latex + 1g thickener

EdM conductive ink was laid down by stencil in parallel lines as positive and negative poles.These two paths were created in replacement of classical wires to join a battery and a LED.
For the test three pieces of the same textiles were used and it was applied one cycle of ink and drying on the first one, two cycles on the second piece and three on the last one. After that starting from fabric with the most thick film on it (the third), battery and LED were joined to the paths. The LED was applied moving the position along the lenght paths looking for light opening, but **having no light**. In the following two pictures the LED and the battery case are fixed on the surface of the fabric by covering

them with EdM conductive ink (fig. 8.16, 8.17). Once the ink was dry the battery was added trying to open the light.

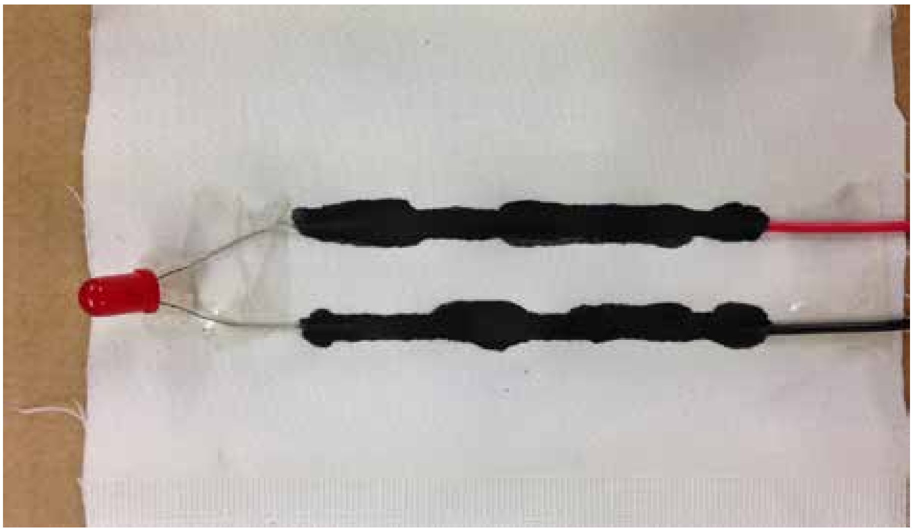


Figure 8.16
Attempt n.1 to connect LED and power supply through EdM conductive ink paths.

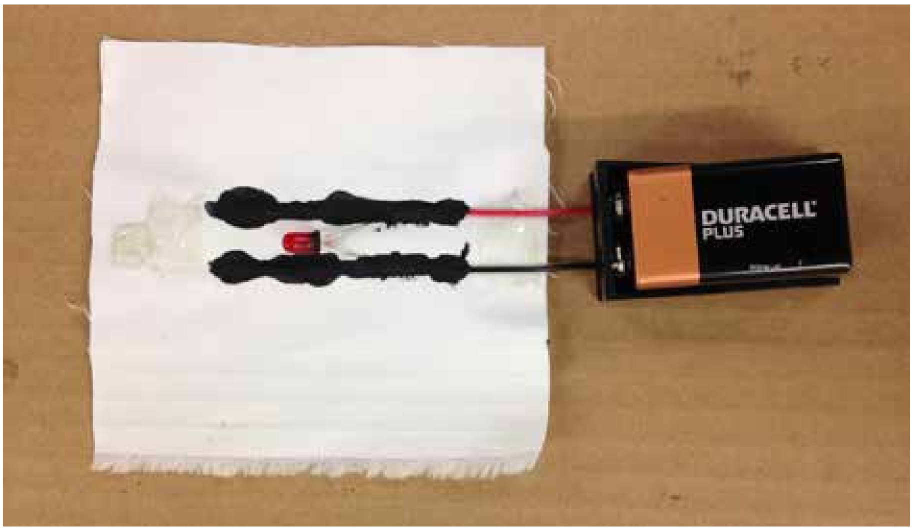


Figure 8.17
Attempt n.2 to connect LED and power supply through EdM conductive ink paths changing the distance between the devices.

Having no light, the LED and the battery were removed and joined again to the fabric, this time by a kind of hand sewing, instead of fixing only on the surface. The attempt was done only in short lenght to increase the chances to achieve light. Thus LED wires and battery case wires were sewn into the textile fibers and covered with EdM conductive ink (fig. 8.18), without any change from the previous attempt.

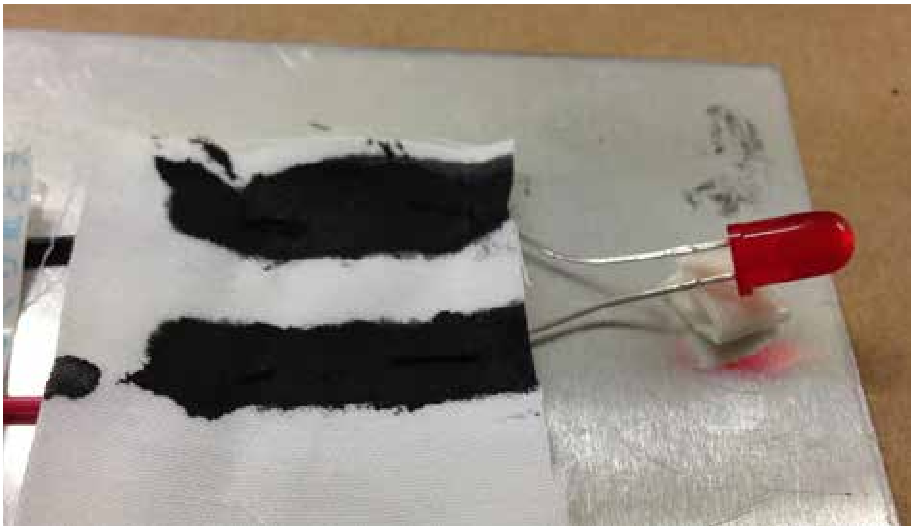


Figure 8.18
Attempt n.3 to connect LED and power supply through EdM conductive ink paths changing the distance between the devices and the join method (sewing).

Note

The first attempts didn't open the light even changing the distance between LED and battery.

Observation

Laying down EdM conductive ink in more cycles (up to 3 in this case), the thickness of the conductive film increases and at the same time the electrical resistance should decrease. Instead the measured resistance on the sample didn't change significantly.

Hypothesis

The deposition of EdM conductive ink in few cycles on the fabric was probably not homogeneus, loss of conductive particles in some parts and aggregation in others.

On the other hand, the join of the devices on the fabric through the conductive paths probably was not accurate enough to allow to the electricity to run.

In addition EdM conductive ink formulation was not conductive enough to achieve the necessary level for opening light from a LED.

After the first attempts the demonstrations went on adjusting the points observed from the previous feedback. Starting from an other ink formulation with an increased percentage of graphene solution in the composite blend in order to increase the conductivity, this time the fabric sample n.15 was used, 100% cotton fiber. The composite blend used for the following attempts is shown below.

21ml concentrated graphene solution + 1ml commercial latex + 1g thickener

EdM conductive ink was laid down by stencil in parallel lines as seen before. The ink was deposited only in a single layer showing an electrical resistance in line with common LED applications. Thus there was no need to lay down more ink cycles as done before. The join method was improved, this time by fixing four metal sheets on the fabric at the right place and then covering them with EdM conductive ink by using a stencil (fig. 8.19).

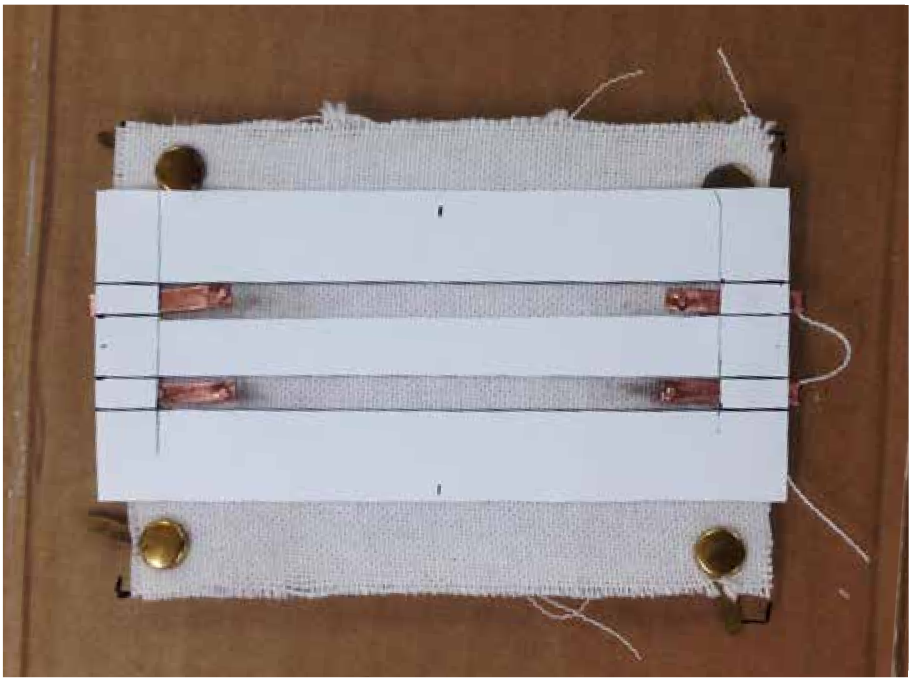
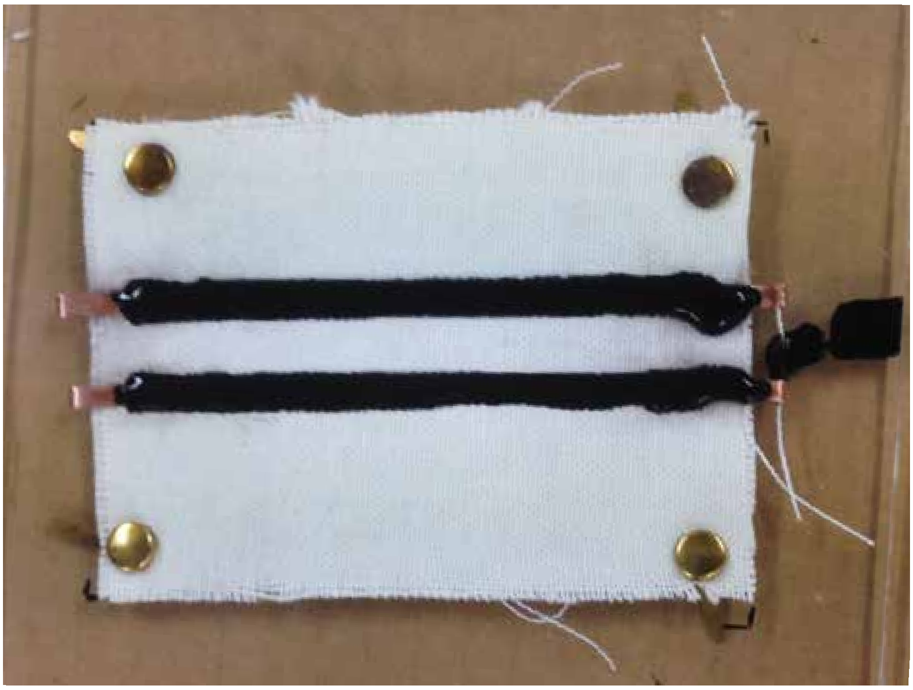


Figure 8.19
Fabric sample n.15, preparation for laying down EdM conductive ink by stencil.

EdM conductive ink was laid down in two parallel lines, the path size is about 100 x 4 mm lenght/wide. On the metal sheets the ink was added manually by a paddle to make sure a good connection with the paths. The picture below displays the ink deposition before drying (fig. 8.20).

Figure 8.20
Fabric sample n.15, EdM conductive ink paths before drying.



After drying the resistance was measured showing values in line with LED application. Thus the devices were joined to the paths. In the following picture (fig. 8.21) the main components are shown: the sample fabric after drying and the devices ready to join it. After that joining the devices to the fabric light opening from LED is shown (fig. 8.22).

Demonstration details

Battery: 9v
Led: 1,8v
Conductive paths: 30Kohms electrical resistance measured in a size of 100 x 4 mm lenght/wide

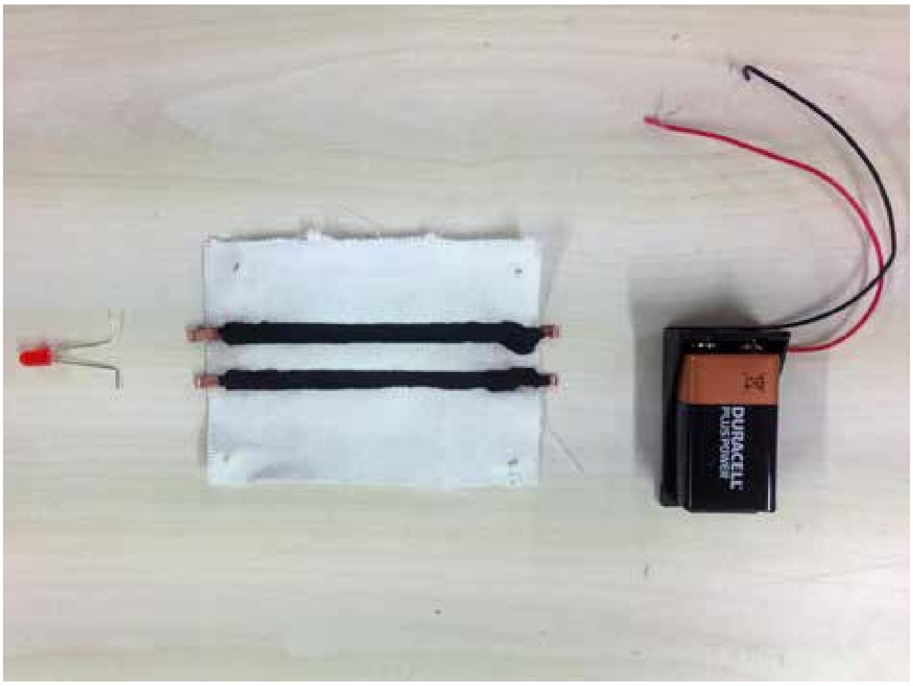


Figure 8.21
Fabric sample n.15 with EdM conductive ink on it, LED, battery.

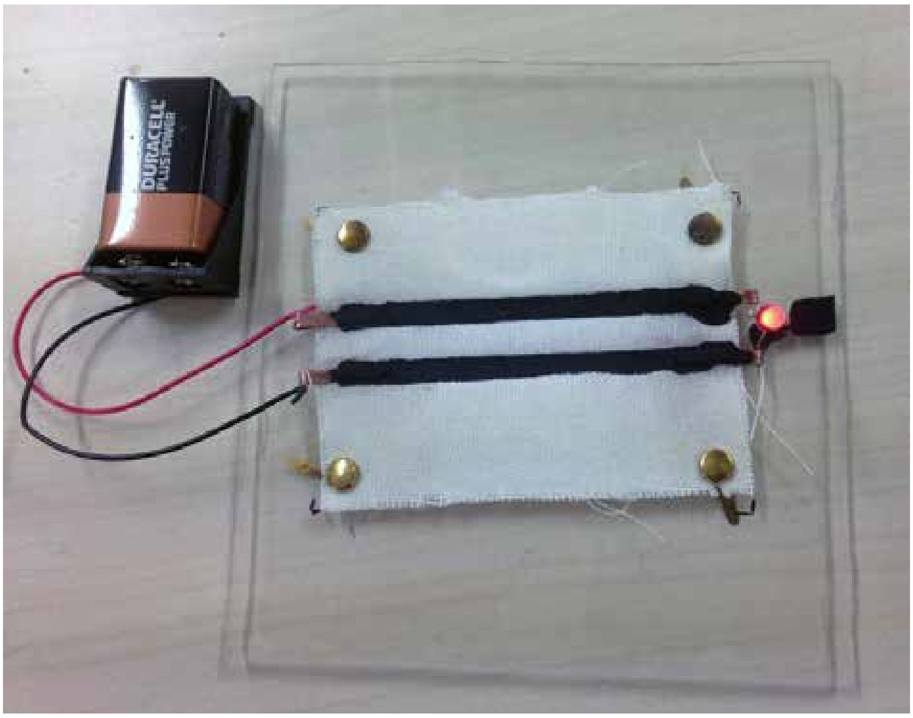


Figure 8.22
Light opening from LED .

8.6 Microscope analysis of the fabric samples

Once the testing phase and demonstrations were done, the fabric samples were examined under a stereo microscope.
Under the microscope were analyse all the fabric samples used in the testing phase 2 at Politecnico di Milano:

- Fabric samples n.6-7-8 (from Ecole des Mines laboratory)
- Fabric samples n.12-13-14-15-16 (from Milan)

In the first examination were analyse the fabric samples n.6-7-8-12-13-14-15-16 with EdM conductive ink on them laid down in lines by stencil.
The composite blend used is shown below.

11ml concentrated graphene solution + 1ml commercial latex + 1g thickener

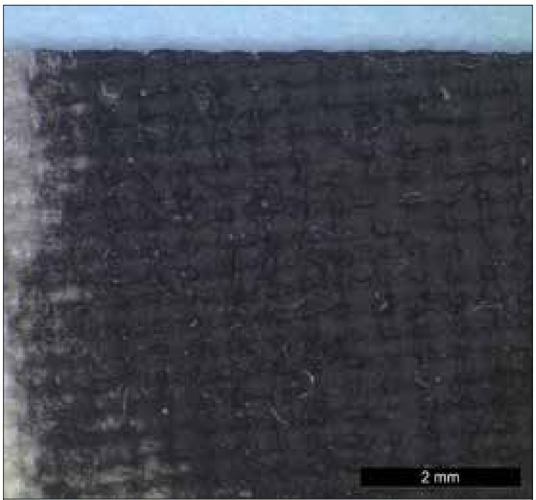
After that, only two samples were analyse, having on them the new composite blend that made possible light opening.
EdM conductive ink was laid down on the fabric samples n.12-15 by the designed pen prototype.
The composite blend used is shown below.

21ml concentrated graphene solution + 1ml commercial latex + 1g thickener

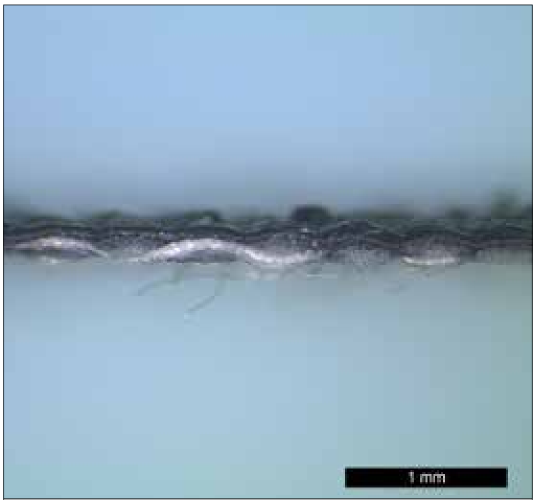
The analysis was done by using a stereo microscope set with a fixed lens and changing the magnification during the analysis. The test was set in two ways: collecting data pictures of the planar view and cross section.

Planar view	Cross section
Lens parametres	
1x	

Fabric sample n.6



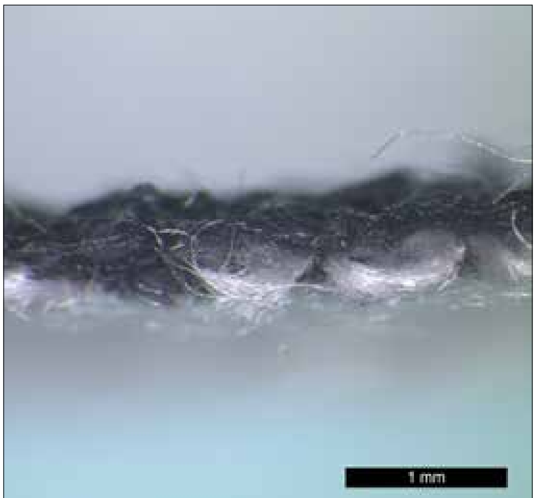
12 magnification



25 magnification

Fabric sample n.7

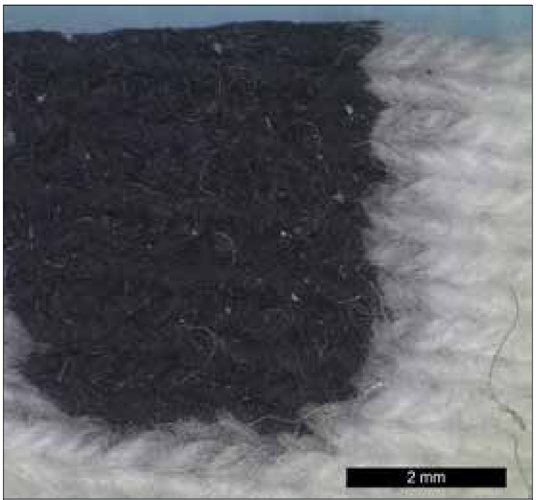
12 magnification



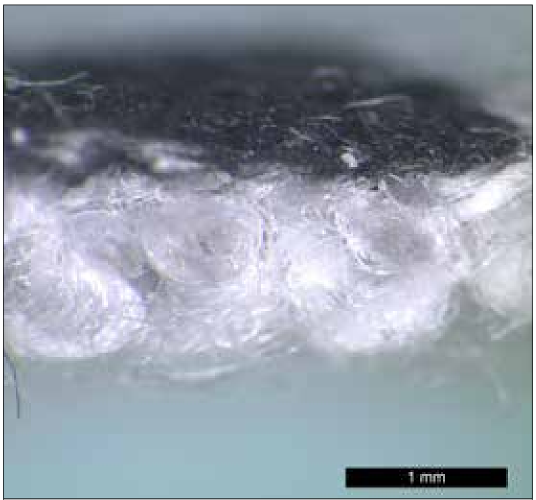
25 magnification

Planar view	Cross section
Lens parametres	
1x	

Fabric sample n.8

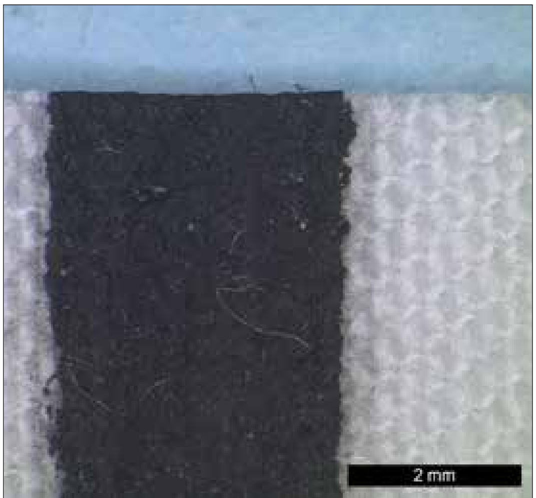


12 magnification

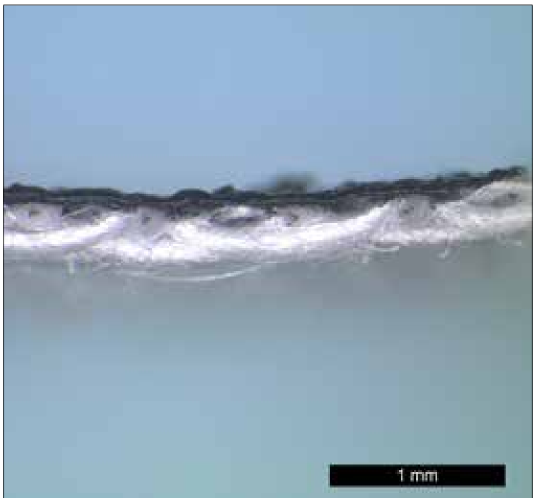


25 magnification

Fabric sample n.12



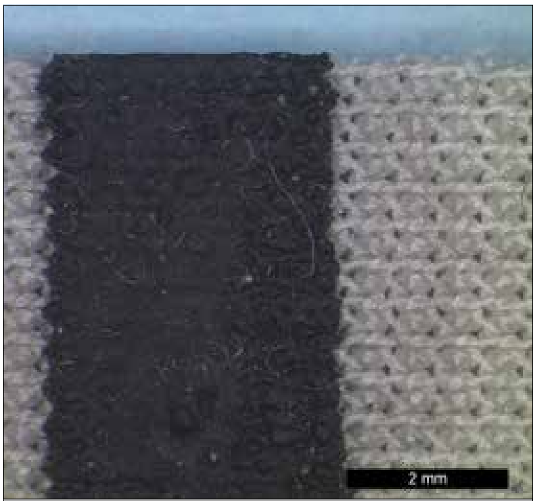
12 magnification



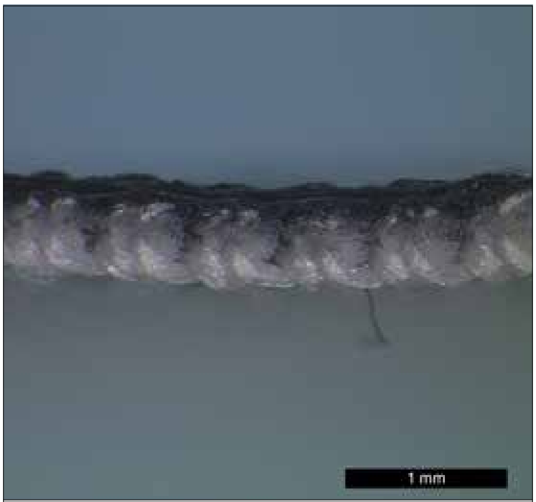
25 magnification

Planar view	Cross section
Lens parametres	
1x	

Fabric sample n.13

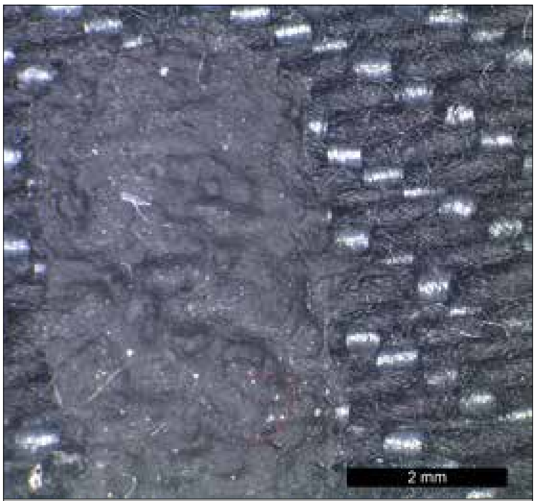


12 magnification

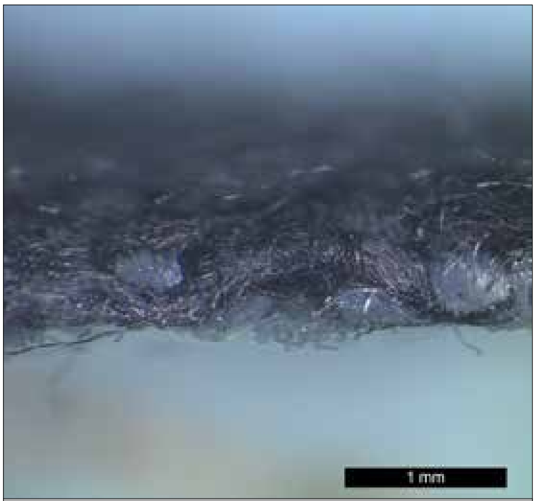


25 magnification

Fabric sample n.14



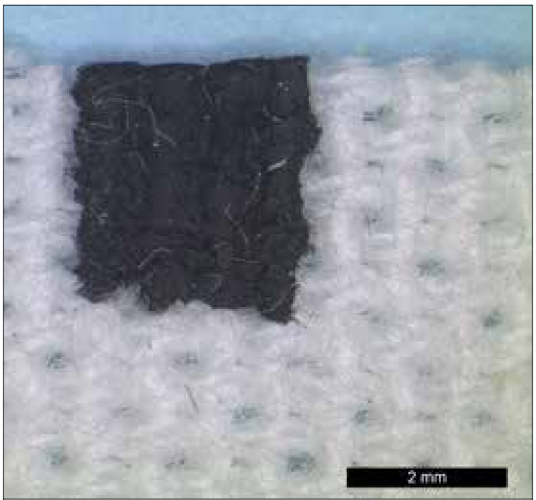
12 magnification



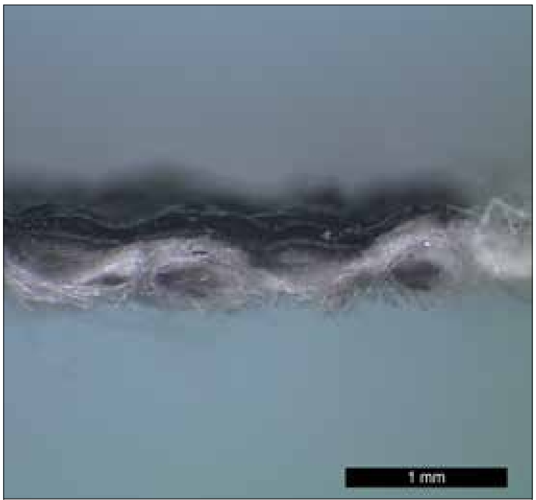
25 magnification

Planar view	Cross section
Lens parametres	
1x	

Fabric sample n.15



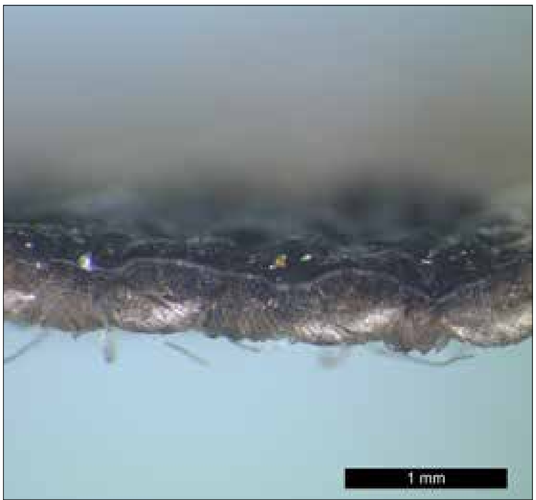
12 magnification



25 magnification

Fabric sample n.16

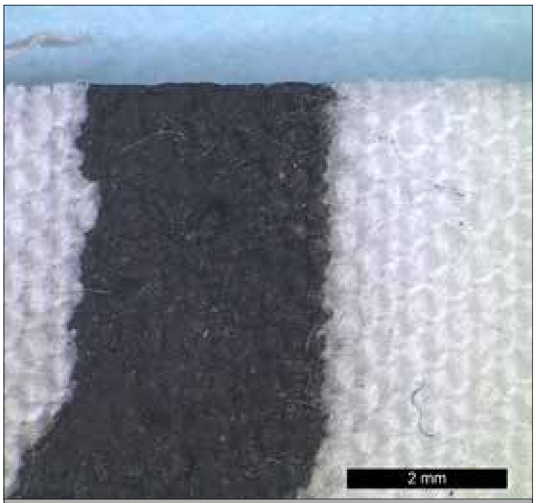
12 magnification



25 magnification

Planar view	Cross section
Lens parametres	
1x	

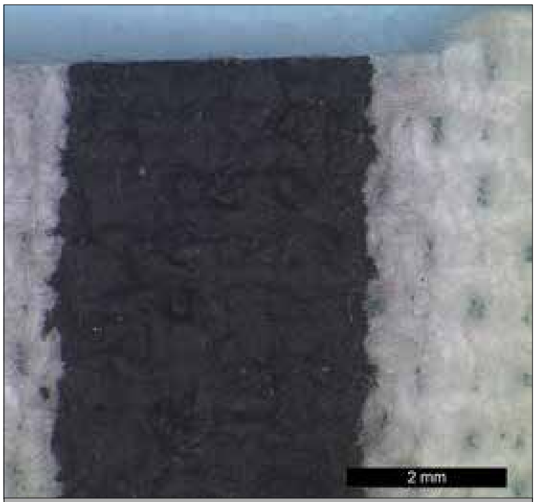
Fabric sample n.12 (ink formulation for light opening on the sample)



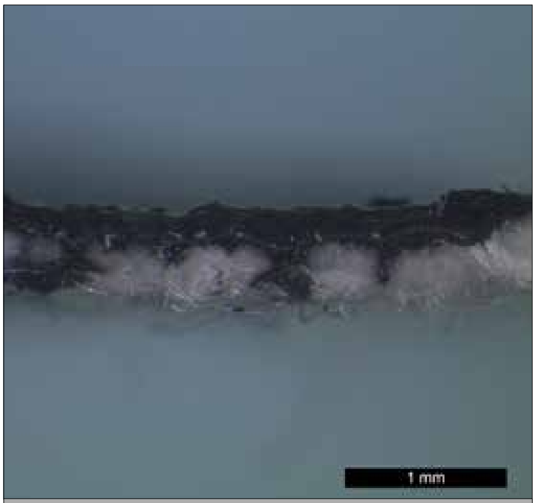
12 magnification

25 magnification

Fabric sample n.15 (ink formulation for light opening on the sample)



12 magnification



25 magnification

Soft washing

After the microscope analysis the fabric samples (fig. 8.23) were dipped in a becher of water (fig. 8.24) for a while. After soft washing the ink was still stable on fabric and after drying it improved the conductivity.

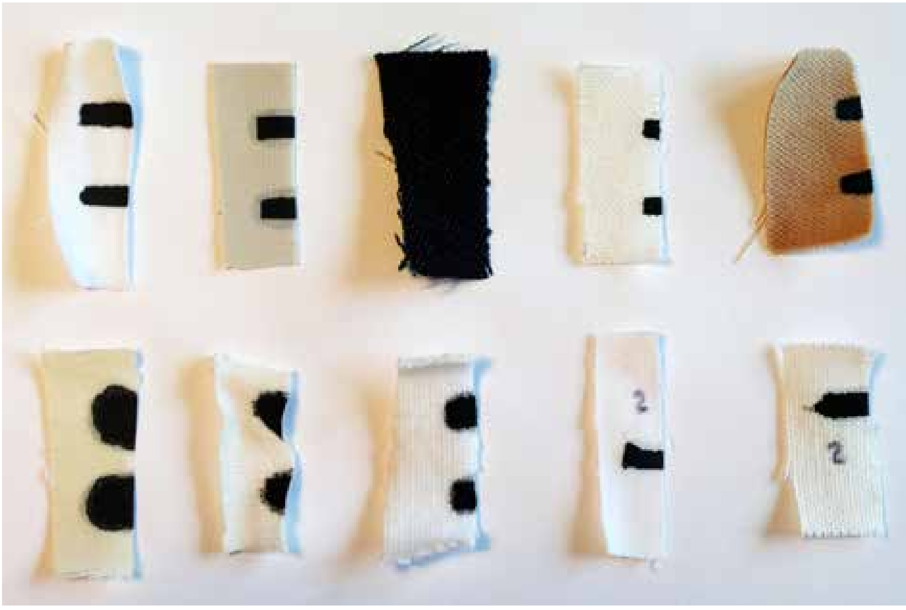


Figure 8.23
Fabric samples after soft washing.

From left to the right **upper part**: samples n. 12,13,14,15,16

From left to the right **bottom part**: samples n.6,7,8, the last two samples n.12,15 have the new ink formulation on them.

Figure 8.24
Fabric sample n.12 in a becher during soft washing.

8.7 Outcome of the testing phase 2

After the testing phase 2, many points have been achieved working on EdM conductive ink.

It has been laid down EdM conductive ink by stencil on a wide variety of textiles improving the conductivity achieved in the previous testint phase 1 with the same composite blend. The results point out the better deposition by using this method (the stencil) closer to a screen printing process than free standing. It is a promising indication for EdM conductive ink, opening the door to a wider use .

EdM conductive ink has been successfully laid down by the designed pen prototype. The measured resistance has shown interesting results comparable to the stencil method. The ink has come out from the nib of the pen prototype homogeneus without loss of filler or aggregation and showing conductivity along all the path once dry. In addition to the ideal ink deposition, the designed pen has shown good usability meeting the necessary requirements.

The attempts on different fabrics have shown good stability and conductivity even stretching some elastic textiles.

After many attempts it has been achieved light opening from a LED on fabric samples n.12-15. A new ink formulation with an increased percentage of graphene solution in the composite blend has been laid down by stencil in parallel lines as positive and negative poles. These two paths were created in replacement of classical wires to join a battery and a LED.

The analysis at the stereo microscope has pointed out how the ink sticks on fabrics. In this case the ink remains more on the surface instead of losing part of it into the fibers as happened in the testing phase 1. This good interaction between the film of EdM conductive ink and the fabrics has allowed a thicker ink layer in a single deposition and as a result a lower resistance.

After one soft washing the ink was still stable on fabric and after drying it improved the conductivity.

The textiles used in the testing phase 2 have provided a more detailed feedback in order to understand the behaviour of EdM conductive ink on textiles in broader terms. The results obtained gave promising indication for the use of EdM conductive ink on a wider variery of textiles not yet tested.

The following part displays in detail the resistance values that have been measured on the fabric samples during the testing phase 2.

Table 8.3 displays the electrical resistance values measured on the fabric samples n.6-7-8-12-13-14-15-16, by a multimeter.
The ink formulation laid down in lines and square marks on the samples by stencil is shown below.

11ml concentrated graphene solution + 1ml commercial latex + 1g thickener

Table 8.3
For every fabric sample is shown the average value of the measured electrical resistance by using a multimeter.

Fabric samples n.	Electrical resistance (MΩ)	
	Square marks (30x20mm size)	Lines (70x4mm size)
6	9	20
7	5	9
8	4	30
12	0,15	0,3
13	0,25	0,85
14	5	0,3
15	7	0,3
16	5	0,3

The following table 8.4 displays the electrical resistance values measured on the fabric samples n.12-15 by amultimeter. The new ink formulation laid down on the samples by the designed pen prototype is shown below.

21ml concentrated graphene solution + 1ml commercial latex + 1g thickener

Table 8.4
For every fabric sample is shown the average value of the measured electrical resistance by using a multimeter.

Fabric samples n.	Electrical resistance (MΩ)	
	Lines by the designed pen (70x4mm size)	Lines by stencil (70x4mm size)
12	0,08	/ (not tested by stencil)
15	0,03	0,03

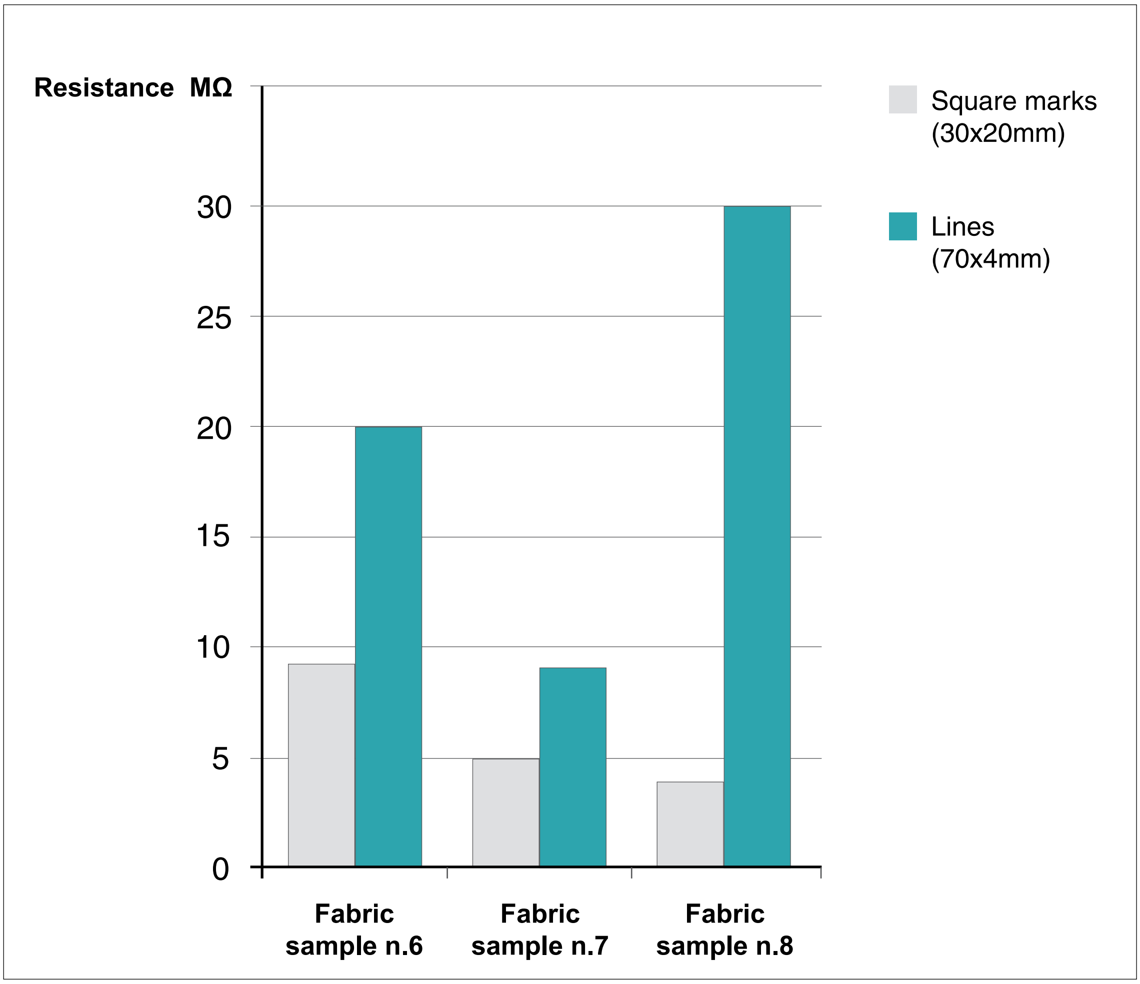


Figure 8.25
The chart above shows the data of the table 8.3 about the measured resistance on fabric samples n.6-7-8,

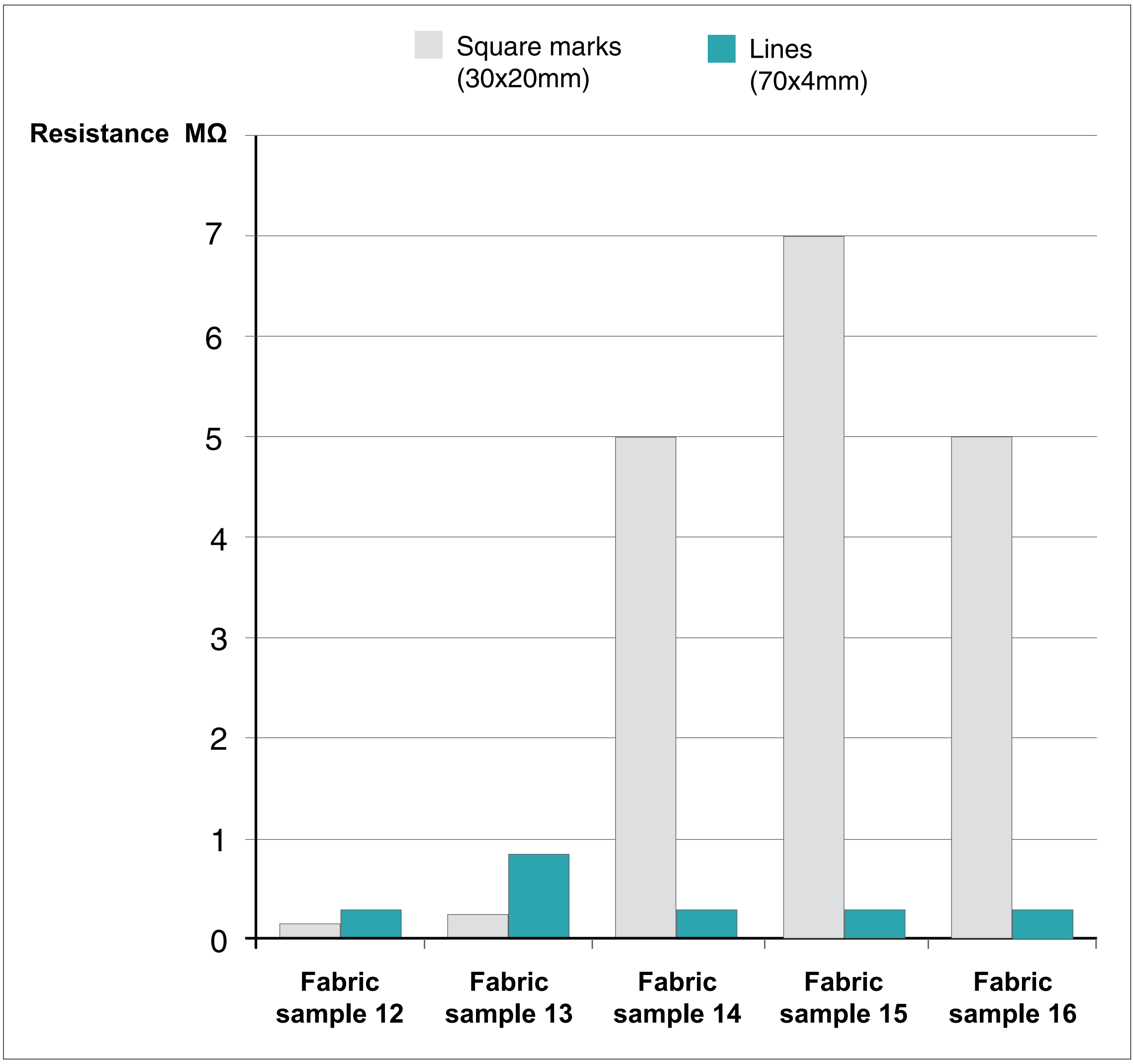


Figure 8.26
The chart above showsthe data of the table 8.3 about the measured resistance on fabric samples n.12-13-14-15-16, by using a multimeter.

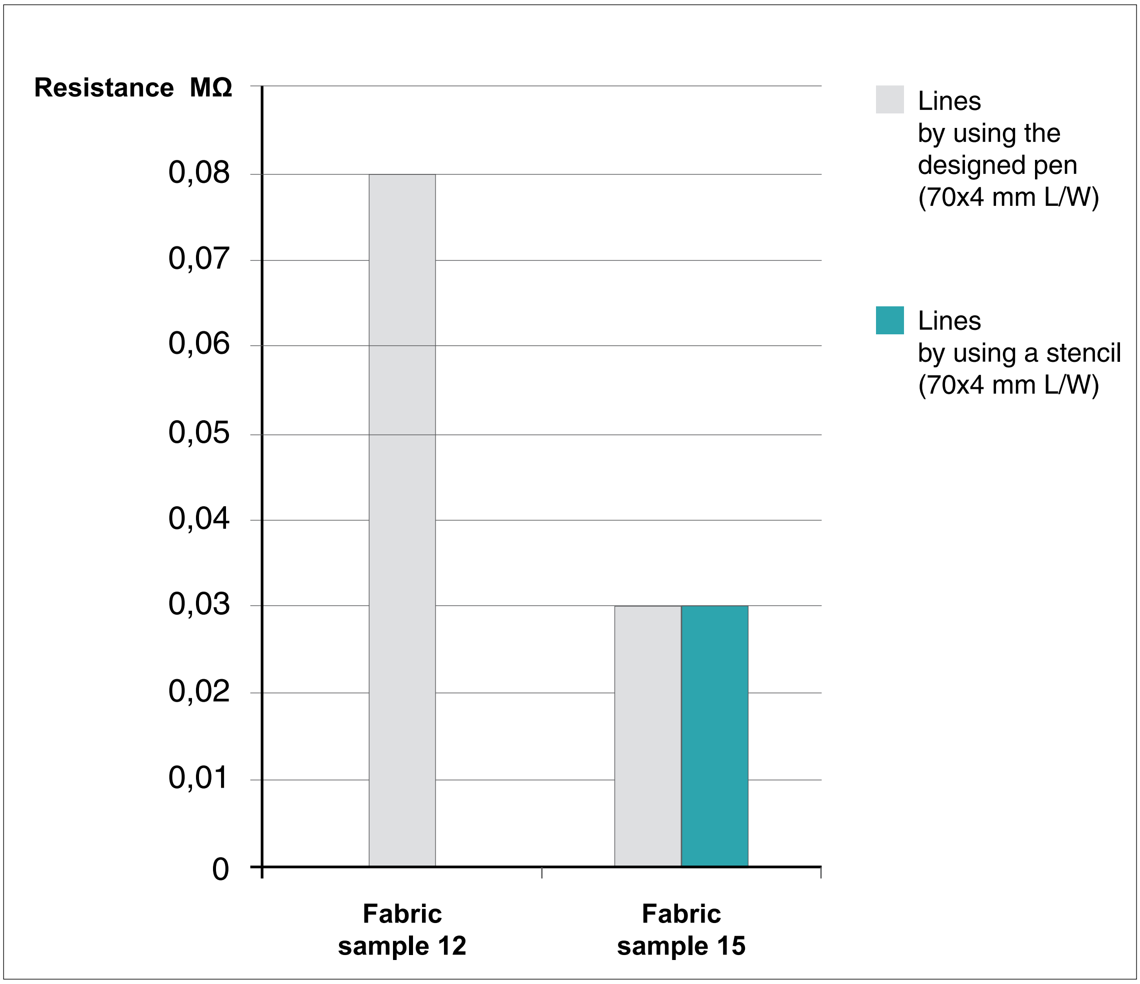


Figure 8.27
The chart above shows the data of table 8.4 about the measured resistance on fabric samples n.12-15, by using a multimeter.

Observation

The electrical resistance on the fabric samples has decreased more than ten times from the first ink formulation to the second, thanks to the increase of graphene solution in the composite blend.

The fabric samples 12-13 (stretchable textiles) have shown a better behaviour, less electrical resistance, than the others laid down by stencil and the pen prototype as well.

References

‘Application notes Bare conductive ink’ can be found under http://www.bareconductive.com/wp-content/uplads/2015/01/ElectricPaint_ApplicationNotes.pdf

Chapter 9 | Process to develop a specific writing instrument for EdM conductive ink

The tasks of the thesis project can be divided mainly in two parts: the first one is about testing the Ecole des Mines (EdM) Conductive ink, then try to lay down it by using a conventional writing instrument. During the first part the work focused on depositing freely EdM Conductive Ink onto different fabrics in order to verify the ink behaviour (compatibility, conductivity). Once tested EdM Conductive ink, there was the need to make the system repeatable in an easy and conventional way. Thus the next step concerned the design of a prototype to make the ink “printable” on textiles.

The following chapter will explain in detail the step that brings from the experimental part (chapter 7,8) to the end-use scenary. Starting from the analisys of the main factors within the end-use scenary, moving through the study of common writing instruments, carrying on with a methodological approach to design a functional prototype. For the thesis project, this chapter should bring to the fabrication of demonstrative products made of printed textiles using the formulated ink while in broader terms to the use of “EdM Conductive Ink Marker” in a new consumer market.

9.1 Use scenario

Before to explain in detail the design of the prototype/pen is necessary to take confidence and make clear the main points that drived most of the choices in the design process. In the following part will be showed: the main actors of the scenario, the fundamental role that each one plays and how they work together, finally a detailed definition of the context and the strong points that make it interesting.

Main actors of the use scenario

Before to explain in detail the use scenario, the main actors are introduced:

• EdM Conductive Ink
• The substrate: textiles
• Writing instrument: prototype/pen
• Users

Each one plays a fundamental role in making a new consumer market possible.

Use scenario

The thesis project concerns the deposition of EdM Conductive Ink on textiles by using a specific tool (prototype/pen).
The purpose of making conductive fabrics freely after the weaving process, it's about opening the doors to new uses/applications of common textiles, in the context of "Do-it-yourself". In this way there is the great opportunity to create or add new functions to existent products, giving them new life, or design new projects.

The concept of "Do-it-yourself"

"Do-it-yourself" refers mainly to the opportunity for everyone to create something new freely instead of buying smart products.
The main advantages to make conductive textiles freely by using a pen after the weaving process are shown below:

- No need to have a "special" textile;
- Great opportunity to express yourself creating/adding new values on "products", developing new functions for existent "objects" or creating really interesting new concepts;
- Huge range of personalization (pattern, functions, textiles);
- No need to be a technician, suitable for everyone;

- Many fields of development and application (from art and design to sport, security, medical & engineering field).

Among the different end-uses, the main methods of using “EdM Conductive marker” can be divided in two ways:

a) Draw free shape (art - design - drawing - calligraphy)
b) Draw straight lines (paths)

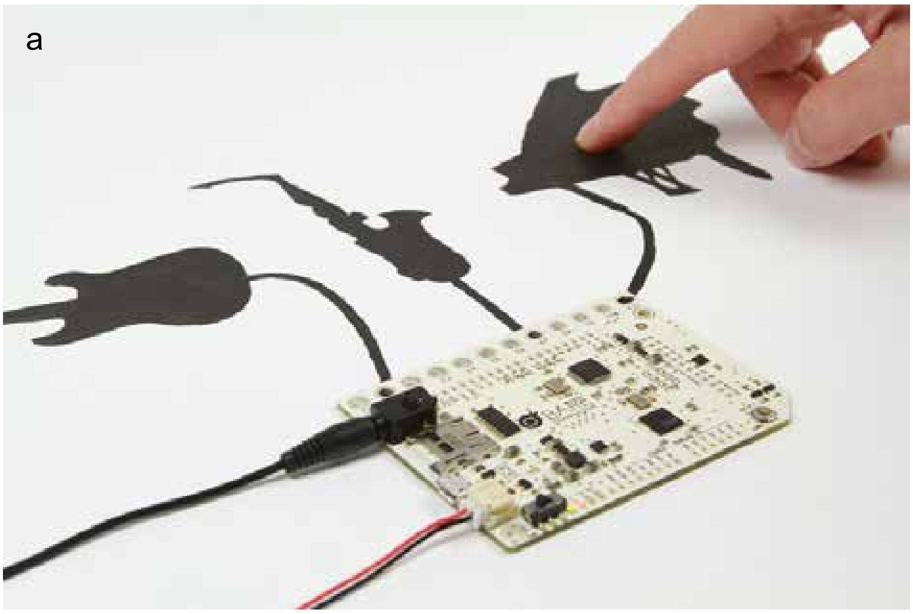


Figure 9.1
Bare Conductive ink touch board, drawing free shape.

Source: http://www.bare-conductive.com/

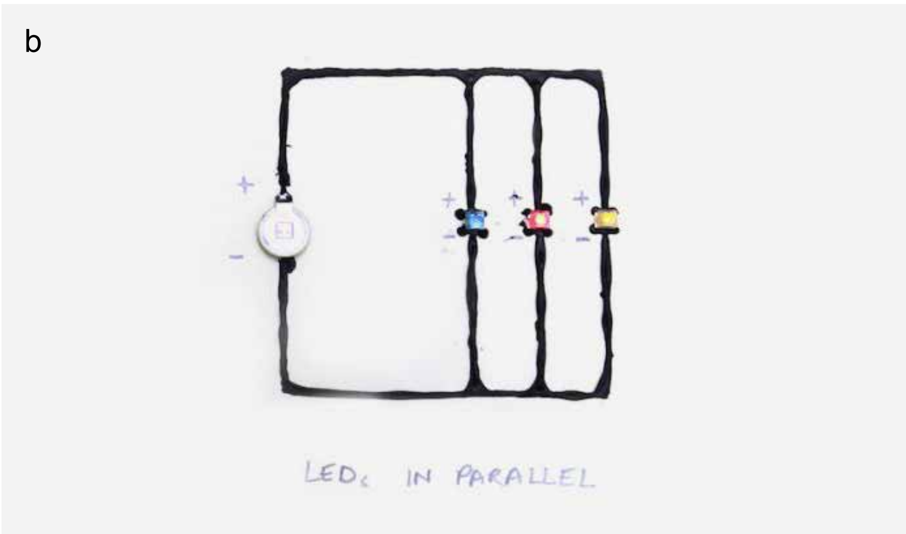


Figure 9.2
Bare Conductive ink, led application, , drawing straight lines.

Source: http://www.bare-conductive.com/

Figure 9.3
Bare Conductive ink workshop, example of use of a conductive ink pen.

Source: http://www.bare-conductive.com/

(pic on the right)

9.2 Writing instruments analysis

The development of a particular pen for EdM Conductive Ink needs the study and analysis of the main writing instruments from the past to nowadays. According to the thesis project, thus the specific use scenario and the context of "Do-it-yourself", the analysis mainly focuses on hand writing instruments, not on printing methods. Among the writing instruments, the category of interest is about the most common hand writing instruments that use an ink to leave a mark on the substrate such as pen, markers.

Hand writing instruments can be basically divided for the working principle to lay down the ink. The working principle is mainly drived by the ink viscosity and the substrate for the end-use. All these aspects are shown in the following analysis.

According to this project the hand writing instruments can be categorized in four different working principles:

In the next page, the following pictures, from the top to the bottom.

Figure 9.4
Fountain pen.
Source: web

Figure 9.5
Ballpoint pen.
Source: web

Figure 9.6
Felt-tip pen.
Source: web

Figure 9.7
Bare conductive marker
Source: web

1. Gravity and capillary action
2. Gravity and mechanical (metal ball) action
3. Felt-tip ink absorbing action
4. Flow control by the pressure

The first three working principles are the most common and they mainly refer to different nibs. The point 4 is more focused on how the ink comes out from the writing instrument, thus in the same category the nib can be different according to end-uses. In this case the ink is more viscous than normal inks, like paint.
This is the reason why the category focuses on "flow control by pressure", it doesn't work well without pressure.

1. Gravity and capillary action

The pen draws ink from the reservoir through a feed to the nib and deposits it on paper via a combination of gravity and capillary action. **Fountain pen** and **rapidograph technical pen** use this working principle.

Substrate: paper **Ink viscosity:** low

2. Gravity and mechanical action

A ballpoint pen dispenses ink by rolling a small metal sphere, usually 0.7–1.2 mm. The ink dries almost immediately on contact with paper. **Ballpoint pen** and **rollerball pen** use this working principle.

Substrate: paper **Ink viscosity:** low

3. Felt-tip ink absorbing action

A **felt-tip pen, marker pen, fineliner,** or **sketch pen**, is a pen which has its own ink-source, and a tip made of porous, pressed fibers such as felt.

Substrate: paper, textile etc.. **Ink viscosity:** low

4. Flow control by pressure

The flow is controlled by the pressure. The main reason for using this principle is about the high ink viscosity, like paint. In this category, the tip can be just an hole, or have a mechanical action according to end-uses. In the following part will be detailed the main tips for this category: **hole, corrector pen tip, rollerball tip**.

4.1 Hole as tip

The paint comes out from the writing instrument by pushing the liquid through the hole.
The flow is managed by the user.

Substrate: paper, textile,etc.. **Ink viscosity:** high

4.2 Correction pen tip

The ink comes out from the correction pen by a double action, air pressure on the body pen and pushing the tip on the substrate. The tip inside has a kind of "piston" that once pushed on the substrate open the ink flow like a valve.

Substrate: paper, textile etc.. **Ink viscosity:** medium

4.3 Dalo Textile Marker rollerball tip

The paint comes out from this kind of textile marker by a double action, air pressure by a rubber bulb and a rollerball tip. The tip is available in three different size: fine, medium and broad.

Substrate: paper, textile etc.. **Ink viscosity:** high

Figure 9.8
Fabric paint pen
Source: web

Figure 9.9
Correction pen
Source: web

Figure 9.10
Dalo, textile marker
Source: web

In parallel to the analysis of the most common hand writing instruments, **the research went on the hand writing instruments for the conductive ink market**.
In line with the use scenario of EdM Conductive Ink, the company "Bare Conductive" is been an inspiration and a guide for the project. Bare Conductive is a company focused on making creative electronic tools for any designer, engineer or aspiring maker

by using an electric paint. It is an electrically conductive paint that makes it possible to draw a circuit, cold solder a component or turn any surface into a sensor. Bare Conductive Electric Paint can be applyed by painting, screen printing, stencilling or markers. The Bare Conductive markers are shown below.

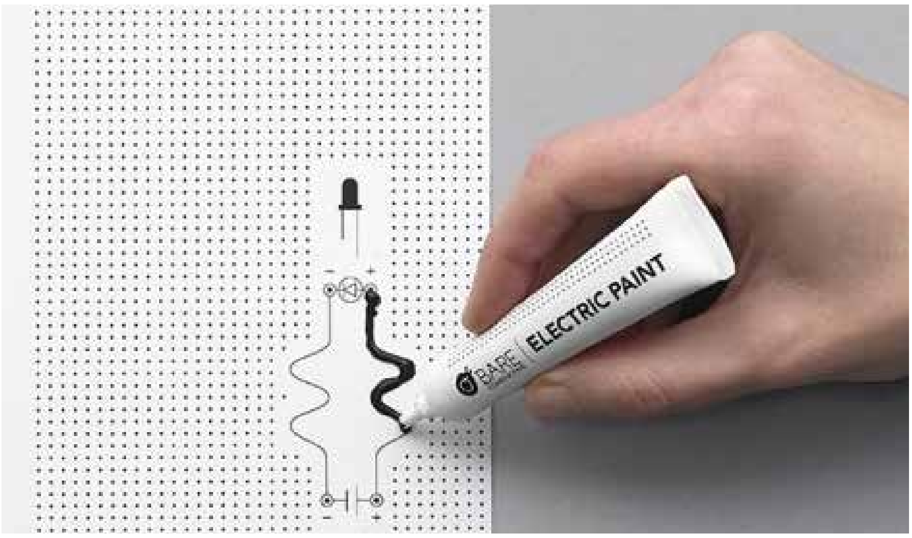


Figure 9.11
Electric paint marker 1, Bare Conductive

Source: web

Figure 9.12
Electric paint marker 2, Bare Conductive

Source: web

Bare Conductive markers use the same working principle analysed in the point 4.1, previous page.

		Requirements	Constraints	Solutions
Technical approach	a	The ink flow deposition have to be continuous.	Conductive ink viscosity, more like a paste. it doesn't come out from the nib by gravity and capillary.	- Pressurize the conductive ink. - The ink comes out from the pen pushing the nib on the substrate, it works like a valve (correction pen principle).
	b	The ink formulation have to come out from the nib homogeneus and uniform.	By using most of the writing instruments the conductive ink comes out not well mixed, the conductive platelets remain trapped into the nib.	Work on the nib opening and action principle (flow control by pressure) to make the ink well mixed.
	c	The writing instruments have to slide at best on the substrate, different fabrics.	- Most of the writing instruments are designed to work on paper, thus they are not as good as on fabrics. - Writing instruments designed to work on textiles usually have a nib that it doesn't fit a viscous ink like EDM Conductive ink.	Work on the nib shape and opening principle to slide on different fabrics.
	d	The ink deposition have to be thick enough in order to reach and mantain conductivity along the path.	If the ink layer deposited is too thin, the conductivity along the path is not continuous and/or too low. Most of the writing instruments don't care about the ink thickness, they only need to make a clear mark on the substrate using less ink as possibile.	Work on the nib opening to adjust the ink thickness deposition on fabrics.
Use scenario and usability approach	e	The wideness of the ink mark on the substrate have to be within a range size in line to the end-uses and enough to mantain conductivity along the path. *Note	The considered end-uses deverge to each other in the deposition requirements.	Design the prototype with two different tip sizes: fine and medium, according to different end-uses.
	f	It's necessary to make the prototype user-friendly. According to this approach, the working principle, the general shape/interface and the production process, have to be in line with the common writing instruments.	Size,weight and shape of the prototype joined to a uncommon way to handle it can make the writing instrument user-hostile, and also more expensive the production process.	A well balance design makes the prototype easy to use, in line with the most common writing instruments and the thesis scenario.

Table 9.1
Design process, requirements, constraints, solutions.

Note:
The work area considered for this project refers to "do-it-yourself" scenario, moving freely from artistic approach to technical. The first approach doesn't need particular adjustaments about ink mark wideness, it works like common pens/markers (free shape, drawing, calligraphy). The second one beeing more focused on technical end-uses, it has to be more precise, thus narrow marks.

9.3 Meeting the requirements to lay down EdM conductive ink by a prototype

The testing part in laboratory with EdM Conductive Ink and the first attempts to lay down it by using some common writing tools, it gave a general feedback to understand and identify the ideal deposition requirements. The study and analysis of the working principles among the main writing instruments from the past to nowadays, it gave me useful indications and inspirations to define design solutions.
The table on the left it represents the first step of the "design process". It gathers the requirements, constraints and solutions about the prototype project, in order to start the development.

Two main approaches in the table define the prototype project:
1. **Technical approach**, in order to have an ideal ink deposition;
2. **Usability approach**, it concerns the use scenario and the usability.

As it was introduced before, among the different hand writing instruments analysed, one of them from Bare Conductive company, it uses a conductive paint. Thus once identifyed the prototype requirements from the table, It was very important to analyse in detail the competitor Bare Conductive marker, before to start a new design. The following part will show the features of Bare Conductive marker to compare with the requirements of the thesis project.

Figure 9.13 Lay down electric paint, Bare Conductive marker.

Source: web

Table 9.2 Bare Conductive marker meets the project requirements.

Grade level	How Bare Conductive marker meets the project requirements
● ○ ○	a. The ink flow deposition have to be continuous. The pressure by hand to push the ink out through the hole make the flow not constant.
● ● ●	b. The ink formulation have to come out from the nib homogeneus (well mixed). The hole size joined to the pressure allow the ink to come out homogeneus without loosing conductive platelets into the nozzle.
● ● ○	c. The writing instruments have to slide at best on the substrate, different fabrics. Usually Bare Conductive marker is used on rigid and uniform surface, not on fibers frame even stretchable. Thus the nib is less sliding than the requirements.
● ● ○	d. The ink deposition have to be thick enough in order to reach and mantain conductivity along the path. The pressure by hand to push the ink out through the hole make the thickness not constant.
● ● ○	e. The wideness of the ink mark on the substrate have to be within a range size in line to the end-uses and enough to mantain conductivity along the path. The wideness of the ink it depends on the hole size of the marker. No different tip size for various end-uses.
● ○ ○	f. Easy to use. The users have to push the ink by hand and write at the same time. Less comfortable and precise than normal pen usability.

In the table 8.3 it was analysed Bare Conductive ink marker focusing on the thesis project requirements to see whether the marker could fit them or be only a starting point for a new one. Among the competitors in the market of conductive ink, Bare Conductive is closer to the thesis project. The other competitors use a less viscous ink (silver-based) and thus they use as writing instrument, an ordinary pen, usually like a ballpoint or correction pen (fig. 9.15, 9.16). The surface to lay down the ink is usually rigid and uniform (not suitable for textiles).

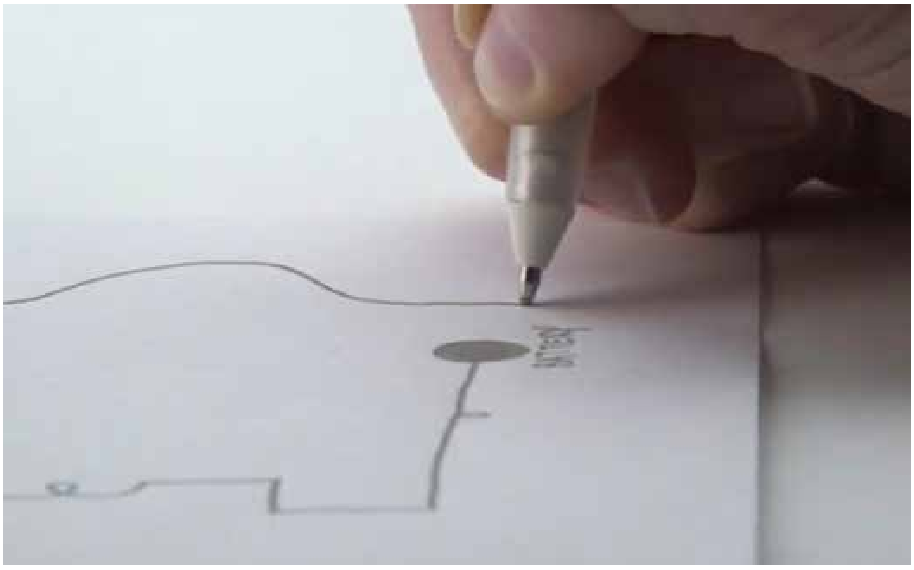


Figure 9.14
Lay down conductive ink by a pen (ballpoint nib working principle).

Source: web

Figure 9.15
Lay down conductive ink by a pen (correction nib pen working principle).

Source: http://store.caig.com/

9.4 Design the pen prototype, a specific writing instrument to lay down EdM conductive ink

The results came out from the table of design process gave the necessary knowledge to develop a specifc writing instrument to layd down EdM conductive ink on textiles.

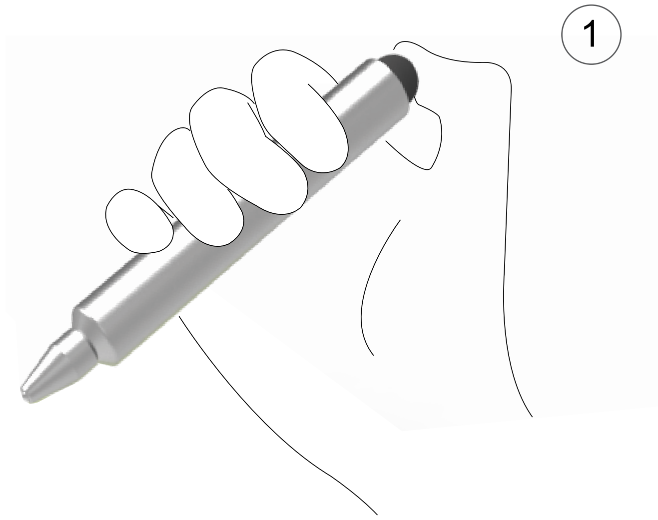
Figure 9.16
Rendering of the prototype for EdM conductive ink.

Function of EdM conductive marker
To allow the lay down of EdM conductive ink on textiles

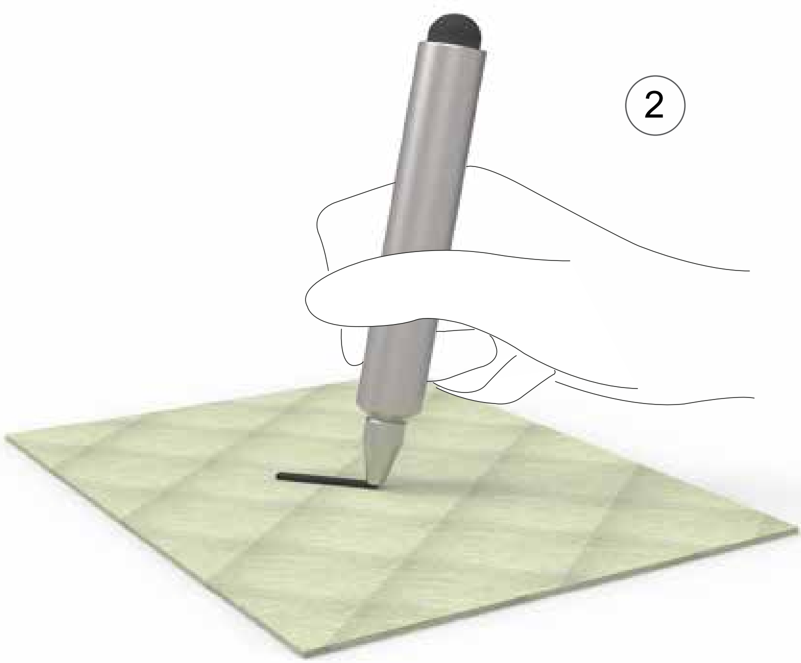
The marker:

- have to mantain a continuos ink flow during writing
- have to mantain the blend homogeneus
- have to lay down an adequate ink thickness to ensure conductivity along the deposited path
- have to slide at best on the substrate, different fabrics
- have to allow a specific wideness of the ink mark on the substrate in line with the end-uses
- have to be user-friendly

How to use EdM conductive ink marker
Ink flow is controlled by the pressure bulb at the end of the barrel



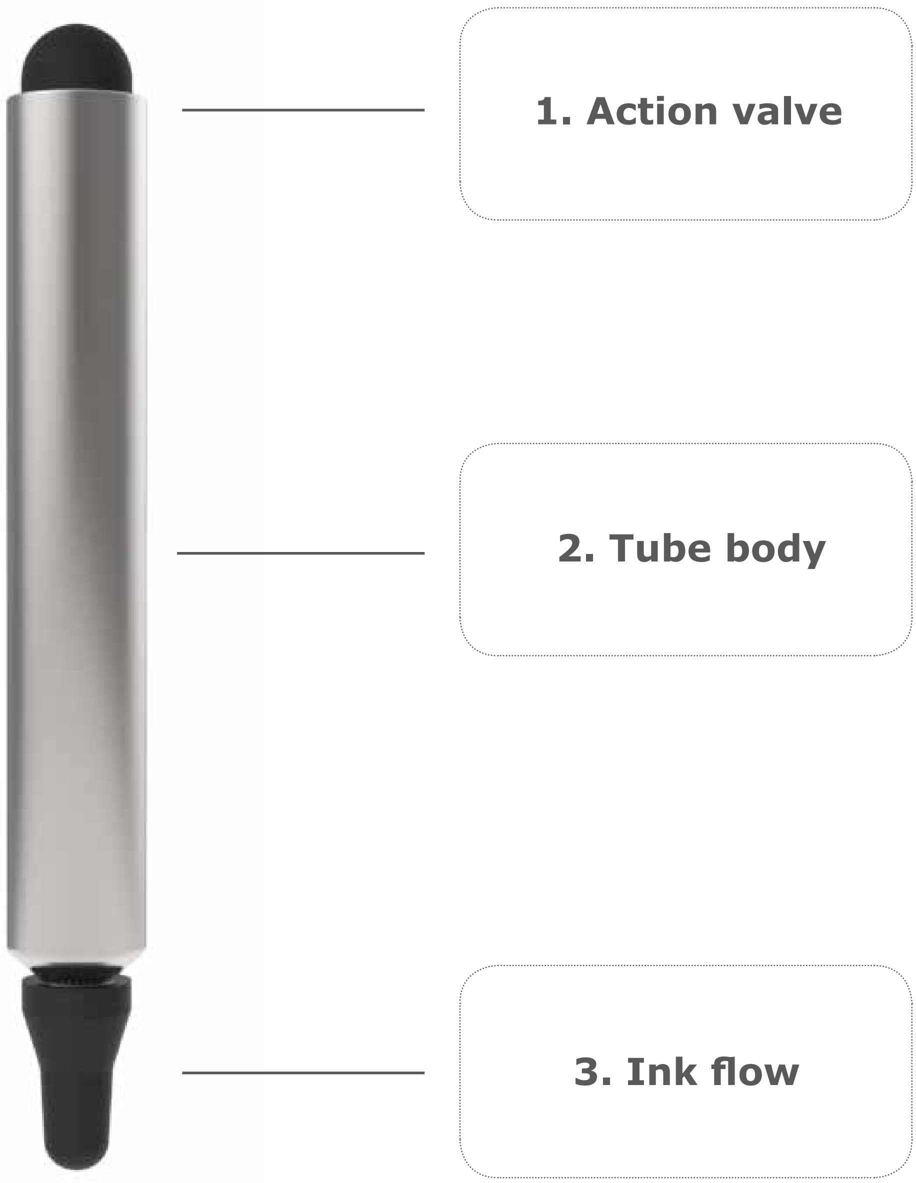
1. Press the rubber bulb to pressurize the ink



2. Depress steel ball tip to start flow.

Components of the prototype
In the following part will be shown how the components work together to meet the requirements.

The prototype can be divided into three parts based on the main functions of the components:

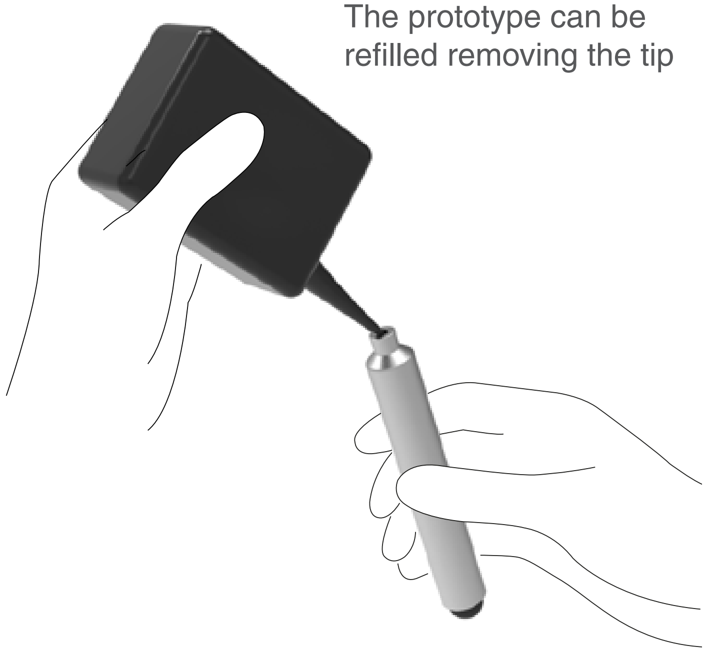


1. Action valve - bulb button to pressurize the flow

2. Tube body - rigid barrel to contain and protect the blend inside

The barrel can contain
up to 26 ml of ink

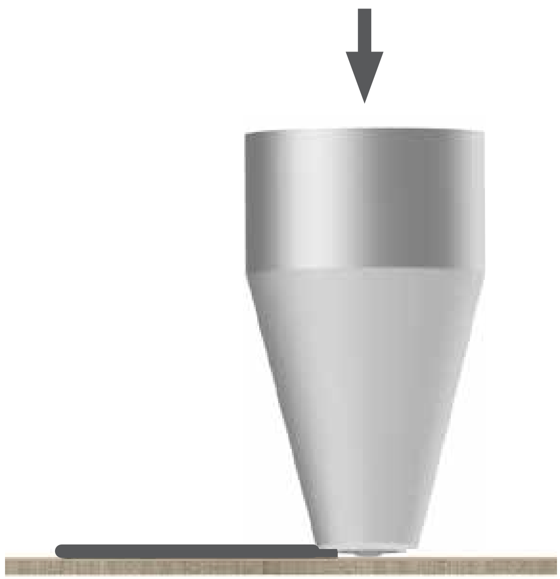
The prototype can be
refilled removing the tip



3. Ink Flow - Ball tip to depressurize and open the the ink flow

Resting phase without pushing the roller ball tip, the nib doesn't flow the ink

Pushing the roller ball tip on the surface the ink comes out from the nib

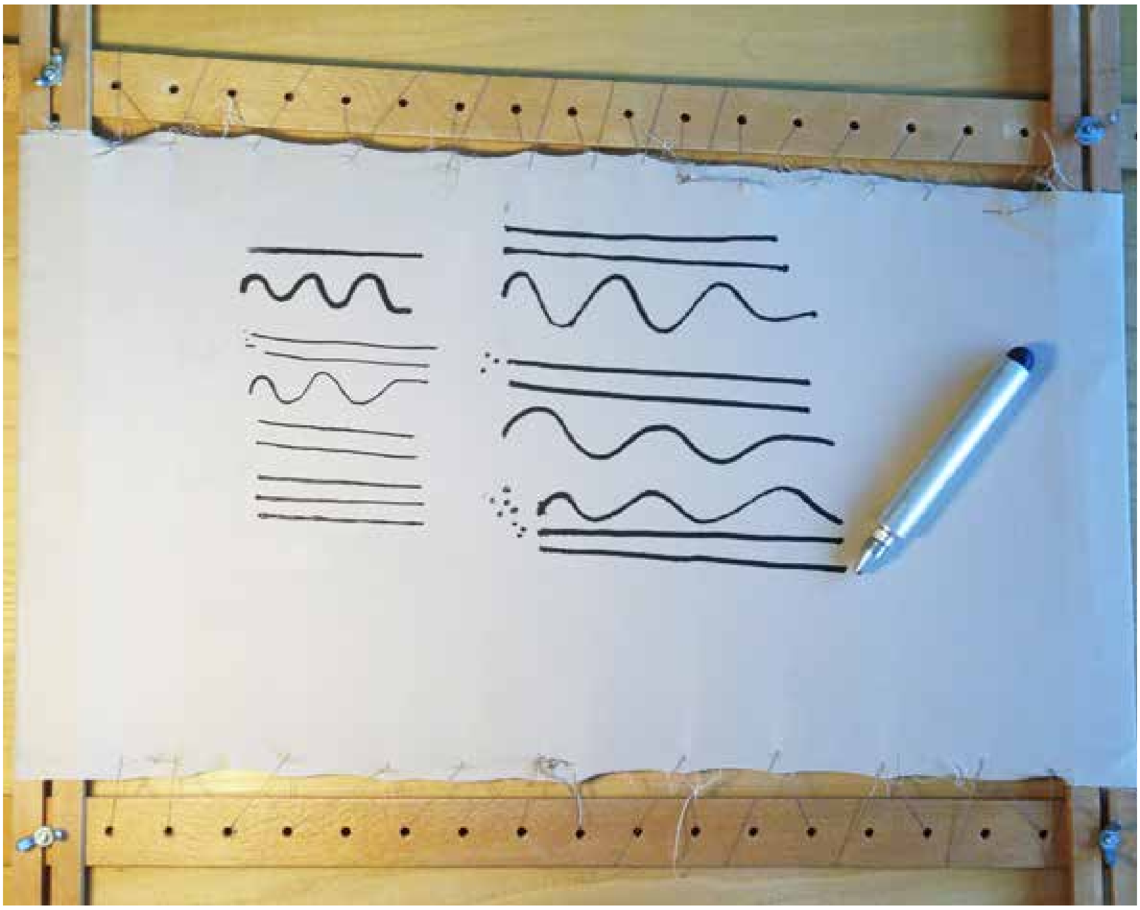


Main features of the prototype

- The size of the writing instrument allows to contain a good quantity of ink inside, in line with the use scenario and the competitors.
- The prototype is easy to handle because of the light weight, the ridid barrel, the conventional shape and sizes.
- The protoype slides well on the substrate, different textiles.
- The writing tool can be refilled turning and removing the nib.

Figure 9.17
Drawing EdM conductive ink on cotton fabric by the design prototype.

In the picture below (fig. 9.18) a textile frame holds a cotton fabric. EdM conductive ink has been laid down on the substrate by the designed prototype with three different tip sizes: 2 - 3 - 4mm.



References

‘Use of Bare conductive ink’ can be found under
http://www.bareconductive.com/make

‘Textpen dykem‘ can be found under
http://itwprofessionalbrands.com/1112/dykem/steel-tip-paint-markers/texpen-marker

Chapter 10 | Outlook for the future of EdM conductive ink

The chapter will start with a brief of the functional textiles, flexible electronic market and the development of conductive inks, to understand the realities of today.
The applications of conductive inks, both today and expected for the future, in comparison with EdM conductive ink, they will give an overview to focus the following part. Finally, the features and the strong points of the conductive ink formulation joined to all the results have been achieved during the thesis project will bring to visualize promising outlook for the future.

10.1 Context

Textile is a familiar material used in variety of situations, such as transport, furniture, architecture, medical care and apparel. Functional textiles refer to a broad range of products that extend the functionalities of common fabrics. Several applications, ranging from military and security to personalized healthcare, hygiene and entertainment can be targeted. [1]
Such smart textiles will be able to sense and react to environmental conditions or stimuli, for example, mechanical, thermal, chemical or magnetic interactions. [2] *Functional textiles already available on the market count, for instance, refreshing or slimming functions using micro encapsulation of active molecules* [3] *and also antistatic and thermo-regulating functions for*

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[1] L. Hu, M. Pasta, F.L. Mantia, L. Cui, S. Jeong, H.D. Deshazer, J.W. Choi, S.M. Han, Y. Cui, Nano Lett. 10 (2010) 708.

[2] M.A.H. Khondoker, S.C. Mun, J. Kim, Appl. Phys. A 112 (2013) 411.

[3] R. Cauchois, M. Saadaoui, A. Yakoub, K. Inal, B. Dubois-Bonvalot, J.-C. Fidalgo, J.

bedding or sport applications by weaving of metallic threads into the fabrics. [4][5]

More recently, wearable electronics or e-textiles, with incorporation of microelectronics onto the fabric, have been developed. [6]

There are different ways to produce electrically conductive fabrics. First, by weaving conductive yarns into the textile structure:[7] *with this technique, the softness and comfort of the final composite textile can be degraded. The conductive yarns themselves can be produced through different processes such as twisted metal wires, metal coating or metal fibers.* [8]

Another approach is to develop surface treatment adequate for application of existing conductive inks meaning inks that were developed for non-flexible substrates, for instance covering the substrate with a polymer layer. The surface treatment can offer excellent printability and adhesion of standard conductive inks.

More recently, conductive coatings and inks have been applied onto fabrics and papers to provide flexibility to the systems and reduce stress on the substrate. The conductive coating can be deposited on a non-conductive substrate through classical printing techniques. [9]

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[4] P.A. Steward, J. Hearn, M.C. Wilkinson, Adv. Colloid Interface Sci. 86 (2000) 195.

[5] C. Wu, X. Huang, G. Wang, L. Lv, G. Chen, G. Li, P. Jiang, Adv. Funct. Mater. 23

[6] X. Li, G. Zhang, X. Bai, X. Sun, X. Wang, E. Wang, H. Dai, Nat. Nanotechnol. 3 (2008) 538.

[7] N. Grossiord, J. Loos, C.E. Koning, J. Mater.Chem. 15 (2005) 2349.

10.2 Competitive landscape of the current conductive inks

Conductive inks *can be coarsely divided into* **two categories** *depending whether they contain a polymeric binder or not.* **In the first case**, *conductive particles are dispersed in an organic solvent using a stabilizing agent. After being deposited onto the substrate, a sintering step at high temperature (>500°C) is required to form the final conductive component [10], which process is not adequate for flexible substrates nor textiles. [11]*
In the second case, *a polymeric binder in solubilized in an organic solvent to formthe medium. Then, the conductive particles are dispersed in that medium. After being depositedonto the substrate, film formation occurs at low temperature (<120°C) and some flexibility of the final conductive component is given by the polymeric binder. This approach is more adequate for printing textiles and it will be detailed in the next part. [12]*

While conductive inks remained fairly stable for decades, in recent years, there have been improvements, as well as innovative new inks to meet the challenges offered by printed electronics.

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[8] Z. Yang, R. Gao, N. Hu, J. Chai, Y. Cheng, L. Zhang, H. Wei, E.S.-W. Kong, Y.

[9] E. Thommerel, J.C. Valmalette, J. Musso, S. Villain, J.R. Gavarri, D. Spada, Mater.

[10] R. Zallen, in: Phys. Amorph. Solids, Wiley-VCH Verlag GmbH & Co. KGaA, 1983,

[11] A. Hunt, R. Ewing, Percolation Theory for Flowin Porous Media, Springer Science & Business Media, 2009.

[12] D. Stauffer, A. Aharony, Introduction to Percolation Theory, Taylor & Francis, 1994.

Printed electronics (PE) is the term that defines the use of traditional graphic printing methods to manufacture circuits on media such as polymer films, paper, textiles, and other materials.
The promise of low-cost, high-volume, high-throughput production of electronic components or devices that are lightweight, small, thin, flexible, inexpensive and disposable has spurred the recent growth in development of PE technology.
Over the past ten years, flexible electronics raised a strong interest and many applications were developed, such as flexible screens, ships for security (RFID) or recently wearable electronics. This new concept enables to transform traditional textile and apparel products into lightweight, wireless and wearable intelligent devices. [13]

Focus on textile printing in the landscape of conductive inks

The movement towards flexibility will impact on conductive inks that must be able to work with new substrates as they become more flexible, bendable and/or stretchable. Currently, conductive inks are mostly based on metallic particles and contain 30 to 70wt.% of these conductive phase in order to reach the adequate conductivity level.
These inks are part of the first category previously introduced and actually they present various issues to be used in printing textiles. First of all they usually need to be sintered at high temperature, this way cannot work on flexible substrates. More recently some different methods have been developed for ink curing at lower temperature, on the other hand the development of

[13] Pira International Ltd, Conductive inks, iSmithers Rapra Publishing, 2012.

nanoparticles inks has allowed to sinter them at lower temperatures. Thus the innovative nanoparticles inks based on metallic particles could now be processed on substrates such as paper, and pet. Despite this, the lack of cracking resistance, the flaking and adhesion loss make this ink category a poor choice for printing on textiles. In addition the high cost of this type of inks recently has moved the focus on lower cost and a more environmentally-friendly solution. Conductive polymers could be a good choice if these materials can be improved to offer enough conductivity.

Carbon-based particles are also attractive candidates for conductive inks due to their low cost and good electrical conductivities. However, carbon particles are hardly stable in water suspensions. Among the various carbonbased materials, graphene, a flat monolayer of carbon atoms tightly packed into a two-dimensional (2D) honeycomb lattice, is considered a potential material for carbon-based inks because of its remarkable characteristics.

10.3 Features and outlook of EdM conductive ink

Features of EdM conductive ink

The ink developed by Ecole des Mines is a conductive ink based on Few Layer graphene mixed with polymeric latex.

The nanocomposite material obtained after drying has a complex microstructure comprised of two interconnected networks, a first network made of the polymer phase and a second network made of conductive fillers in contact leading to a conductive material.

This morphology allows taking advantage of the properties of a polymer matrix such as the formation of a cohesive material at ambient temperature without high-temperature sintering step and a greater deformability after film formation.

Results from the testing phase on textiles

- EdM conductive ink during the testing part has been laid down on various textiles showing good stability and conductivity even stretching some elastic fabric samples.
- After one soft washing the ink was still stable on fabric and after drying it improved the conductivity.
- It has been achieved light opening from a LED on fabric, opening the opportunity to use EdM conductive ink for electronic functions.
- The ink deposition on fabric through stencil and the designed pen prototype have shown comparable electrical resistance values.

The results obtained give promising indication for the use of EdM conductive ink on a wider variety of textiles not yet tested and to visualize different scenery of use for today and the future.

Use scenario of EdM conductive ink for the thesis project

The use scenario that has drived the thesis project concerned the use of EdM conductive ink on textiles by using a conventional writing instrument in the context of “Do-it-yourself“.

“Do-it-yourself“ refers mainly to the opportunity for everyone to create something new freely instead of buying smart products.

The main advantages to make conductive textiles freely by using a pen after the weaving process are shown below:

- No need to have a “special” textile, it fits everyday textiles;
- Great opportunity to express yourself creating/adding new values on “products”, developing new functions for existent “objects” or creating really interesting new concepts;

- No need to be a technician, suitable for everyone;

There are many applications available to EdM conductive ink, for instance, anti-static, thermal or electronic functions could be imagined. About electronic functions, actually ink paths can be painted as wires to connect small devices or create sensors directly onto fabrics by using the designed pen or stencils.

Examples of smart products are shown below (Fig.10.1,10.2).

Figure 10.1
Example from Sounding Textiles workshop.

Source: http://www.kobakant.at/DIY/

Figure 10.2
Example of a smart product.

Source: http://www.kobakant.at/DIY/

The features of EdM conductive ink and the results from the testing part has brought to visualize promising use for the future. From the current lay down by pen or stencils to the use of printing processes in the future, opening the oppurtunity to enlarge the market and improve the performance of this conductive ink.

Looking to the future of EdM conductive ink

The stability and conductivity of EdM conductive ink exhibited also on some elastic fabric samples, even applying an axial tensile force. The huge deformability of EdM conductive ink joined to the conductivity and stability on textiles could bring to the use as stretchable sensor. Showing a clear encrease of the resistance during the elongation EdM conductive ink could be used for instance, to measure large and small strains, and transmit the data accurately to a bluetooth enabled device.

The big expansion in printed electronics in the near future could make possible to print EdM conductive ink on textiles overcoming the issue of low throughput.

Figure 10.3
Scheme of a strain sensitive sensor.

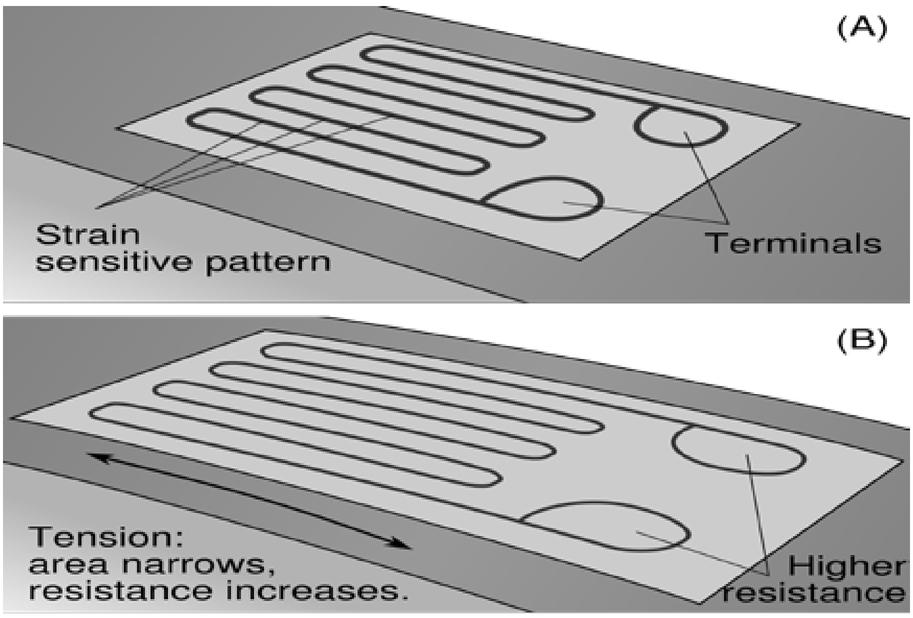

Figure 10.4
Textile strain sensor.

Source: http://www.mdpi.com/sensors/sensors-14-04050/article_deploy/html/images/sensors-14-04050f5-1024.png

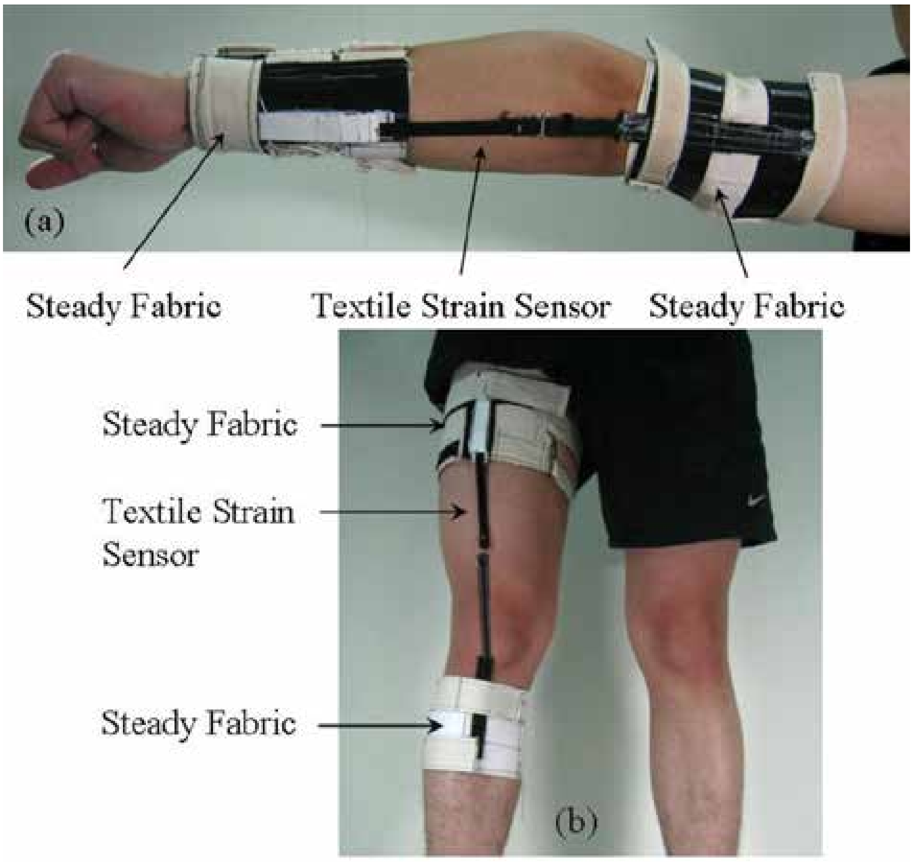

Figure 10.5
Prototype Sensing Garment. Spandex pants with conductive fiber sensors for lower body monitoring.

Source: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC555561/

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‘Wearable sensors’ can be found under
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‘Wearable sensors’ can be found under
http://www.mdpi.com/sensors/sensors-14-04050/article_deploy/html/images/sensors-14-04050f5-1024.png

‘Wearable conductive fiber sensors’ can be found under
http://www.ncbi.nlm.nih.gov/pmc/articles/PMC555561/

Conclusions

Many points have been achieved working on EdM conductive ink during the thesis. The research part has laid the foundations to manage the experimental part considering all the main actors involved and their foundamental role.

The experimental part of EdM conductive ink on textiles has shown the general behavior of the ink.
The following points will detail the results have been achieved during the testing phase.

EdM conductive ink has exhibited a good interaction with the tested textiles, showing stability after drying.

The fabric samples tested have shown conductivity after ink drying. Along the testing phase the measured conductivity on textiles has been lower than the free standing film. This result has pointed out the influence of applying the blend on fabric.
To counteract this decresase, the leverage that have been managed are:

- playing on textile type (absorbent or not)
- playing on the thickness on the ink (adjusting the viscosity)
- working on the process of the ink deposition.

EdM conductive film has exhibited stability and conductivity also on some elastic fabric samples, even applying an axial tensile force, showing a clear encrease of the resistance during the elongation.

After one soft washing the ink was still stable on fabric and after drying it improved the conductivity.
The analysis at the stereo microscope has pointed out how EdM conductive ink sticks on fabrics. In the final tests the ink remained more on the surface instead of losing part of it into the fibers as happened at the beginning. This good interaction between EdM conductive ink and the fabrics has allowed a thicker ink layer in a single deposition and as a result a lower resistance.

During the tests EdM conductive ink has been laid down by stencil on a wide variety of textiles improving the conductivity achieved at the beginning with the free deposition on fabric. The results exhibited a better deposition by using this method (the stencil) closer to a screen printing process than free standing by hand. It is a promising indication for EdM conductive ink, opening the opportunity to a wider use .

A specific writing instrument for EdM conductive ink has been developed for ink lay down on textiles.
Using the designed prototype has been drawn some lines. The electrical resistance measured on them has shown interesting results comparable to those achieved through the stencil. The ink has come out from the nib of the pen prototype homogeneus without loss of filler or aggregation and showing conductivity along all the path once dry. In addition to the ideal ink deposition, the designed pen has shown good usability meeting the necessary requirements for the use scenario of the project.

After many attempts it has been achieved light opening from a LED on fabric samples n.12-15. A new ink formulation with an increased percentage of graphene solution in the composite blend has been laid down by stencil in parallel lines as positive and negative poles. These two paths were created in replacement of classical wires to join a battery and a LED.

The textiles used during the testing part have provided a detailed feedback to understand the behaviour of EdM conductive ink on textiles in broader terms. The results obtained gave promising indication for the use of this ink on a wider variety of textiles not yet tested. In addition the conductivity showed even under tensile forse could open the oppurtunity to the use of EdM conductive ink as stretchable sensor on textiles.