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Topical Review

Smart fabric sensors and e-textile technologies: a review

Lina M Castano and Alison B Flatau

Department of Aerospace Engineering, University of Maryland, College Park, MD 20742, USA

E-mail: linacs@umd.edu and aflatau@umd.edu

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Abstract

This paper provides a review of recent developments in the rapidly changing and advancing field of smart fabric sensor and electronic textile technologies. It summarizes the basic principles and approaches employed when building fabric sensors as well as the most commonly used materials and techniques used in electronic textiles. This paper shows that sensing functionality can be created by intrinsic and extrinsic modifications to textile substrates depending on the level of integration into the fabric platform. The current work demonstrates that fabric sensors can be tailored to measure force, pressure, chemicals, humidity and temperature variations. Materials, connectors, fabric circuits, interconnects, encapsulation and fabrication methods associated with fabric technologies prove to be customizable and versatile but less robust than their conventional electronics counterparts. The findings of this survey suggest that a complete smart fabric system is possible through the integration of the different types of textile based functional elements. This work intends to be a starting point for standardization of smart fabric sensing techniques and e-textile fabrication methods.

Keywords: fabric sensors, textile sensors, e-textiles

(Some figures may appear in colour only in the online journal)

1. Introduction

Fabrics are the new silicon wafers; they have generated much interest due to the advent of portable devices and soft computing. Though not a replacement for conventional electronics, this field possesses a market of its own that is still in its development phase, as it does not currently have a standardized set of methodologies or elements. It has become a concomitant development of wearable technologies. This paper includes a review of technologies essential for the development of fabrics with incorporated functionality, with an emphasis on sensor applications. Fabrics which are imbued with sensing properties are called smart fabric sensors (SFSs); these are sensitive to multiple physical and chemical stimuli such as changes in temperature, pressure, force, and electrical current, among others. Sensing elements can be incorporated into fabrics at any level depending on the structural fabric element being modified or sensitized. SFSs are part of the more generalized category of smart fabric transducers (SFTs), which are fabrics that have been treated or modified to act as sensors, actuators and/or other types of transducers. The ubiquitous nature of fabrics makes them an ideal vehicle for the design of sensors that are in direct contact with human beings. These wearable technologies are an active focus of research in diverse fields, including commercial [1], medicine [2], military [3] and aerospace [4], because SFTs provide technological possibilities which are not possible with conventional electronics alone. The intent of this paper is to convey a sense of the breadth of possibilities that fabrics have for being utilized and for either creating new application fields or improving current technologies. It also serves as an initial approach towards standardization of e-textile materials and methods as well as fabric sensing techniques.

SFTs provide functionality for measuring or influencing the environment or subject in which they are employed. Three major categories of SFTs are:

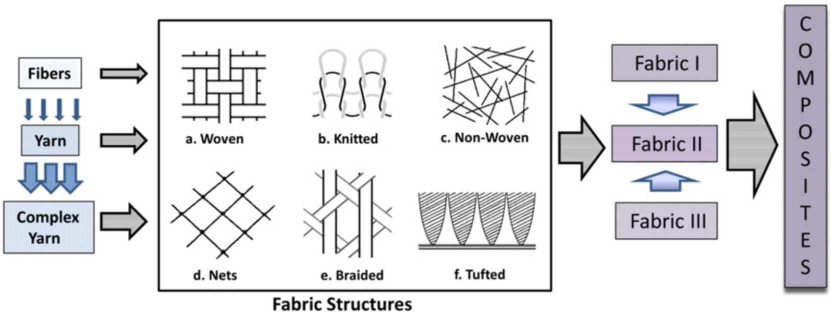

Figure 1. Fabric construction platform and hierarchy. Fabric structures: (a) woven, (b) knitted, (c) non-woven, (d) nets, (e) braided and (f) tufted, which can be assembled in layers (e.g. three layers) to form composite structures.

- *Sensors.* Fabrics which are given sensing properties of diverse physical nature, such as capacitive, resistive, optical and solar.
- *Actuators.* Fabrics which are able to actuate or move some aspect of their environment. Examples of these types of fabrics are electroactive fabrics and auxetic fabrics.
- *Batteries and energy harvesting.* Fabric based batteries and fabrics which use the kinetic energy or the thermal energy of the wearer or their environment to generate electrical power.

There are many additional categories of specialty, high tech, functional and/or advanced material fabrics that will not be examined in this review. Examples of fabrics with functionality that will not be addressed in this review include those which have been modified to address a particular purpose; whether it is to act as a fire retardant (Nomex), have increased strength (Kevlar) or possess luminescent properties [5]. These types of fabrics are beyond the scope of this paper given that they do not possess sensing qualities but rather a very specific property. Other examples/uses of these specialty fabrics include: heat regulating [6], EMI shielding fabrics [7], geotextiles and geosynthetics [8] and specialty fabrics for medicine [9], transportation and defense [10].

Several review works have been published which summarize the eclectic collection of developments in smart fabrics and intelligent clothing, as well as e-textiles and wearable fabrics [11–15]. This paper provides a unique review of the different types of fabric sensor and e-textile technologies from the materials and components point of view, as well as the construction procedures and techniques associated with them. The current topic of review was not previously available in the literature.

This paper is organized as follows: first, fabric sensors platforms are explained in the context of the broader field of SFT platforms. Second, fabric construction and hierarchy is presented for a general fabric transducer and hence for fabric sensors. Smart sensing functionality is then shown to be a result of intrinsic and extrinsic modifications to the fabric platform. Third, the materials, connection and fabrication methods used in e-textiles are presented in the context of SFSs and the wider field of SFTs. Section 4 contains a summary of the different types of smart fabric sensors found in the literature; force, pressure, strain, optical, chemical, temperature, humidity and shape memory sensors. Finally, some conclusions and observations are presented.

1.1. Fabric structure platform influence on SFSs

Fabrics are hierarchically structured fibrous materials. The smaller units, or first level of integration, are called fibers, which are characterized by having a high ratio of length to thickness [16]; these units interlace to form thread. Thread gets twisted to form yarn, considered as the second level of integration. Yarn gets turned into what we call fabric, the third level of integration, using different techniques such as weaving and knitting. Larger scales of hierarchical levels (fourth level and up) entail composite or compound fabric units [17]. Figure 1 shows the general progression of fabric structures; from fiber to cloth. A disambiguation must be made: sometimes thread is defined as yarn; however, yarn is usually thicker than thread and sometimes it can be made directly from the constituent fibers. Textiles are defined as anything made from fibrous materials. This includes fabrics and refers to any material constructed through weaving, knitting or other fabrication techniques. Cloth refers to a fabric used for a specific purpose. In this review the words textiles and fabrics are used interchangeably.

The construction of fabrics is crucial when building SFSs and SFTs in general; it will determine the type of bond needed for mechanical attachment to the fabric in the case of externally modified textiles, or the type of constituent element modification required for a more intrinsic integration. Knits are easily deformable while wovens are usually stable fabrics and hard to deform. A third category, non-wovens, are normally made from filaments or fiber webs and are strengthened by different bonding techniques such as adhesive bonding, mechanical interlocking by needling, fluid jet entanglement, thermal bonding and stitch bonding [18]. Other types of fabric structures are those made by compressing yarns or by creating nets out of them. Wovens, knits and some non-wovens are set together mechanically, while nets or compressed fabrics usually undergo chemical modifications. Wovens are typically constructed using fairly straight interconnections of wefts (transverse threads) and warps (longitudinal threads). Knits are typically made up of looped interconnections of courses and wales, where the wales are the threads that run vertically

Table 1. Impact of fiber origin properties on SFT platforms.

Natural fibers	Synthetic and regenerated
Comprised of: cellulosic, vegetable, animal, protein, mineral, natural rubber, i.e. cotton, wool, asbestos	Comprised of: cellulosic regenerated, protein regenerated, mineral regenerated, synthetic long chain polymer, synthetic rubber, i.e. rayon, graphite, nylon, polyester, spandex
Mostly in staple fibers, need staple treatment but present better adhesion properties for coatings	Mostly in continuous multi- and mono-filament, can be manufactured with specific characteristics
Mostly hydrophilic, help prevent static buildup, but fiber diameter increases upon wetting	Mostly hydrophobic, fiber diameter does not increase upon wetting
Increase in tenacity when wet (natural cellulosic)	Almost constant tenacity when wet
Decrease in tenacity when wet (animal and regenerated)	
Low mechanical compliance	High mechanical compliance
Non-thermoplastic (except modified cellulosics)	Mostly thermoplastic
Char/melting point varies: wool (570 °C), cotton (255 °C)	Melting point varies: spandex/Lycra (250 °C) polypropylene (150 °C)
Shorter lifespan	Good resistance to aging and abrasion (except for some regenerated fibers)
Readily flammable	Flammability depends on composition

and the courses run horizontally across the fabric. Typical interconnection paths of wefts and warps in wovens and of wales and courses in knits are depicted in figures 1(a) and (b) respectively.

An independent factor which also plays a role in the final characteristics of the fabric is the nature or origin of the fiber units [19]; these can be natural, or synthetic and regenerated. The synthetic fibers have much better mechanical compliance and less water absorption (hydrophobic) than natural ones, which tend to absorb water (hydrophilic). The nature of the fiber determines the susceptibility of a fabric to chemical and photonic (UV) reactions, compatibility with coatings, adhesion, water absorption, and fabric lifetime, and as a result the origin of fibers employed in STF design should be an important design consideration. For instance, the moisture absorption attributes of certain fibers can influence their dimensional stability, affecting their mechanical, frictional, and electrical properties as well as their shape, stiffness and permeability. A hydrophobic platform might be preferred if metalized connective elements are to be integrated with the fabric structure, to reduce the possibility of short circuits due to sweat or high humidity. On the other hand, hydrophilic fabrics may prevent the buildup of static electricity, a potential threat to electronics boards attached to the surface of a SFT. Table 1 shows a summary of fiber origins and their impact on SFT performance.

In general, SFTs are expected to perform properly in a range of environments and to withstand a garment-specific number of wash cycles. However, only a few of existing SFT systems are fully impervious to water. *A priori* knowledge of the melting points of the constituent fibers should be used to prevent heat radiated by attached electronics or components from damaging the fiber platform. The projected temperature rise needs to be within the fabric thermal tolerance for it to remain functional and safe [10].

The construction of an SFT requires careful determination of the fibers and yarns needed for a desired application. Standard descriptions of the properties of textile yarns may include: (1) linear density measured in denier (weight in grams of 9000 m), tex or decitex (weight in grams per 10 000 m); (2) strength, a measure of the force required to break a yarn or individual fiber, described in terms of tenacity (g/denier or cN/dtex), tensile strength (cN) or breakpoint (gr or N); and (3) percentage of elongation at break (non-dimensional) or ductility. However, this information is not always available since the textile yarns are typically described by their function—machine sewing, warping or knitting—and as a result many of the mechanical properties end up being assumed. For example, machine embroidery yarns are of higher tenacity, smoother finish, have less percentage of elongation at break and are spooled differently than knitting yarns. They are also usually of a small enough denier for machine sewability. Knitting yarns are assumed to be more resilient, present a coarser finish and have a higher percentage of elongation at break. They also need to be resistant to shear and permanent deformation under bending. A curl test has been suggested to test for flexibility requirements of machine sewable yarns [20].

Other important considerations when choosing textile yarns for SFTs are a consequence of the fiber properties. Increasing fiber linear density or decreasing fineness increases bending rigidity, which is not desirable for machine sewing but desirable for handmade sturdy platforms. Linear density also has an influence over softness, handling and drape-ability qualities [21]. Flexibility, or the resistance to permanent deformation under stresses like folding or bending, is also correlated to the yarn's fineness, flatness and elastic modulus. The degree of yarn twist affects the tensile properties of the textile, as well as fabric durability, low load deformations (i.e. wrinkle, recovery, drape), resilience, stiffness, abrasion resistance and compressibility. A high percentage of elongation at break or elasticity and ductility will enable large fabric platform deformations. All relevant properties should be taken into consideration when building an SFT. For instance, if a fabric sensor needs to be incorporated by hand to the elbow section of a garment, it will most likely need to be based on a knitting yarn with lower linear density for a small bending resistance, machine sewability, a high percentage of elongation at break and a good tenacity. In general, the knitted structures have a higher elongation percentage and the wovens have a higher strength [22]. However, this general trend does not simplify the analysis of the finalized fabric structure as its mechanical characteristics will ultimately depend on the type of platform: weave/knit/non-woven/composite, thread count, type of fibers and yarns, yarn twist, finishing processes and loading direction.

2. Platform modifications for smart sensing functionality

The platforms or substrates of fabrics can be modified at all levels of the structure hierarchy to be transformed into SFTs. For the purpose of this work all the platform transformations which will be discussed directly apply to SFSs. A level-one modification would entail the construction of fibers made out of conductive materials from which a textile can be constructed. A level-two modification would involve the replacement of yarns with sensitized yarns. This is what is seen in e-textiles. A level-three modification would involve altering the surface of a fabric, for instance with a coating, to give it sensing properties. A level-four modification would entail the use of multiple sensing fabrics to form a sensing composite.

All the sensors presented in the later sections of this document can be classified as having undergone either intrinsic or extrinsic modifications, a distinction that is discussed next.

2.1. Extrinsic modifications to enable sensing features

Modifications to enable sensing features can be introduced at any level of the fabric structure. Fabrics that are modified extrinsically, i.e. by attaching discrete or self-contained sensing elements, are usually referred to as 'electronic textiles' and they usually entail the superficial attachment of conventional electronic elements like resistors or integrated circuit chips (ICs) to the fabric. Coatings are another type of extrinsic or external modification to fabric substrates, i.e. fiber, yarn or woven fabric. Coating techniques found in fabric sensors include screen printing, ink-jet printing, electrodeposition, electroless plating, sputtering of thin films, vapor deposition, and thermoset coatings. Coatings alter the fabrics mechanics in their tensile, shear and bending properties [23]. This composite behavior is mainly due to the change in yarn mobility after the coating is applied [24]. The parameters that influence the consistency of coatings include the viscosity and uniformity of the coating material, and the tension, flexural rigidity [18], porosity and coating factor of the substrate [22]. The coating factor, C, gives a measure of the fabric openness, air permeability, degree of moisture resistance and adhesion [10]. The porosity P, or the ratio of the volume of voids contained within the boundaries to the total volume, is given by

$$P = 1 - PF, \tag{1}$$

where PF is the fiber packing factor. The porosity can be correlated to the permeability of the fabric by the modified Kozeny–Carman equation in the McGregor approach for textile assemblies [24]. The permeability of the fabric to roller knife coating with a blade angle of 1° can be calculated as

$$K = \frac{d_f^2}{16k_0}\frac{P^3}{(PF)^3}, \tag{2}$$

where d_f is the fiber diameter, and k_0 is the Kozeny constant, an empirical constant. Therefore, the permeability is dependent only on geometrical factors. It has been shown that a greater coating penetration depth prevents the yarns from rotating, stiffening the fabric and increasing flexural rigidity. Coating penetration can be modeled using Darcy's law for the flow through porous media, where the average velocity of the porous media is proportional to the vertical pressure gradient on the fabric substrate. The following calculation applies to the case of a coating blade of longitudinal dimension L, separated a distance $h(x)$ from the substrate, with upstream gap distance $h1$ and downstream distance $h2$. Assuming a Newtonian incompressible fluid coating flowing in the x-direction and no absorption of the liquid into the fibers, the vertical penetration of the coating can be calculated as [24]

$$z(x) = \sqrt{12\frac{KL}{P}\int_0^L \frac{(h1 - h(x))(h2 - h(x))}{(h2^2 - h1^2)h(x)^2}\mathrm{d}x}. \tag{3}$$

From this expression it can be observed that the penetration depth $z(x)$ increases by decreasing the gap distance and is independent of the coating speed and the viscosity of the coating. Depth, tension and viscosity have an impact on leveling, which refers to the critical step to achieving a uniform coating. If there is high surface tension, then the coating tends to crater generating microcracks [25] and if it has a very low viscosity it will sag, therefore leveling needs to have a balance of these quantities. These dependencies can be quantified using the leveling half-time $T^{1/2}$ of the striation marks produced during the coating application process [22].

2.2. Intrinsic modifications and design of fiber, yarn and fabric sensor properties

Fibers and yarns can be made of materials which are sensitive to different mechanical or chemical stimuli. Integration can become more intertwined as fibers and yarns get replaced by sensorized fibers and yarns down to the point of creating sensing elements out of fabric materials themselves (see section 3.4). It has been reported that passive and active electronic circuit elements can be made out of conductive yarn [25] and other soft materials [26]. These methods include embroidering and silk screening of conductive materials. Fibers themselves can be made of sensing materials by conventional and unconventional methods. Electrospinning, wet-spinning, self-assembly, carding, combing and die extrusion are some of the methods used to make fibers out of sensing materials. However, depending on the intended functionality, these intrinsic construction mechanisms need to also incorporate fabric parameters such as crimp, degree of fabric cover, density, flexural rigidity and thickness in order to suitably integrate the element into the fabric. These fabrication options can be customized as needed for a specific application.

A useful tool for the construction of smart fabrics is the reliable prediction of fabric properties using computational or analytical studies, especially when fibers with particular properties are available and can be assembled into fabrics. This can be done by using fabric models which include internal geometries of basic textile structures such as continuous-filament, staple yarns and the structures portrayed in figure 1. The majority of the models found in the literature describe only one level at a time, i.e. the fiber level or the yarn level, and not the entire set of hierarchies. However, an ideal model for many attributes requires information on multiple structural levels; e.g. a model of fabric permeability would need to include microporosity (fiber spacing), macroporosity (yarn spacing) [17] and porosity at the composite level, in the case of fabrics with plies. Broadly applicable multi-level models have not yet been fully developed.

Other parameters that should be considered for modeling of intrinsic fabrics include: number of fibers in the cross-section, torsional and bending curvature, friction coefficient, interlacing topology and geometry [17]. Simulation tools can greatly help in the task of predicting fabric qualities. Fabric computational models and simulations have been implemented with the following software: Wisetex [17], CAD [27], Visual C++ [28], weave-point based software [29], ANSYS [30], and Comsol Multiphysics [31], among others, where the modeling platform chosen was selected to fit the problem characteristics as well as the type of information available for describing the fabric structure and the interaction level(s) under study.

3. Materials, connections and fabrication methods for SFSs

SFSs are textiles which can react to a wide variety of stimuli, including mechanical, chemical, electrical, magnetic, thermal, and optical. The extent of complexity found in implementation varies significantly, and depends upon the methods of fabrication, the types of materials used, the types of sensing elements involved and the type of accompanying electronics used. Alongside the development of SFSs is a growing multidisciplinary research field that draws upon expertise in the fields of textile, materials, electrical, electronic, mechanical, and computer engineering. SFSs were initially manufactured using an adapted electronics or e-textiles approach, as presented in the following section. This is rapidly changing and it is increasingly common to see SFSs that have been fabricated out of new material combinations and new fabrication techniques. These new techniques frequently adopt elements from the flexible electronics industry [32], to suit the portability and compliance characteristics of fabric substrates.

3.1. Adapted fabrics: e-textiles fabrication methods

Advances in macroscale wearable technologies, such as eyeglasses with built-in digital or electronic displays, and the MIThrill project [33], which investigates advances in body-worn computing platforms, were precursors to the field of wearable electronic textiles. Electronic textiles (e-textiles) are a superficial way of integrating sensing functionality to fabrics, though some researchers make the term all-inclusive by including intrinsically developed sensing qualities. E-textiles usually entail the use of adapted conventional electronics with certain mechanical modifications to match the flexibility of fabrics. They have opened an entire new area of wearable technology and soft computing [34]. In these large-area systems, the sensors and electronic components are encapsulated and attached to the surface of a fabric. The sensors used are typically miniaturized conventional elements in addition to adaptations of off-the-shelf components such as microcontrollers, integrated circuit chips, resistors, capacitors and optical fibers [35]. These are directly inserted into fabric structures or they are first attached to small element interfaces such as socket buttons and sequins [34] for flexibility and ease of manipulation. In theory, for e-textiles, any kind of sensor which is sufficiently compliant, compact, lightweight, and ‘adaptable’ (e.g. made waterproof) can be incorporated into fabrics. These systems usually need customized hardware/software architectures [36] and need an optimized infrastructure for powering computational nodes [37] which are already able to perform digital or analog transmission through acquisition boards. An open area exists in the design of repeatable units or swatches of e-textiles for ease of manufacturability [38] and possible expansion to an industrial scale. Developments in wearable systems will progress beyond the superficial attachment of discrete components to fully integrated e-textiles and the associated broader field of Smart Fabrics.

In e-textiles, the conductive lines are established typically by: (1) manually attaching conventional wires or sewing conductive thread [26], (2) replacing non-conductive fibers with conductive ones [36], (3) machine embroidering of conductive thread [20], and (4) printing rigid [39] and stretchable [40] conduction lines (i.e. inks, polymers) using macroelectronics [25] and microelectronics techniques [41]. Connections to data acquisition systems are achieved by either mechanical [42] or electrical attachment mechanisms [43]. The remainder of section 3 will present e-textile technologies—connectors, interconnects, textile circuits and elements.

3.2. Connectors, interconnects and electrodes

SFSs cannot be implemented without the technologies associated with transmission and use of the sensed information. Fabric sensors need to be connected to other fabric circuit elements, to other sensors and/or to data acquisition circuitry. Some of the more common interconnection methods found in the literature are shown in table 2; they depend on the type of sensor and the application. Connectivity to data acquisition is one of the biggest challenges of SFTs; given each application has its own particular demands. For instance, the requirements for sensor mechanical stability in a garment are very different from those of a fabric sensor placed on a piece of furniture for environmental monitoring [44]. In the first case, the sensing element has to be firmly and elastically attached to data connectors as well as interconnection lines. If the signal is being sent by a telemetry method, interconnects need to robustly

Table 2. Examples of conductive yarns and fibers used in SFTs.

Material	Resistance per unit length	Characteristics	Mesh or core	Advantage	Disadvantage
Copper wire/tinsel wire[a]	~21 Ω cm^{-1}	Flattened and twisted with cotton, nylon, Nomex or Kevlar thread	Polyester, copper (tinsel)	Robust connection, conventional	Difficult to integrate into clothing
Stainless-steel staple fibers[b]	BK 50/2 (~50 Ω cm^{-1}, broken)	Composite-broken bundles (sewable)	Blended with polyester	Strength, resistance to corrosion, biological inertness	Difficult to attach to existing electronics components
Aracon-MCAF metal clad aramid (polymer) fibers[b]	~0.001 Ω cm^{-1}	Composite core: Kevlar cladding metal: Ag, Ni, Cu, Au, Sn (24–200 fibers)	Kevlar	Light, flexible, stable, high temp resist. Can be soldered like normal wire	Conformability in integration with fabrics
Metallic organza[b]	~10 Ω m^{-1}	Composite fiber: Ag	Cloth	Yarn level integration	Challenging connections to data acquisition
Silver thread[c]	~85 Ω ft^{-1}	Composite-2 ply Ag fiber, nylon	Fabric	Machine sewable	Sensitive to humidity and aging
Strips of conductive fabric[d]	Varies	Carbon based, PPy, PEDOT, PANi, metal-plated (i.e. Cu, Ni)	Coated or intr. conductive fabric	Can be glued, sewed to other fabrics	Compatibility and specialty of connectors
Thin Kapton sheet[e]	Varies	Stacking of thin film layers including silicon nitride	Kapton	Enables flexible electronics techniques	Cannot be machine sewn

[a] Reference [54]. [b] Reference [26]. [c] Reference [55]. [d] Reference [56]. [e] Reference [57].

carry the signal with minimum losses to the transmission board or the processing electronics. In the case of a fabric that is attached to furniture, interconnects are not required to withstand wear and tear and can even be composed of modified conventional electronics.

Typical interconnects found in e-textiles that are applicable to all the SFTs are the conductive yarns (table 2). There is a wide variety of these yarns, ranging from super-fine metal threads wrapped around a non-conductive core fiber, to fibers with a metal core covered by non-conducting yarns [45], to fibers made from intrinsically conductive materials. It has been suggested that conductivity can be increased by two or three orders of magnitude if the substrate undergoes galvanization [46]. Yarns are typically hand sewable and for the most part not machine sewable due to additional mechanical stretching and bending requirements [20]. Stretchable fabric electrodes can be constructed by weaving stretchable fibers [47], knitting conductive fibers [40], doping polymers, i.e. polyurethane with conductive particles [48], and conductive coating of stretchable fabric structures [49]. Other interconnection techniques include the use of conductive paints, pastes [39], glues [50] and adhesives [51]. Some of these materials also possess sensing properties and are discussed in section 4.2.1.

The adhesion of interconnects to the fabric sensing element and to the acquisition electronics depends on the composition of the sensing element as well as the application requirements. The three common categories of bonds for connectors and interconnects are mechanical, physical and chemical. Mechanical connections entail the gripping or joining of components to conduction lines. Physical connections include microwelding [26], thermoplastic adhesion [41], mixed conductive polymer adhesion [44], joint soldering and electroplating [52]. Examples of chemical connectivity include covalent chemical bonding, acid oxidation, hydrogen bonding, and plasma pre-treatments [53]. Other effects similar to those found in conventional electronics also appear in smart fabrics. Induced capacitance in adjacent fabric interconnects and signal propagation directionality are instances of these effects [54].

Connectors and wires to added circuitry remains an open field of research due to the diverse application environments; each solution is customized and almost unique. Table 3 summarizes the most common techniques used for connecting sensors to circuit elements, sensors to conduction lines, and circuit conduction lines to electrodes and to interfaces for data acquisition. The application of these techniques depends on the type of element involved and their functionality in terms of permanent or removable interconnections.

Figure 2 illustrates some of the connection techniques used for fabric circuits and transducers. Knitted, woven fabric data buses can be fabricated using conductive yarns. These can be interfaced with conventional connectors. Using some of these wire interconnection techniques, a soft fabric cable can end in a conventional USB or in a buckle-type connector [64].

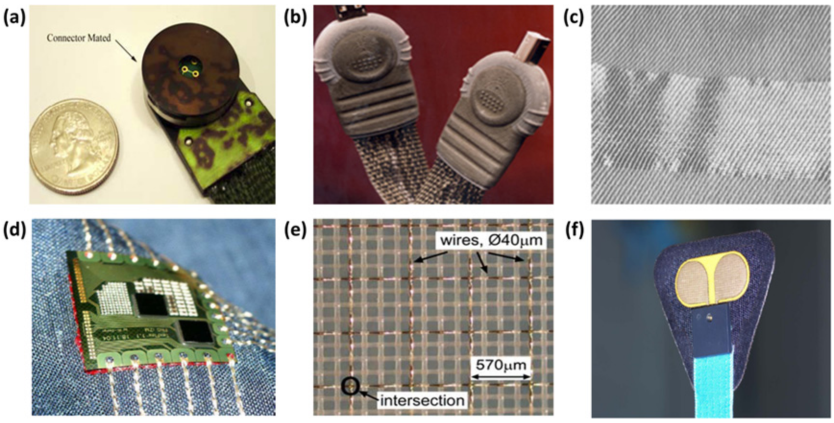

Figure 2. Different connection techniques and electrical connectors for fabrics. (a) Universal fabric snap fastener. Reproduced with permission from [40]. Image courtesy of the US Army. (b) Fabric USB connector. Reproduced with permission from [3]. Image courtesy of the US Army. (c) Stainless-steel wires woven in fabric and used as bus for electronic system. Reproduced with permission from [2]. Copyright 2005 IEEE. (d) Flexible electronic test module connected with embroidered conductive yarn. Reproduced with permission from [42]. (e) Petex (Sefar)—embedded copper wires with insulation varnish. Reproduced with permission from [51]. (f) Polyurethane mechanical connector for EMG sensor. Reproduced with permission from [42].

Table 3. Connection techniques for SFTs.

Technique	Types of fibers	Connection to	Type of bond	Strength	Typical connector
Miniaturized electronic connectors[a]	Wires, threads require a pre-connection	Other wires, acquisition system	Mechanical	Strong	Pin socket
Mechanical gripping, crimping[b]	Wires, conductive fibers	Fabrics, electronic components	Mechanical	Medium/flexible	Gripper snaps, sewable ring magnets
Soldering and wire bonding[c]	Solderable metals	Electronic components, wires	Physical/chemical	Strong/brittle	Soft alloys of Pb, Sn, Ag
Microspot-welding[d]	Stainless steel	Leadframes, (with threaded connections)	Physical	Strong/brittle	Cu, Sn, Pb
Conductive epoxy[e]	Any type	Wires	Electrical/mechanical	Strong	Doped epoxy
Conductive paint[f]	Any type	Sensors, fibers and fabrics	Electrical	Weak/brittle	Silver paint
Machine-printed line[g]	PEDOT, silver	Electronic components	Electrical	Medium	Printed PEDOT line
Screen-printed line[h]	Silver conductive paste	Electronic components	Electrical	Weak	Screen-printed line
Conductive polymer[i]	Any type	Sensors, fibers and fabrics	Mechanical/electrical	Medium–weak/very flexible	Conductive adhesive
Interposer pad with conductive adhesive[j]	Copper wires	Fabric	Electrical/mechanical	Strong	Interposer pad
Lamination[b]	Textile surface	Fabric, fibers, electronics	Mechanical/electrical	Strong	Non-conductive thermoplastic elastomer

[a] Reference [34]. [b] Reference [25]. [c] Reference [58]. [d] Reference [26]. [e] Reference [59]. [f] Reference [60]. [g] Reference [61]. [h] Reference [51]. [i] Reference [62]. [j] Reference [63].

3.3. Textile circuitry

'Textile circuitry' refers to the methods and techniques used to fabricate circuits on fabric substrates or fabric circuit boards (FCBs). It is a necessary component of a fully integrated SFT. SFSs usually require a degree of processing, making circuit techniques essential. Even if the processing is done off-board the signals need to be successfully carried to the acquisition interface. These techniques are also important when incorporating distributed sensing or sensing with multiple sensing elements.

An important step in textile circuitry is to find textiles and yarns that are suitable for use with fabrics and methods which are non-corrosive and non-destructive to fabric structures. One

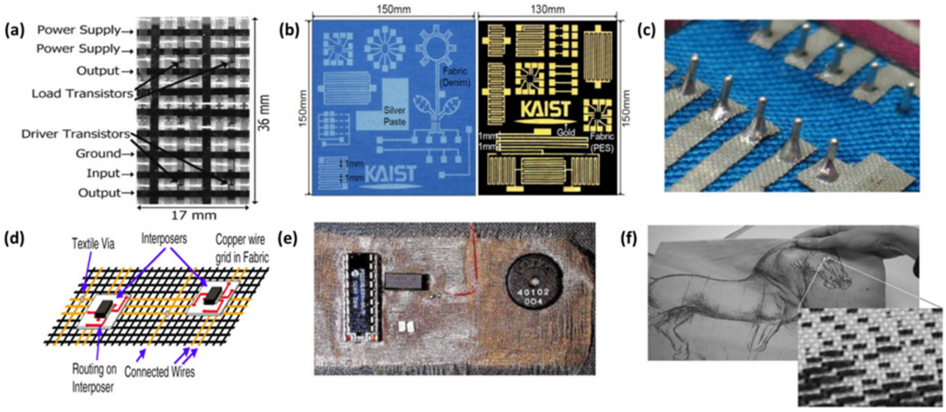

Figure 3. Different types of fabric circuits. (a) Woven circuit made from active component fibers, logic circuit. Reproduced with permission from [57]. Copyright 2004 IEEE. (b) Silk-printed (left) and sputtered (right) flat circuit technology. Reproduced with permission from [39]. Copyright 2009 IEEE. (c) Solder joints on a fabric PCB, laser cut and ironed on. Reproduced with permission from [34]. Copyright 2007 Springer. (d) Electronic circuit on fabric with interposers and copper connections. Reproduced with permission from [51]. (e) Metallic organza circuit with adapted elements. Reproduced with permission from [68]. Copyright 1997 IEEE. (f) Machine woven circuit. Reproduced with permission from [69]. Copyright 2002 IEEE.

primary method which was introduced in e-textile techniques is called e-broidery [26] which consists of machine controlled embroidery using conductive thread. It is used to stitch patterns that define circuit traces, component connection pads or sensing surfaces. The design of stitch patterns (circuit patterns) can be done using CAD. Weaving can also be computer assisted. The on-fabric circuit is designed to have a low power consumption rate and high input impedance, which is opposite to the conventional requirement of low impedance for component interconnections. Several available yarns (table 2) can be used for connections and circuit elements; these include silverized yarns, stainless-steel thread, NiCr, FeCr alloys, titanium, gold or tin. An ideal yarn or textile for fabric would have completely adjustable electrical properties and would maintain those properties while being sewn, flexed, and worn. Another technique for fabricating FCBs is to iron on a solderable (Sn/Cu-coated) circuit to the fabric [34]. Once the circuit is attached to its backing cloth, it can be soldered like a traditional printed circuit board (PCB). Flexible conduction lines could also be made of any suitable conductive ink and conductive polymer or conductive solutions. Techniques which make these possible include both thick printing processes as well as thin printing processes. An example of a thick film process is silk screening, where an adhesive conductive ink is applied to the open areas of a mesh reinforced stencil allowing the ink to pass through the mesh onto the substrate fabric [65]. A thin film process, i.e. sputtering, is used to form high resolution (micrometer scale) circuits on fabric. The fabric, kept at 150 °C, needs to be placed in a vacuum chamber with an inert gas like argon and needs a shadow mask to form the circuit patterns. Table 4 presents a summary of the techniques available for building FCBs.

A final integration of sensing elements with electronics, chips and data acquisition will depend on the type of application and the type of circuit board technique used. Some of these concepts are illustrated in figure 3. Interposers resemble the island concepts of flexible macroelectronics in that they try to provide distributed rigid connectors while allowing the overall structure to be flexible.

3.4. Textile circuit elements

Textile circuit elements can be miniaturized and encapsulated to be adapted to the fabric structure. Small off-the-shelf components can be sewn into the conductive lines on the fabric [26] either directly or by using holders, sockets or sequins which can be attached to the fabric by different methods [34]. Sequins can be sewn into conductive thread lines while holder leads can be soldered to a fabric FCB, which is a pre-treated solderable fabric. These sewing tabs add a negligible amount of resistance to the circuit. The resistance across a typical fabric tab to stitching joint is less than 1 Ω. Components can then be easily attached to the e-textile, providing a convenient platform for the wiring of textile circuitry [38]. The same techniques can be applied to microcontrollers and other circuit elements. A good complementary implementation of this approach is to use gripper snaps or to staple them in place using pressure—this allows mobility while still in contact, but restrains motion. Fabric switches are another way of connecting the electronic elements and can be made by putting two pieces of conductive fabric together but separated by a piece of felt with a hole in it. When the switch is pressed the two pieces of conductive fabric contact one another through the hole making an electrical connection [34].

Electronic elements can be made out of conductive thread [26] by sewing thread fibers in patterns, possibly with multiple crossings, to achieve desired electrical properties. Conductive properties can be given to thread by several techniques before and after the thread manufacturing process, as depicted in figure 4. Each of these can be tailored to become a circuit element with desired characteristics.

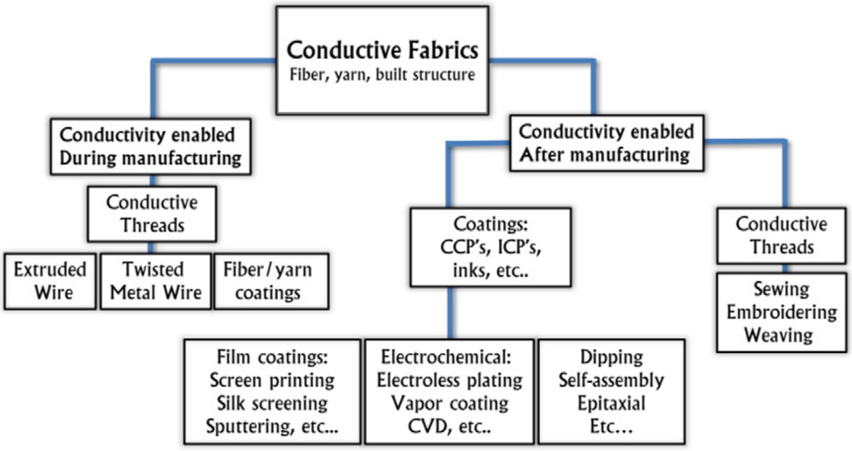

Figure 4. Techniques to enable conductivity in fabrics [51].

Table 4. Fabric circuit board fabrication techniques.

Type	Characteristic elements	Advantages	Disadvantages	Flexibility	Connection
Couched circuits[a]	Conventional wires insulated by a layer of non-conducting thread	Uses conventional wires	Lacks flexibility	Low	Mechanical attachment to conventional connector
Woven circuits[b]	Alternating conductive thread and insulating fibers	Can be automated, or made in a hand loom	Connection of electrodes to PCB	High	Mechanical attachment to conventional connector
Knitted circuits[c]	Conductive fibers on non-conductive knit	Machine/automated	Additional yarn requirements	High	Varies on conductive thread chosen
Embroidered circuits[d]	Conductive yarn sewn into fabric	Flexibility	Needs to be crafted	Medium	Snap grippers
Conductive ink circuit[e]	Patterned conductive ink	Can be masked	Endurance	Medium	Conductive glue/liquid conductive ink
Fabric PCB[a] (iron on)	Layers of conductive and non-conductive fabric	Flexibility, can be soldered to wires	Elaborate handcrafting	High	Soldering terminals
Thick film process[f]	Silk screening of conductive ink, glues and conductive polymers	Straightforward path manufacturing	Tendency to brittleness	Medium	SMA soldered connectors
Thin film process[f]	Sputtering of Au particles	High resolution of paths	Specific fabrication environment	Medium	SMA soldered connectors

[a] Reference [34]. [b] Reference [51]. [c] Reference [66]. [d] Reference [26]. [e] Reference [67]. [f] Reference [65].

Another very common technique entails the application of metal or conductive polymer coatings to the fabric surface. Laminating techniques are also used, including those adapted from conventional and flexible electronics [39]. Passive elements can be formed with conductive inks and polymers. Resistors (i.e. 2.8 Ω mm^{-2}), capacitors (i.e. 1 pF to 1 nF) and inductors (i.e. 500 nH–1 μH at 10 MHz) can be made by planar printing techniques such as screen printing or sputtering metal inks onto fabric substrates such as cotton, polyester, silk, wool, polyacrylonite and fiberglass fabric [39, 65]. It has also been shown that resistive elements can be made by adjusting the dimension of an already coated conductive polymer fabric [70]. In the case of transistors, the core of a metalized yarn can be used as gate while source and drain

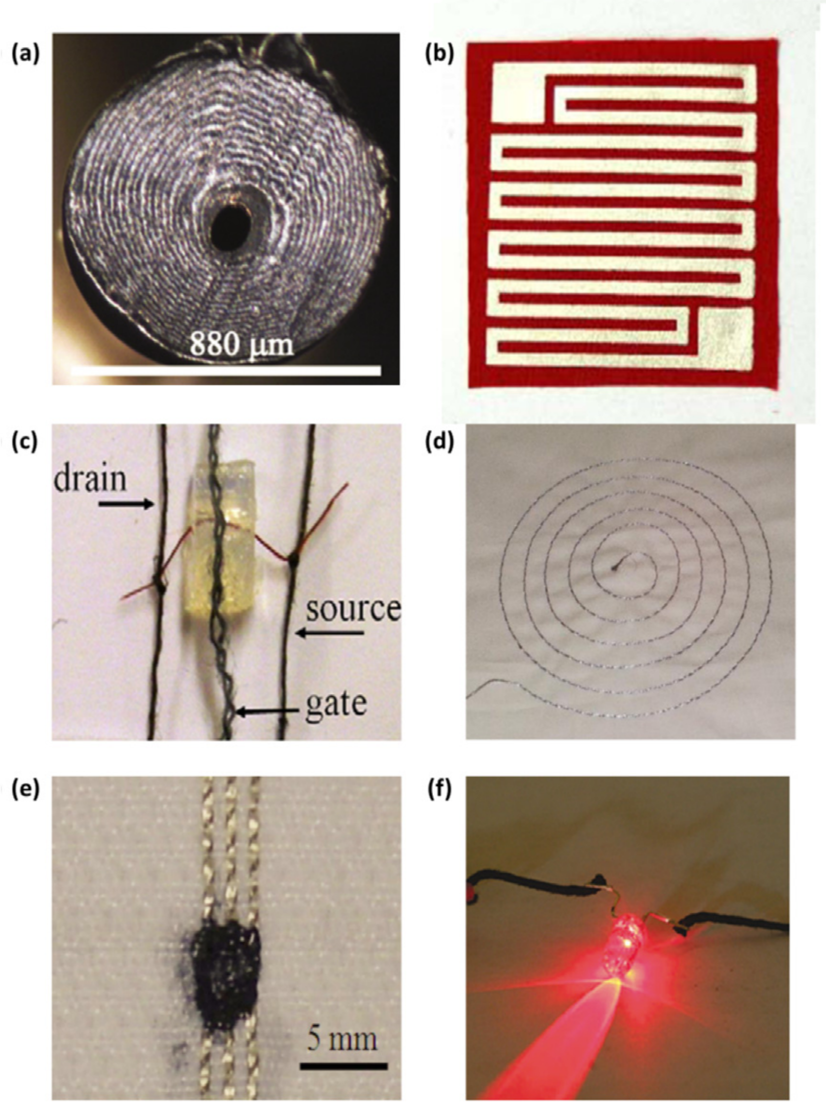

Figure 5. Examples of fabric circuit elements. (a) Hollow core fiber with the first electrode lining the inside of a hollow core and a second plastic electrode wrapping the fiber from outside. Conductive layer is a polyethylene based carbon black, and the dielectric layers are made of low density polyethylene (PE) [76]. (b) Resistor made by planar printing technology. Reproduced with permission from [39]. Copyright 2009 IEEE. (c) Organic transistor on a cotton fiber. Reproduced with permission from [77]. Copyright 2011 Elsevier. (d) Embroidered stainless-steel inductor. Reproduced with permission from [78]. Copyright 2004 Elsevier. (e) Top view image of PEDOT based charge storage device on a textile substrate. The PEDOT coats are placed over three, silver-coated polyamide yarns interwoven in the substrate's weft. Reproduced with permission from [79]. Copyright 2009 American Institute of Physics. (f) Fabric conducting element—LED emission with the current passing through a SWNT/cotton yarn. Reproduced with permission from [80]. Copyright 2008 American Chemical Society.

contacts can be made by depositing metals or polymers by evaporation or soft lithography [71–74]. Transistors can also be fabricated on strips of Kapton which can later be interlaced into a textile substrate [57]. An illustration of some of the fabric elements can be seen in figure 5. This figure shows the variety of possibilities when building a textile electronic element. Other examples include building thin film transistors on Kapton thin flat fibers [57] and piezoelectric films on textiles [75].

Due to increasing interest in miniaturization and compliance of components, fibers turn out to be a very appropriate target for standalone element construction. Conductive polymers can be used to make fibers with sensing properties and use them to build fabric structures. Such is the case for soft capacitor fibers [81] where multiple layers of carbon based polymer/polyethylene are drawn over an air/copper core.

Other functionalized fibers are made by wet-spinning of polyaniline (PANi) [82] yielding a temperature sensitive fiber; by using carbon nanotubes (CNTs) to coat cotton yarns which are humidity sensitive [80]; or by low temperature hydrothermal decomposition to grow piezoelectric nanowires into arrays that are capable of producing sufficient power to operate real devices [83]. Conducting fibers can also be intrinsically grown. This is the case of the CNTs shown in figure 5; they were grown by electrophoretic deposition into forming yarns. These can subsequently be woven into textiles to either increase their mechanical strength or to increase the conductivity if they are used as conductive lines.

Table 5. Insulating techniques.

Type	Characteristic insulation	Advantages	Disadvantages
Embroidery or couching[a]	Insulating thread covering conductive thread	Good flexibility and fabric-like texture	Not well insulated from humidity
Fabric paint[a]	Flexible paint spread over conductive line	Good mechanical stability	Not good resilience
Non-conductive fibers/fabric[b]	Dense fabric layer on top of elements to be insulated	Good flexibility	Not insulated from humidity
Lacquers[c]	Waterproofing sprays	Ease of use	May be brittle
Interface paste[d]	Waterproof	Screen printable	UV/heat cured
Rigid plastic encasing/glob top[e]	Typical electronics insulation	Excellent insulation from electricity and humidity	Poor flexibility and compliance to substrate
Molding[f]	Rigid encasing	Allows defined geometry	Requires localized flat fabric
Hot melt[g]	Thermoplastic material encasing	Inexpensive	High thermal stresses

[a] Reference [34]. [b] Reference [26]. [c] Reference [87]. [d] Reference [88]. [e] Reference [51]. [f] Reference [89]. [g] Reference [90].

Mixtures of carbon nanotubes and inherently conductive polymers can have increased conductivities—a mixture of PANi–CNT composite fiber with 750 S cm^{-1} has been reported. Other mixtures such as polyaniline single-wall nanotubes (PANi-SWNT) [84] and PANi-MWNT [85] have also been reported to increase the overall conductivity. Other nanofillers used to increase conductivity besides CNTs and SWNTs are metal oxide nanoparticles (i.e. TiO_2, ZnO) which also have antimicrobial qualities, and carbon black nanoparticles which have a high chemical resistance. Furthermore, there can be fibers with conventional electronic features such as antennas [78], batteries [166], powering elements [86], and other electronic functional units.

3.5. Encapsulation techniques and environmental requirements

Insulation of conductive threads is important to prevent shorts and to preserve the quality of the textile. It can be achieved using different methods depending on the requirements of the intended application. To insulate a single fiber when there is not a stringent requirement that humidity be repelled, a tubular intarsia sewing technique is appropriate. It consists of a non-conductive thread sewn around the conductive thread producing a very compliant connection. Another way of insulating threads is to apply fabric paint on the thread that needs to be insulated [34]—though not as flexible as the couching technique it is a straightforward method. Conductive threads and conductive fabrics can also be insulated by sewing a piece of non-conductive thread on top of them, although this last approach is not suitable for complex circuit configurations. For the insulation of single electronic components, traditional epoxies and plastic insulators can be employed. For instance, microcontroller fabric-soldered joints are created by soldering the leads of the microcontroller to a fabric PCB, then both the solder joints and the microcontroller are encapsulated in epoxy [34]. Molding techniques can also be applied but the region on the fabric where it is applied needs to be flat. However, this is feasible for small covering areas, as the molding materials are usually dense fillers with reduced resilience. Transfer molding, a process which is very common in the electronics industry, entails heating of a two part epoxy with SiO_2 filler particles which is pressed or transferred into a mold with the electronics. Glob top encapsulation is a similar process by which epoxy or silicone are dispensed with a syringe and cured afterwards [51]. Alternatively, hot melt encapsulation uses thermoplastic materials which are kept above their melting temperature and cooled down once they have been molded. Another technique that has been proposed for encapsulating components is the plastic threaded chip carrier (PTCC) [26]. This is designed to be stitched or woven into a fabric circuit and therefore has long and flexible conducting leads which connect to the threads. The threads that leave the package are microspot welded to the lead frame stubs and then the entire structure is sealed in a plastic carrier. These packages can be washed without harm to either their internal electrical properties or their connections to the substrate and other components.

Table 5 shows a summary of the insulating techniques being used for smart textile connections.

3.6. Coating materials and methods

Polymer materials used to bestow sensing properties on fabrics can have different physical sensing mechanisms. These can be of piezoresistive, thermoresistive, magnetoresistive, chemoresistive, and photoresistive origin [91], among others. Piezoresistive coatings typically entail either conductive particle polymers (CPPs) or inherently conductive polymers (ICPs). CPPs can be made either of organic or inorganic constituents. Organic (i.e. carbon) particles and inorganic (i.e. metal) particles can be mixed in with polymeric matrices; these are also referred to as conductive doped polymers. It would be reasonable to assume that polymers doped with metal particles have better conductivity than those doped with semiconductors. However, carbon doped polymers based on increased-surface particles such as nanoparticles and nanotubes can achieve very high conductivities, i.e. SWNT-coated polyester/cotton can have a conductivity of 125 S cm^{-1} [92]. Inherently conductive polymers or ICPs are those which do not need to be doped to achieve conductivity. Most ICPs are prepared via chemical or electrochemical oxidation of the monomer in solution or in the vapor phase [93]. Examples of these polymers are: PANi, polypyrrole (PPy), polyacetylene, polythiophene, PEDOT–PSS (poly(3,4-ethylenedioxythiophene)-(4-styrenesulfonate)), poly(p-phenylene), poly(p-phenylene vinylene) and poly(para-phenylene). Conductivity in most of these polymers is based on a pi-conjugated system which is formed by the overlap of carbon p_z orbitals and the presence of alternating single and double bonds in the polymer chains. The degree of conductivity depends on the oxidation state of the main chain as well as the degree of protonation of nitrogen atoms in the polymer backbone [94]. Their conductivities range from that typical of insulators $<10^{-10}$ S cm^{-1} to that typical of semiconductors $<10^{-5}$ S cm^{-1}. These polymers can achieve a higher conductivity when doped with other particles—e.g. iodine doped acetylene has a conductivity of about 10^5 S cm^{-1}. Layer combinations of conductive elements may also increase the overall conductivity, as is the case, for instance, for PEDOT-tosylate vapor deposited onto a conformal layer of Au nanoparticles on a cotton fiber [77].

CPPs and ICPs are categorized as electroactive polymers (EAPs), which means that besides the sensing properties they also possess active properties, i.e. actuating properties. EAPs are organic materials capable of responding to an applied electrical stimulus with a change of shape and/or dimensions. The EAPs used in sensing applications applicable to fabrics can be found in [89]. They can be classified into two categories based on their activation mechanism: ionic or electronic. Ionic EAPs are activated by induction of ions or molecules and electronic EAPs are activated by an external field and by Coulomb forces [91]. Polyelectrolyte gels, ionic polymer–metal composites and carbon nanotubes are examples of the first category. Piezoelectric, electrostrictive, electrostatic, ferroelectric and dielectric elastomers are examples of the second category.

Methods for applying coatings onto fibers and fabric depend on the consistency of the materials being applied. Liquid polymers can be applied to fabrics by metal plating methods (Cu, Sn, Ag), electroplating, electrochemical deposition [44], sputtering (Au, Cu) [95], electrospinning, printing, ink-printing [96], microcontact printing [97], spraying [98], wet-spinning [10], or by silk screening [39]. Thicker coatings such as carbon loaded pastes or other organically doped polymers can be applied by hand [99] or by masking techniques and screening, dip-coating [22], soft lithography [5], embossing, or imprint. Many other types of coatings can be applied to fabrics—these include magnetorheological, electrorheological, visible light sensitive/photoresponsive, self-oscillating, electrostrictive, pH sensitive, humidity sensitive, and electrochromic [100]. Commercially available fabrics constructed using some of these techniques include tin- and copper-coated polyester taffetas and fused silica plain weaves [49].

4. Smart fabrics sensors

Fabric sensing concepts have been explored for use in many different capacities and with a huge variety of applications in mind. However, no standard fabric elements or components have been recognized as the most promising candidates for establishing the foundation of the field. Using charts, figures and summary tables, this section will illustrate the more common sensing mechanisms found in fabric sensors.

4.1. Pressure and force sensors

4.1.1. Capacitive. Capacitive fabric sensors are usually designed for pressure and tactile sensing applications. Many different designs and materials have been tested and prototyped for application to fabrics. They range from adapted electronics to intrinsically modified materials, yet all have in common a dielectric element that separates two electrodes. In adapted electronics, e-textiles employ conventional capacitors that are attached to fabrics using customized methods. Usually, an adapted capacitor will be mounted on a frame which can be sewn, snapped or glued to a fabric substrate and soldered to other electronics or wires. Fabric capacitors can also be constructed from compliant conductive materials acting as electrode plates that are separated by dielectrics and spacers of various origins. The plates can be woven [101], sewn [102, 103], and embroidered in the case of conductive thread/fabrics, or they can be painted, printed, sputtered, and screened in the case of conductive inks [39], polymers and paints [67]. The dielectrics used are typically synthetic foams, fabric spacers, and/or soft polymers. Capacitive fibers can also be manufactured using techniques similar to those found in flexible electronics, such as a silicon fiber sputtered with metals [104]. Fabric sensor capacitors can be used as a single element but they can also be placed in arrays to obtain distributed measurements [55]. In both cases they usually follow the classic capacitor construction. In arrays, capacitance is measured at intersecting rows and columns of electrodes [104], which are in turn connected to multiplexers and microcontrollers to DAQ systems. Other distinct capacitive sensing mechanisms include switches, tactile contact and those which use the human body capacitance [95]. Table 6 presents examples of the different ways in which capacitive sensors can be made out of compliant materials.

Next, we consider compressible foams, fabrics and polymers. These materials have several drawbacks, including creep, poor resilience, signal drift, and hysteresis. Compensation for these problems depends on the intended usage and the acceptable operating range. Capacitive fabric sensor outputs are typically non-linear, with regions of approximate linearity (table 6). Foams typically have more hysteresis than other 3D fabric spacers, but negligible long term drifting and creep [107]. Humidity and temperature effects have not been fully studied across the range of sensors discussed above. Studies by Meyer *et al* [55] suggest that there is a change in capacitance between wet and dry spacers, with wet spacers exhibiting an increase in capacitance. Robust insulating methods and compensation need to be developed to account for these issues. Capacitive fabric sensors can be built at many scales, from microcomponents to large sensing areas (figure 6).

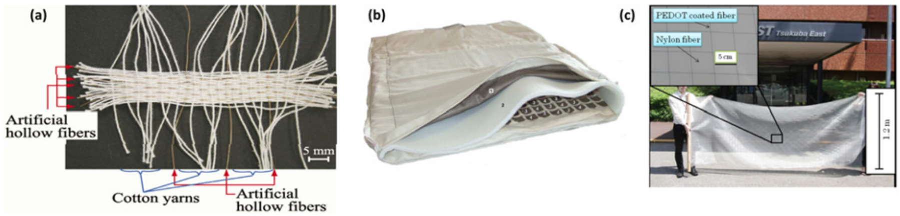

Figure 6. Capacitive based pressure sensors. (a) Artificial pressure sensitive hollow fibers interwoven with conventional cotton yarns. Reproduced with permission from [104]. Copyright 2007 IEEE. (b) Classical structured embroidered electrodes where 1—common electrode, 2—spacer, 3—sensing electrodes and 4—electrodes switched to ground. Reproduced with permission from [55]. Copyright 2010 IEEE. (c) Meter scale PEDOT:PSS and UV-curable adhesive-coated fiber capacitive array. Reproduced with permission from [105]. Copyright 2011 IEEE.

Table 6. Pressure sensing fabric capacitors.

Type	Elements[a]	Meas. variable	Sensitivity	Pressure range	Size
e-broidery[b]	c—conductive thread, d—cloth	Electrical contact	Switching voltage threshold of a CMOS logic buffer	Contact sensing	mm–cm range
Patterned electrodes[c]	c—conductive ink, d—synthetic foam	Thickness compression	0.214 V pF^{-1} (pixel) for Cf = 3.37 pF Cf = 25.2 fF to 12.8 pF	Max 13.6 kPa	Core area: 32 mm^2, 64 × 64 pixels
Embr. electrodes/coated fabric[d]	c—silver-coated woven, conductive thread, d—textile spacer	Thickness compression, $t = 6$ mm	0.192 pF (N^{-1} cm^{-2}) with 20%–30% hysteresis error	0–12 N cm^{-2}	Core area: 35.1 cm × 40.5 cm Pixel = 2 × 2 cm
Surface touch[e]	c—PEDOT, d—Nylon	Capacitance coupling between fingers and c-film	0.02 pF mm^{-1}, w.r.t. object width	0–2 pF	Core: 470 μm diameter Pitch = 5 cm
Laminated electrodes[f]	c—thin film deposited metals, d—parylene substrate–silicone rubber	Capacitance change at intersecting points	0.01ΔC mN^{-1}	0–50 mN	Diameter = 250 μm thickness = 40 μm
3D textile capacitor[g]	c—conductive fabric, d—3D textile	Thickness compression tmin = 5.5 mm	2 pF N^{-1} cm^{-2} mean, 1.25 pF N^{-1} cm^{-2} for (0.1–0.4 N cm^{-2})	0–0.75 N cm^{-2}	Sensor area = 3 × 3 cm^2
Croslite™ capacitor[h]	c—silver-coated textile, d—PCCR (proprietary closed cell resin)	Thickness compression $t = 5$ mm	0.05 pF N^{-1} cm^{-2}	0–30 N cm^{-2}	10 mm × 10 mm

[a] For the element column: c stands for conductive element, d stands for dielectric element. [b] Reference [26]. [c] Reference [67]. [d] Reference [55]. [e] Reference [105]. [f] Reference [106]. [g] Reference [107]. [h] Reference [103].

4.1.2. Resistive. Finding a correlation between pressure and electrical resistance is another way of constructing fabric pressure sensors. These types of sensors can be manufactured at all fabric structure levels, i.e. yarn, fiber or coatings. Pressure applied to a grid of intersecting embroidered conductive yarns produces a change in the contact resistance of intersecting yarns. The location of the pressure applied on the fabric can be identified by detecting the position where the change of the resistances occurs [108]. A similar sensing principle is found when conductive elastic yarns are woven so that the contact resistance between them increases under an applied pressure [109]. Combinations of conductive yarns and sheets of conductive textiles are also used in making pressure sensing units. An example of this is a Cu–Ni electroplated polyester conductive fabrics with layers separated by a net that forms a grid of sensing regions which behave as discrete electrical switches [56]. When pressure is applied the plates on opposite sides of the net come into contact, generating a contact event. The number of regions activated will give a measure of the pressure being exerted. Changes in pressure can also be detected by electric current [110] and impedance tomography [111]. Tangential traction can be measured by shear resistive contact [112]. Several of the resistive pressure sensing mechanisms found in the literature are shown in table 7. Electrical resistivity can be quantified by measuring resistance, conductance or resistivity changes.

Foams, although elastically hysteretic, can be made pressure sensitive by applying surface coatings using conducting polymers; the application of pressure produces a change in conductance due to an increase in volumetric contacts [94].

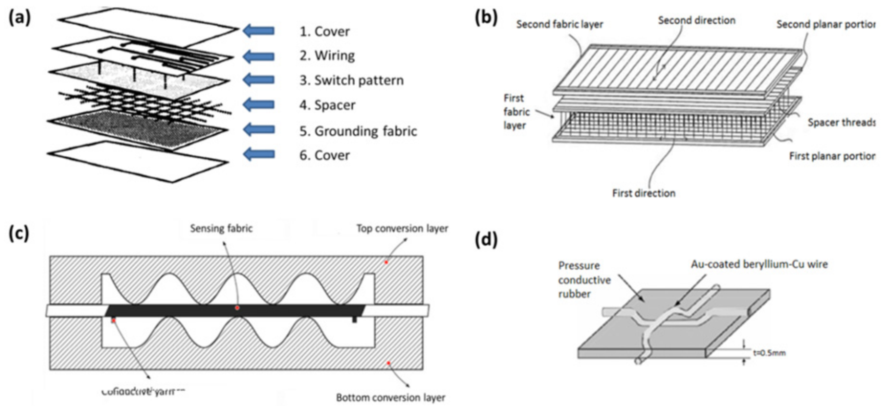

Figure 7. Pressure sensitive fabric sensors. (a) Tactile pressure sensor based on resistive switches. Reproduced with permission from [56]. Copyright 1996 IEEE. (b) Pressure sensor based on electric current in Elektex's fabric sensor technology. Reproduced with permission from [110]. Image courtesy of Eleksen Ltd. (c) Tooth-structured resistive fabric pressure sensor [121]. (d) Pressure sensitive rubber with beryllium copper Au-coated electrodes. Reproduced with permission from [113]. Copyright 2004 IEEE.

Table 7. Fabric pressure sensors based on resistive mechanism.

Type	Elements	Sensitivity	Pressure range	Size	Characteristic
Switch tactile sensor[a]	• Plated fabric Cu, Ni • Base Polyester Net e192	Threshold at 500 g mm^{-2}	70–500 g mm^{-2}	Sensing cell: 2.3 mm × 4.35 mm	Sensing mechanism is upon number of sensing cells activated
Tooth-structured[b]	• Conduct. fabric • Soft elastomer base	$>2.98 \times 10^{-3}$ kPa^{-1}	0–2000 kPa	$10 \times 16 \times 4.8$ mm^3	Teeth produce a strain in the fabric under applied pressure
Polyurethane foam[c]	• PPy • Polyurethane	0.0007 mS N^{-1}	1000–7000 N m^{-2}	1.7 cm × 1.7 cm × 1.3 cm	Conductance increases with compressive stress
Conductive rubber based[d]	Carbon polymer with beryllium Au-coated copper wire	0.25 kΩ MPa^{-1}	0–0.2 MPa	3 mm × 3 mm	Resistance changes with applied load
QTC—Ni based[e]	Pressure sensitive composite	$\sim 10^6$ Ω/1% compression	25% compression	Diameter = 5.5 mm, thickness = 2 mm	Switching behavior

[a] Reference [56]. [b] Reference [108]. [c] Reference [94]. [d] Reference [113]. [e] Reference [114].

Other ways of fabricating pressure sensitive fabrics is to coat them with pressure sensitive polymers, such as the ones obtained by embedding ferroelectret chippings (e.g. small pieces or chips of piezoelectric material) in conductive silicone [115, 116]. These composites generate electric signals upon touch [117]. Other types of fillings which enable pressure sensing include carbon based particulates [113] and inorganic particles. Electric conduction can also occur without physical conductive particle contact or percolation. Such is the case for particles with sharp surface protrusions, these enable Fowler–Nordheim quantum tunneling [114]. Some of the fillers for the quantum tunneling composites (QTCs) include Ni, Cu, Ag, Al and Fe [118]. These types of composites can be used to measure electric current intensity under applied pressure. Other mechanisms used to implement resistive pressure detections schemes are shown in figure 7. Commercially available capacitive and resistive devices for pressure sensing are found in various fields, especially in the medical field [55]. Other mechanisms to sense pressure with fabrics include the resonant frequency of loop antennas [119] and light intensity changes in fiber optics [35]. Fabric pressure sensors can detect normal loads [55], tangential loads [120] and shear loads [119].

4.2. Fabric strain sensors

Fabrics can be made sensitive to mechanical strain by different methods at the different levels of the structure hierarchy; fibers can become strain sensitive when made out of strain sensing materials, yarns can have different topologies by interlacing sensing fibers with non-sensing fibers and fabrics can be modified by introducing sensing fibers or by applying a coating with strain sensing materials to achieve the same goal. Electronics involved in the measurements are usually not as involved as those for capacitive measurements; therefore prototype implementation is relatively simple when compared to other fabric sensing technologies.

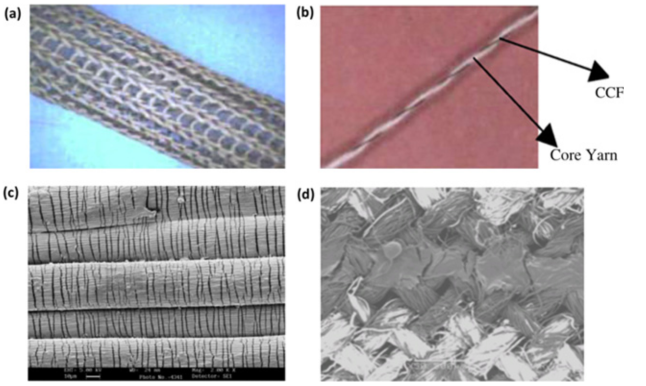

Figure 8. Strain fabric sensors. (a) Stainless-steel knitted fabric sensor. Reproduced with permission from [122]. Copyright 2006 Elsevier. (b) Yarn sensor composed of a single wrapping of carbon-coated fiber (CCF) with elastic fibers and polyester fibers. Reproduced with permission from [99]. Copyright 2008 Elsevier. (c) SEM micrograph of polypyrrole-coated Lycra fibers at 6% strain. Reproduced with permission from [128]. Copyright 2011 Elsevier. (d) PEDOT-printed sensor on woven cotton fabric. Reproduced with permission from [61]. Copyright 2008 Taylor and Francis.

Metal fibers such as stainless-steel fibers can be knitted to construct a piezoresistive textile [95, 122], as shown in figure 8. When stretched in the wale direction, the resistance of the knitted sensor initially increases and then decreases. The initial increase in resistance is due to the increased length that the current sees. However, in the decreasing resistance phase, the gaps between the strands of yarn reduce, allowing better contact adding parallel conductivity paths which results in a lowered net resistance. This sensing principle can also be applied to conductive thread [123], metal fibers [124] and carbon fibers [122]. A spandex core can be added to increase fiber/yarn resilience. Other mechanisms that enable strain sensing entail inserting sensing fibers into non-conductive knits. Such is the case for a carbon knitted piezoresistive sensor [125] and a knitted polyacrylonite based sensor [126]. In a similar way, yarns can become sensing elements by wrapping piezoresistive fibers around an elastic core [99]. Hysteresis is also present in knitted sensors [122]. Linearity increases at the expense of sensor sensitivity [127]. Fiber and yarn transducers found in the literature are shown in table 8.

4.2.1. Piezocoatings to enable sensing features. Fabrics can be converted to 'smart fabrics' by applying piezoresistive [129], piezoelectric [130] or piezocapacitive [131] coating materials, usually in the form of polymers due to their elastic properties. Dyes and paints can be used as well but they have limited flexibility and compliance. Coatings are usually either externally modified by conductive fillers or intrinsically sensitive to changes in elongation, pressure and other mechanical stimuli. Sensing coatings are typically applied to stretchable substrates such as fibers, yarns and fabrics to make them strain sensitive. These substrates usually have a percentage of spandex to add recoverability. Elastic recovery of the coated sensor will usually depend on the resilience of the fabric construction, the constituent fibers and the content of spandex fibers.

Coated sensor characteristics will depend on several factors; internal mechanics and geometry of the yarn or fabric substrate; the thickness, consistency, brittleness, elasticity and composition of the coating; and the coating mechanism. The sensor characteristics will also depend on how the coating permeates the substrate and whether lateral compressive stresses cause fibers to be drawn together internally increasing fiber contact. In the case of piezoresistive coatings, a change in electrical resistance will be observed as a result of the application of strain to the substrate. This change can be quantified by the gauge factor, which is a measure of the sensitivity of a given strain sensor. It relates the normalized change in resistance with the applied strain. Positive or negative gauge factors are obtained depending on the material itself and depending on how the fabric substrate deforms under applied load. Gauge factors of conventional strain gauges (i.e. made of metal-coated thin films) are typically $\sim+2$. A positive gauge factor indicates an increase in resistance with applied strain, typical of metals. A negative gauge factor in turn indicates that there is more conductivity when the fabric sensor undergoes strain. To illustrate the complexity of coated sensor behavior and response dependencies, two strain models are presented. Wang *et al* developed an analytical model of resistance as a function of strain in PPy-coated Lycra fibers that includes microcrack behavior [128]. Their model is given by

$$\frac{R}{R_0} = \left[\frac{L_0(1+\varepsilon) - N(\varepsilon)W(\varepsilon)}{\pi d_0(1-\upsilon\varepsilon)} + \frac{N(\varepsilon)W(\varepsilon)}{\pi d_0(1-\upsilon\varepsilon) - 2L'}\right]\frac{\pi d_0}{L_0(1-\upsilon\varepsilon)}, \tag{4}$$

where L_0 is the unstrained fiber length, υ is Poisson's ratio, L' is the average length of the microcracks and d_0 is the initial diameter of the fiber. The N and W contain higher order polynomials of strain and depend on the characteristics of the microcracks that are associated with the coating method. Xue *et al* present a model of PPy-coated lycra fibers that includes the effect of strain rate, temperature and humidity as seen in equation (5), where f_1 is a function of strain rate, f_2 of temperature, f_3 of relative humidity and α, β, γ are experimental parameters [132]:

$$\frac{R}{R_0} = \frac{\rho}{\rho_0}(1+\varepsilon)(1+2\upsilon\varepsilon+3\upsilon^2\varepsilon^2) f_1(\alpha, \dot{\varepsilon}) \times f_2(\beta, T) f_3(\gamma, RH). \tag{5}$$

In the case of coated fabric sensors, the relationship between resistance and strain is often obtained experimentally. A gauge length is chosen and a conventional tensile test is conducted for such a characterization [43]. Substrate composition influences strain recovery rates. Cotton woven fabrics have poor strain recovery compared to nylon fabrics, both of which are generally worse than knitted fabrics where strain recovery can approach 100% [60].

4.2.1.1. Intrinsically conductive coatings. Polypyrrole is one of the most important conductive polymers that is being applied to fabrics due to its high conductivity, good environmental stability, ease of synthesis, good adhesion and non-toxicity. This polymer has been extensively studied in

Table 8. Fiber and yarn strain transducers.

Type	Elements	Meas. variable	Sensitivity	Strain range	Size	Charact.
Metal fiber knitted sensor[a]	Stainless-steel fibers	Electrical resistance/surface contacts	0.75 Ω/% elong. in linear range (10–30% elong.)	0–30%	1 cm × 10 cm	Knitted
Carbon knitted sensor[b]	Stabilized carbon fibers	Electrical resistance/surface contacts	3.0 tubular, 6.6 single warp	0–30% tubular 0–15% single warp	Tb: 5 mm diameter, Sw: 2 mm width	Knitted tubular and single warp
Polymer knitted fiber transducer[c]	Carbon filled fibers in course direction	Electrical resistance/elastic deformation	On linear range ∼1–8 mm, 0.014 MΩ mm^{-1}	0–12 mm extension	1.4 cm × 2 cm	Flat-knitted sensor, requires pre-tension,
Conductive thread knitted[d]	Conductive yarn, Nylon 6 with carbon	Conductive contacts	Gauge factor = 1.42, in 7.6–26% linear range	0–65% strain	20 mm × 60 mm	Made with intarsia technique
Yarn transducer[e]	Carbon-coated fiber/polyester/Lycra	Electrical resistance/elastic deformation	Gauge factor = 5.7	0–25% strain	CCF = 24 dtex	Double wrapping of CCFs

[a] Reference [95]. [b] Reference [122]. [c] Reference [125]. [d] Reference [124]. [e] Reference [99].

microelectronics applications. The strain gauge factors associated with changes in resistance of a bulk PPy sample in thick film form (34 mm) can range from 0.45 to 0.9 depending on the degree of doping [62]. Intrinsic piezoresistivity is a minor factor in the sensing response. When applying PPy to fabrics, different coating methods and substrates are possible. These have an impact on final sensor properties such as gauge factor and maximum strain. Polypyrrole is typically grown by chemical polymerization or oxidative coupling of the monomer, pyrrole or aniline [133, 134]. It can be coated on polycaprolactam (PA6) yarns with a resulting gauge factor of +2 with a linear response of up to 43% strain. Coated lycra yarns on the other hand do not have a very linear response to strain [132] but do possess a much larger ultimate strain, about 600%, which makes them attractive for large deformation applications. A useful response is also found using structured fabric substrates, i.e. knitted fabrics. Using solution polymerization, the resulting gauge factors are close to ∼2 on Nylon/Lycra [135, 136] and PET/Spandex knitted substrates [134]. Chemical vapor deposition of thin coatings of polypyrrole on Tactel/Lycra knits has been shown to be effective for increasing the sensitivity or gauge factor to values of 160 and 300 [137] by Li *et al*. The degree of polymerization will also have an impact on the overall value of resistance of the coated sensor [134]. Negative gauge factors for PPy-coated fabrics can be obtained when resistance increases as a result of applied strain.

Polythiophenes are another type of ICP useful to enable coated sensors. They represent an important class of conducting polymers due to their solubility, processability and environmental stability, with not only electrical conductivity but also electroluminescent properties and non-linear optical activity [138]. However, they are non-soluble in water which makes spin coating techniques difficult to apply. Poly(3,4-ethylenedioxythiophene) with poly(4-sulfonate) or PEDOT/PSS, however, has the desired viscosity characteristics for coating methods which required high solubility. PEDOT–PSS has been widely used as electrode material in organic thin film transistors or as a hole transport layer in organic light emitting diodes. From the literature, it has been reported that these polymers can coat hard surfaces of microelectronics and MEMS thin films [139] as well as fibers and fabrics and other stretchable substrates such as polyurethane foams [140]. PEDOT can also be microfabricated into shapes such as nanotubes [141], nanowires [142], nanofibers [143] and nanorods [144]. PEDOT based piezoresistive sensors can be used as strain sensors for various applications ranging from microelectronic strain gauges [145] to biomechanic measurement devices [60]. PEDOT–PSS has excellent conductive state characteristics such as low band gap, superior electrochemical and thermal stabilities and high transparency. Similar to the case of PPy sensors, the conductivity of PEDOT-coated sensors will be determined by the polymer fabrication and coating methods. PEDOT can also be spin-coated [5] as well as dip-coated [138] when in aqueous solution form over different types of substrates. Other methods of application include chemical vapor deposition, ink-jet printing, laser ablation and lift-off processes [139]. Substrate interaction may also increase conductivity. Gauge factors obtained with these substrates can be up to 42 in the case of PDMS [146] or can go as high as 396 in the case of Kapton [147]; however, this is produced at the expense of reduced overall strain in the case of Kapton and irreversibility in the case of PDMS after a 30% strain. They can also be enhanced by using localized plasmon gold nanoparticles, where the conductivity increases upon increased lighting [148].

PANi is another ICP with multiple properties. PANi-coated fabrics have many sensing applications such as in ammonia sensors, EMI shielding, and precious metals recovery. It can be synthesized on fabric surfaces by chemical

Table 9. ICP piezoresistive coated strain sensors.

Coating material	Conductivity/initial resistance	Gauge factor	Application technique	Strain range	Size	Substrate
PEDOT–PSS[a]	~kΩ range/25 S cm^{-1}	−20 to 5	Ink-jet printing (suspension)	10%	~1 mm × 5 cm	Woven cotton
PEDOT–PSS[b]	Max 2.0 S cm^{-1}	~0.18 S cm^{-1} per strain unit (up to 20% strain)	Dip-coating in aqueous dispersion	Max 80%	2 cm^2	Spandex knit (50% nylon, 50% polyurethane)
PEDOT–PSS–PVA[c]	Max 1.7 × 10^{-5} S cm^{-1}	Max 396	Electrospun nanofibers	Max 1.2%	3 cm × 8 mm, thickness = 250 μm	Kapton (flexible substrate)
PEDOT–PSS[d]	Bulk conductivity = 550 S cm^{-1}	Max 42 from 50% to 188% strain	Spin-coated solution	Max 188% Reversible = 30%	70 nm thick 3 mm × 2.5 cm	PDMS activated substrate
PPy/nylon Lycra[e]	~kΩ	2	Chemical polymerization	70%	40 mm × 15 mm	Knitted nylon 80%, lycra 20%
PPy/PET Spandex	~1 Ω cm (vol resistivity) for 8% filler content	~2.3	Chemical and electro-chemical polymerization	50%	1″ × 3″, t = 0.356 mm	Knitted PET 97% Spandex 3%
Polyaniline[g]	~150 kΩ	0.74	Chemical or electrochemical deposition	Max 70%	1 cm × 2 cm	PMAS templated wool nylon Lycra
Polyaniline[h]	Max 10^{-2} (Ω cm)$^{-1}$	3 in range 0–400% strain	*In situ* chemical oxidative polymerization	Max 1500%	n/a	Polyurethane
Polyaniline[i]	~7 kΩ at 2% concentr.	8 at 5% concentr.	Aggregate polymer mixture	Max 5%	25 mm × 6 mm	PVA/emulsified polymer

[a] Reference [60]. [b] Reference [153]. [c] Reference [147]. [d] Reference [146]. [e] Reference [135]. [f] Reference [134] [g] Reference [154]. [h] Reference [155]. [i] Reference [156].

or electrochemical deposition [149] and fabricated by wet-spinning and electrospinning techniques [150], among others. The application technique as well as the nature of the substrate will have an impact on the sensor properties. Polyaniline has been coated on polyester, nylon, wool, acrylics, cotton, silica, and glass. Results of oxidative polymerization over all these substrates has shown that the conductivity of PANi-coated wool and polyester yarns is considerably less than the ones on coated cotton, nylon, and acrylic [151] which have a specific resistance around 3 Ω cm^{-2}. PET (polyethylene terephthalate) spun yarns can be coated as well by PANi solutions—these have resistances in the order of about 10^3–10^8 Ω cm^{-2} [152]. Depending on the percentage of fibers spun, less resistance will result as the number of core fibers increases. A much lower resistivity is found in the sol gel coated PET yarns, where a system is transitioned from a mostly colloidal liquid phase into a solid gel phase. All these properties are reflected in the resulting values of the gauge factors and maximum strains. Table 9 illustrates different combinations of application techniques and substrates for ICPs.

4.2.1.2. Extrinsically conductive coatings. Intrinsically conductive polymer coatings by themselves are typically not as flexible as other polymeric based matrices with conductive inclusions [134]. This is part of the motivation for exploring extrinsically conductive polymers. These consist of mixtures of conductive or semiconductive fillers and non-conductive insulating matrices. Coatings of these mixtures can be applied to fabrics to give them sensing properties with an added compliance due to the polymeric matrix. The particles can be of any size; in particular, nanocomposites have been shown to possess special sensing properties. Conductive polymers can be obtained by adding enough doping particles to reach the percolation threshold, i.e. providing enough conductive contacts to enable the passage of current. The conduction mechanism may also be due to electron tunneling effects in the case of conductive nanoelements, i.e. nanoparticles and nanotubes.

Carbon doped polymers have piezoresistive properties. Many semiconducting materials can be used to dope non-conductive matrices and obtain piezoresistive composites. Graphite epoxy mixtures can be coated on polyester substrates [157]. Short carbon fibers and epoxy [158] present gauge factors of up to 23 for tensile stress. These are higher than long carbon fiber/epoxy composites, which tend to have gauge factors of up to 2. The combination of a large aspect

Table 10. Carbon based piezoresistive sensors.

Piezoresistive sensor	Typical values	Gauge factor	Fabrication method	Strain range	Approx. dimensions	Substrate material
Gel carbon black[a]	~5 Ω	−2 to 0.3	Printed	Strain 10–15%	~1 cm × 1 mm	Cotton poplin
Short carbon fibers/epoxy[b]	~3 × 10^{-3} Ω cm^{-1} per fiber (5.5 vol%)	Max 23	Mixing/vacuum	Max 62%	80 mm × 8.5 mm × 3.8 mm	Epoxy resin
Carbon black/cotton[c]	~1 kΩ cm^{-1}	~2.8	Screen printing/laser	20%	5 mm width	Cotton lycra
SWNT/PDMS[d]	~50 kΩ	0.82 (0–!40% strain), 0.06 (~60–200% strain)	Patterned catalysis/ CVD	Max 280%	1 mm × 16 mm × 6 μm	PDMS/fabrics substrate
MWCNT/PSF[e]	(0.5 wt%)	~2.78	Solution casting	Max 1.5%	25 mm × 3 mm × 200 μm	MWCNT/PSF film with applied field

[a] Reference [61]. [b] Reference [158]. [c] Reference [167]. [d] Reference [162]. [e] Reference [163].

ratio and discontinuous nature of the filler favors large strain sensitivity. Carbon black on polymeric matrices has generated a lot of interest due to its interesting electrical properties. These types of composites have a different piezoresistive behavior depending on the amount of carbon black filler (CB).

Other possible combinations to obtain a conductive polymer include acrylonite butadiene rubber (NBR) and ethylene propylene diene monomer (EPDM) mixed with acetylene black [159]. Conducting gels are yet another form of piezocoatings, as reported by [61]; carbon black 10 wt% can be added to a reacted solution of amine-cured epoxy to form a conductive gel. Examples of the carbon based strain sensors found in the literature are detailed in table 10. Carbon nanotubes have also generated a lot of interest due to their multiple sensing properties; they can be coated onto yarns, fabric substrates and polymer surfaces. Single-walled CNT-coated yarns can have a negative piezoresistive effect when subjected to strain—that is they have an increasing resistance with applied load [160]. This is due to an increase in the number of fiber contacts. SWNTs can be used in the form of dies to make conductive fabrics with not only piezoresistive but capacitive properties as in the case of PPy/SWNT-coated knits [161]. SWNTs can also be used as strain sensors by printing them onto PDMS layers which can be attached to fabric substrates [162]. MWNTs can also have piezoresistive properties when in film form. Furthermore, they can have an increased sensitivity upon alignment of the nanotubes using an electric field [163]. As in the case of the carbon black particles, the piezoresistive sensitivity of carbon nanotubes decreases with increased filler concentration—this has also been shown theoretically [164]. Electrostatic self-assembly of conductive nanoparticles onto fabric layers is another possibility to create conductive fabrics with possible strain sensing features. Here the surface of the fiber is infused with combinations of polymers and metals or metal oxides or semiconductors [165]. In addition, CNTs have electroactive properties and can be used to build electroactive fabrics [84, 166].

The variation in strain caused by the microstructure of a textile composite can have a significant effect on the output of strain gauges [157]. It has been shown that carbon loaded sensor sensitivities are affected by choice of substrate composition and type of knit [43]. The strain range will usually be determined by the stretchability and resilience of the substrate, added to the fabric construction parameter. In general, the resistance variation associated with a uniaxial applied strain for a resistive type coated sensor can be described as a functional of all the aforementioned parameters:

$$\frac{R}{R_0} = G(\varepsilon_{\text{coated}}) = F\{\{p_{\text{weave,knit}}\}, \{p_{\text{filler}}\}, \nu, E_{\text{coating}}, E_{\text{substrate}}, K, z, T, H\}. \qquad (6)$$

In this equation, p denotes the set of parameters that belong to fabric construction $p_{\text{weave,knit}}$ and all the parameters involved in the conductive filler characteristics p_{filler}. The permeation distance z and permeability K are consistent with previous equations. E refers to each Young's modulus and ν to a generalized Poisson's ratio. In general, coated sensors can be treated as composite laminates; however, this may not apply for the nanoelement coatings. Lamination theory adequately describes the linear elastic stress–strain under small deformation if such an approach is undertaken. Analysis of larger deformations would require Eulerian or Lagrangian formulations of non-linear stress–strain theories for predicting the finite deformation of flexible fabric composites.

4.2.1.3. Piezoelectric elements and coatings. Piezoelectric sensors will generate a voltage difference in response to many different physical stimuli such as pressure [168], tensile forces [130] compressive forces [169] and torsion. They can also be used for shape sensing, sound detection and sound emission [75]. They come in many form factors such as coaxial cables, films, and paints which can be directly attached, interwoven or applied to fabrics, respectively. Polyvinylidene Fluoride (PVDF) films can be coated with silicone rubber and inserted into fabric sleeves for heart rate monitoring [130]. Piezoelectric cantilevers can be fabricated by screen printing layers of PZT (lead zirconate titanate) on cotton fabric [170]. These cantilevers can be used as accelerometers (force sensors), energy harvesters and resonators. Piezoelectric resonance can be used for tactile sensor applications [171]. PVDF nanofibers realized by spinning polymer solutions in high electric fields present not only piezoelectric properties but also ferroelectric properties [172]. Ferroelectret chippings can become piezoelectric when placed in a conductive matrix enabling simple surface position detection [115]. Cellular polypropylene ferroelectrets can be used as tactile sensors [116]. Some considerations need to be made when interfacing piezoelectric materials. Coupling capacitance may be present in the output voltage levels. A similar type of coupling is present when the piezoelectric material is in contact with the human body. Wire interconnect lengths need to be minimized to avoid noise and interference [130].

Piezocapacitive fabrics can be built using membranes made of a dielectric elastomer [131]. These membranes are placed in a classical capacitor configuration with electrodes attached to each surface. The piezocapacitive effect can be observed when a high voltage difference is applied between the two electrodes of the actuator (one of the membranes). The induced membrane displacement causes an increase of the separation between the electrodes of the sensing capacitor, producing a decrease in capacitance.

4.3. Optical fabric sensors and fabrics with optical qualities

An optical fiber is typically composed of a transparent core wrapped in a transparent material of lower refraction index or cladding material. Some of the inherent advantages of optical fibers are low density, small size, flexibility, ease of embedment into a structure and immunity to electromagnetic fields [173]. The internal reflection of light produces light waves that travel along the fiber, which acts as a waveguide. Fiber optic sensors typically need a sensor system composed of a light source, a photodetector and other electronic equipment. Any small enough optical fiber can potentially be adapted and introduced into fabric substrates by interweaving [35], interlacing, or other types of fiber bonding [174]. Plastic and polymeric optical fiber sensors and devices can be introduced into fabrics and be used to detect strain [173], temperature [175], pressure [28], humidity, presence of organic and inorganic compounds, and wind speed. Fiber Bragg-grating sensors (FBGS) can also be embedded into fabrics to measure different physical quantities [175].

Sensing mechanisms are typically related to changes in absorbance and transmitted light intensity which are typically produced by changes in fiber cross-section geometry [35], refractive index of the cladding materials [174], spectral wavelength shifts [173], transmittance, and other intrinsic material properties. Materials which have been used as core material include poly (methyl methacrylate)-PMMA [176], polycarbonate, polystyrole, thermoplastic silicone [35], polyether sulfone, polysulfone, polyether-imide and polystyrene [177]. A number of critical issues associated with integrating these types of sensors into fabrics are discussed by Tao in [178].

Textile displays on fabrics are possible by weaving arrays of LED components using conductive yarns. The only requirement in this case for fabric robustness is the electrical reliability of the conductive yarn connections. Chromic fabrics can be made out of chromic fibers or coated with chromic materials, albeit with careful consideration of other factors such as chemical compatibility. Chromic materials are those which change their color reversibly upon external stimuli such as light (photochromic [179]), temperature (thermochromic [174]), electricity (electrochromic [149]), pH (halochromic [180]) and pressure (piezochromic [181]). In particular, electrochromic properties arise when the fabric changes its color in response to an applied electric potential field: this is the case for polyaniline/polyester fabrics which change their color from green yellowish at -1 V to dark green at $+2$ V [149] and PEDOT–PSS-coated lycra [153]. Electroluminescent fabrics can be constructed by applying coatings made of electroluminescent polymers. These types of polymers are thoroughly reviewed by Akcelrud in [182].

4.4. Fabric sensors for the detection of chemicals and gases

Detection of toxic gases and chemicals is of importance in the workplace and as a safety measure in unknown environments. Fabric sensors with chemical sensing features can be either e-textiles or coated polymers with sensing properties. In the case of e-textiles, miniaturized chemical or gas sensors can be attached to a fabric substrate by stitching or sewing. In the second case, chemically sensitive polymers can be used as coatings on textiles. Chemo-resistors are those sensors whose electric resistance is sensitive to the chemical environment. H_2 and CO can be detected using conducting polymers doped with metallic inclusions; polypyrrole doped with copper and palladium inclusions [183] shows a change in resistance when exposed to these gases. Toxic gas sensors [133] can be fabricated by depositing thin films of polypyrrole [184] or polyaniline onto poly(ethylene-terephthalate) PET or nylon threads, which are later woven into a fabric mesh. A change in resistivity is observed when the film is exposed to ppm levels of ammonia (NH_3) and nitrogen dioxide (NO_2). PEDOT nanotubes can be fabricated by vapor deposition polymerization (VDP) mediated electrospinning for ammonia detection [141]. Nanowire arrays of PEDOT can be used to monitor concentration levels of nitric oxide (NO) [142]. Detection of ethanol and ozone can be achieved by using coated polypyrrole filament sensors obtained by electrochemical deposition [44]. A PANi based optical fiber changes its light absorption when exposed to HCl and NH_4OH. An exhaustive review of all the chemicals detected by the common ICPs is provided in [185]. Semiconductors such as carbon black can also be incorporated in vapor sensor arrays. Swelling of the host polymer occurs when the vapor gets absorbed, causing a change in resistance. QTC composites change resistive properties when exposed to hexane vapor and tetrahydrofuran vapor at approximate rates of 100 kΩ min^{-1} and 10 kΩ min^{-1} respectively [114]. Carbon nanotubes have sensitivity to many analytes, including albumin, the key protein of blood [80, 82]. Single-walled

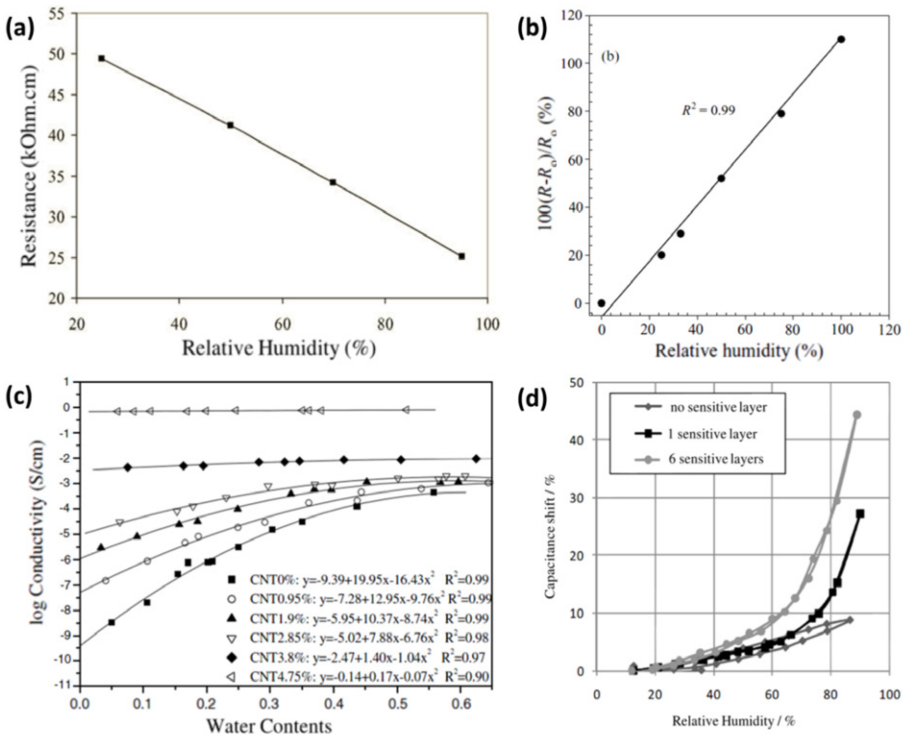

Figure 9. Humidity fabric sensors. (a) Resistance of PEDOT–PSS-coated fibers versus relative humidity during. Reproduced with permission from [138]. Copyright 2005 Elsevier. (b) Sensitivity of the PEDOT–PSS/PAN sensor prepared using 9 wt% PAN solution. Reproduced with permission from [188]. Copyright 2010 The Royal Swedish Academy of Sciences. (c) The effect of water content on the electrical conductivity of GPS with different MWCNT content. Reproduced with permission from [192]. Copyright 2008 Elsevier. (d) Capacitance shift versus relative humidity for different sensitive polymeric ink layer thicknesses and without sensitive layer (unmodified polyimide substrate). Reproduced with permission from [193]. Copyright 2011 IEEE.

carbon nanotube yarn composites can discriminate amine volatile compounds such as ammonium hydroxide, ethanol, pyridine and triethylamine [186]. There are other types of chemical sensing mechanisms such as those which operate with transistor and diode principles. In the transistor case the source–drain current is changed when the sensing film interacts with the analyte. In the diode case, a heterojunction is formed between the polymer and electrode. The barrier of the saturation current density can be modulated by the analyte. Other mechanisms for detecting gases with polymers include optical devices, piezoelectric crystals, and amperometric methods.

4.5. Temperature and humidity sensitive fabrics

Multiple humidity sensing mechanisms are possible. Polymeric based humidity sensors can be divided into two fundamental categories: resistive type and capacitive type. The first one responds to moisture variation by changing its conductivity while the second one responds to water vapor by varying its dielectric constant. A stainless-steel yarn undergoes a change in resistance when humidity is changed; such a change is possible using fabric humidity collectors which are then in contact with the sensing yarns [187]. Combinations of polymer/substrate; PEDOT–PSS/PAN nanofibers [188], PEDOT–PSS/polyimide, PEDOT–PSS/lycra tactel [138] and Polypyrrole [189] are also responsive to humidity changes by changing their electrical conductivity. These sensorized substrates can later be woven into textiles [190]. Polymers suitable for capacitive humidity sensors include polyethersulfone (PES), polysulfone (PSF) and divinyl siloxane benzocyclobutene (BCB), among others. Other humidity sensing devices entail flexible transistors [74] and changes in spacer fabric dielectrics [50]. Coated sensors on fabrics typically react to humidity if they are organic or carbon based. Water is well known for its protonation and the released proton interacts with universally conjugated C=C double bonds. Examples of humidity sensors found in the literature are shown in figure 9. Almost all of the humidity sensors based on polymers operate at room temperature due to the polymers' high sensitivity to heat.

Temperature sensors which are compatible with fabrics can be fabricated on flexible substrates such as plastics and polyimide sheets. These can be later attached to fabrics or integrated into their structure. Resistance temperature detectors (RTDs) have elements such as platinum and nichrome (NiCr) and related materials that can be coated on flexible surfaces. Kapton based plastic stripes of platinum RTDs can be woven into fabrics to manufacture a temperature sensitive textile [191]. A gold RTD has been manufactured on a flexible polyimide substrate [190]; its resistance changes linearly with temperature. This sensor is also woven into the textile. Thermoelectric generators can also be attached to fabrics using molding techniques and fabric connection

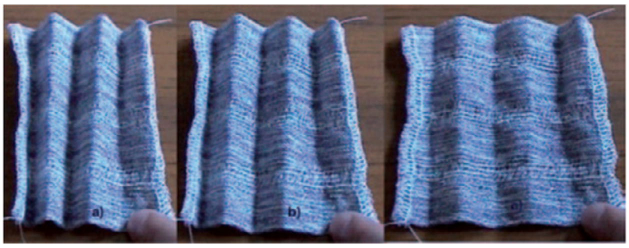

Figure 10. Shape memory recovery of SMP composite woven uniformly and densely of SMP yarn at 50 °C with recovery time of (a) 0 s, (b) 15 s and (c) 30 s. Reproduced with permission from [196]. Copyright 2007 SAGE Publications.

technologies [58]. All inherently conductive polymers and carbon based conductive particle polymers have a temperature dependent response. For instance, PEDOT–PSS-coated fibers experience a decrease in resistance when subjected to higher temperatures [138]. Fiber optic sensors can also be used for this task [175] as well as temperature sensitive inks and paints which can be applied to fabrics.

4.6. Shape memory fabric sensors

SMFs typically consist of either adapted shape memory alloys (SMAs) or shape memory polymers (SMPs) applied to textiles. Shape memory polymers have properties that can surpass those of shape memory metallic alloys in that they offer deformation to a much higher degree and can have many more variations of mechanical properties in addition to being inexpensive and lightweight. They can also be biocompatible and non-toxic. Albeit a field to be fully explored, sensing and actuating features have been shown for these types of materials. Examples of shape memory fabric sensor implementations include temperature and position sensors [194] and structural failure detectors [195]. Temperature sensing features can be achieved on fabrics by spinning shape memory polymers, i.e. polyurethane fibers, with other fibers or by coating shape memory polymer film emulsions over a woven or knitted fabric. In the case of the strain sensor, a shape memory alloy such as Nitinol is woven or stitched to a fabric to measure the strain experienced under an applied stress. This type of sensor can measure strains up to approximately 20% [194]. Similar to SMAs, SMFs can be trained and have a similar physical thermomechanical response. The shape memory behavior strongly depends on thermomechanical treatment of the materials and the cooperation of shape memory materials with other flexible and rigid materials in the fabric design [196]. A shape memory coefficient has been suggested for characterizing the behavior of SMFs; their thermosensitivity is captured by measuring the shape memory angle change [197]. Figure 10 shows the recovery process of a trained SMF made of shape memory polymer yarn densely woven into a fabric structure. Other shape memory materials applicable to fabrics include SMP fibers [195], shape memory foams and shape memory nanofibers [198]. SMFs can be trained to serve different purposes as self-regulating shape-changing structures responding to environmental variations [196].

5. Conclusions

This paper has provided a review of the current state of the field of SFS and e-textile technologies. The different levels of structure used in the design of fabric based sensors, ranging from the intrinsic level with active fibers to the extrinsic level with discrete electronic components attached to fabrics have been discussed. Intrinsic sensing elements can be constructed from inherently conductive polymers and doped polymer composites. Extrinsic sensing elements which can be discrete units or coatings can be constructed by modifying elemental fabric units to give them sensing properties which can be optical, resistive, capacitive, to name a few. The fabric pressure sensing capacitors typically follow the classic configuration and have a capacitance in the order of picofarads. The capacitive plate layers can have a thickness in the range of microns to millimeters and can have different geometries depending on the intended application. Strain sensing elements have a largely increased maximum strain percentage compared to conventional ones and can conform to any surface. The range of sensitivity for each type of fabric sensor strongly depends on the purpose of the application and on the geometry and mechanical requirements. Overall, the sensitivity of such sensors will have a dependency on the elastic properties of the composite structure, temperature and humidity. Other fabric sensors include those with sensitive optic fibers, sensitive to chemicals and gases and those sensitive to variations in environmental parameters.

Connectors, interconnects and electrodes depend on the type of sensor, mechanical constraints and type of application. Each connecting solution is customized and almost unique. Textile circuitry is possible by using techniques which have been adapted to fabrics. Concepts that combine conventional electronics and large-area electronics are crucial to the development of circuitries on textiles. An SFT needs a high degree of flexibility and robustness, but these qualities are interdependent. Flexibility is achieved by using soft fabric-like unique interconnects which makes the fabric circuit less robust. Robustness however is improved by reducing the flexibility of the fabric components, for example by means of molding and encapsulating techniques. Insulating techniques are mostly comprised of methods adapted from the fabrics industry whereas connections are mostly adapted from conventional electronics. SFTs are also greatly complemented by all flexible macroelectronics technologies: flexible displays, OLEDS, MEMS, fabric photovoltaic and energy harvesting devices, among others. These will gradually allow for complete soft-computing wearable fabric based sensing platforms.

The main challenges for rapid expansion in the use of smart fabric technologies are (1) the lack of standards; (2) the lack of mass availability of components; (3) cost; and (4) lack of reliability. Manufacturing time and sophisticated methods for some of the fabric sensors add to the final cost of fabrication; but these two challenges will be overcome once the technology matures and items are mass produced. However, many of these technologies are still in the research phase, and challenges that need to be addressed are as basic as that fabric sensors must be washable, non-toxic, and resistant

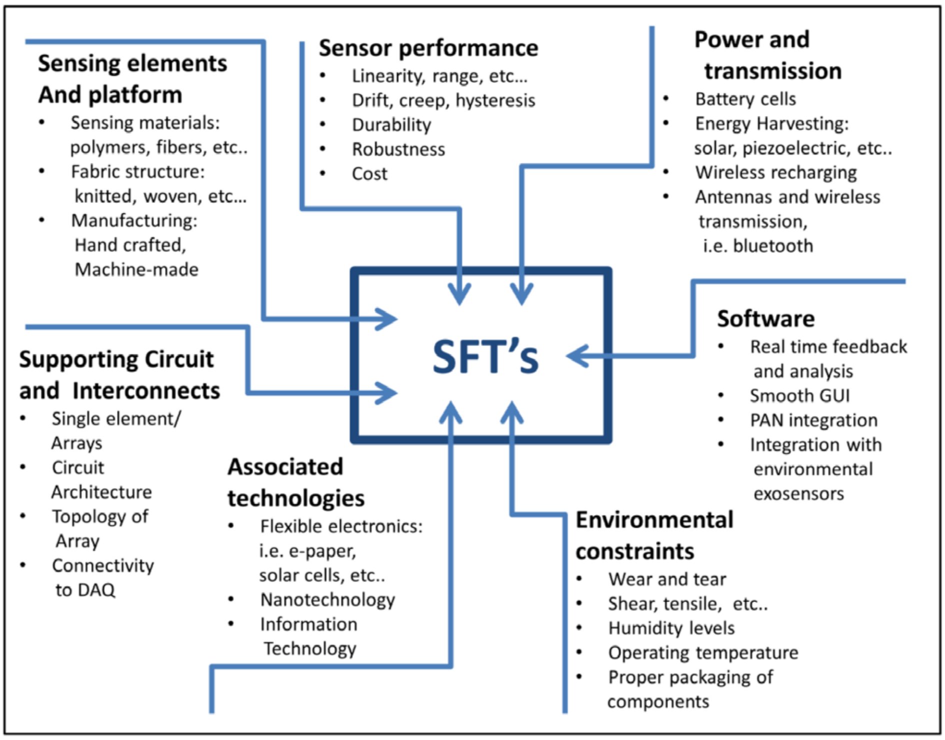

Figure 11. Key areas of development of SFTs (modified chart based on [199]).

to surface shear. Mechanical and electrical connections must also be washable and resistant to not only water but also to bending, torsion and other stimuli characteristic of what a wearable item is subjected to. Connection techniques also need to be improved for robustness and optimized for compliance. Strategies for encapsulation of components and extension of system lifetime are also areas to be improved. Challenges increase with the level of integration because there is an increased number of degrees of freedom when modifying fabric structures at each level. Realizing mass production techniques for SFTs will be a major milestone for this technology. Flexible electronics technologies will give a boost to the implementation of fabric transducers when they reach a more mature stage. An increased number of applications will arise with increased miniaturization of existing electronics components and advances in nanocomposites. New sensing materials will always be both an opportunity for new markets but also a challenge when interfacing with acquisition and conventional electronics devices.

A successful fabric sensor design needs to draw on the expertise of professionals in many different fields, including textile scientists, polymer chemists, physicists, bioengineers, software engineers, and mechatronics engineers, among others. This multidisciplinary collaboration as well as a complete analysis of the desired sensor qualities and a thorough device development will increase the possibilities of a successful prototype. Several factors influence the design and development of a smart textile transducer and therefore need to be taken into account. Figure 11 shows the different key areas that need to be considered, tested and implemented according to the requirements of the targeted application. The different nature of the elements of a particular application makes each solution unique. A completely fabric based SFT technology will set another milestone—sensors, connections, and electronics all made of fabric materials or polymers. Self-regulating fabrics made of integrated fabric units are also possible if actuators, power devices and wireless transmission are all achieved with only fabric components. The potential applications for self-regulating SFTs are numerous.

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