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Published in:
DIS 2022 - Proceedings of the 2022 ACM Designing Interactive Systems Conference

DOI:
10.1145/3532106.3533566

Published: 13/06/2022

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Pouta, E., & Mikkonen, J. (2022). Woven eTextiles in HCI – a Literature Review. In *DIS 2022 - Proceedings of the 2022 ACM Designing Interactive Systems Conference* (pp. 1099-1118). ACM.
https://doi.org/10.1145/3532106.3533566

Woven eTextiles in HCI — a Literature Review

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ABSTRACT

Advances to functional materials and flexible electronics have yielded new means of integrating electrical properties into textile materials, which invite researchers in various fields to apply woven-textile construction methods in eTextile development. However, common ground for woven eTextiles' prototyping is still taking shape. This calls for greater understanding of how the knowledge now scattered across diverse research fields can benefit the textiles' development for HCI. To investigate how eTextile research has employed weaving and extract insight for HCI purposes, the authors reviewed and categorised applications of woven structures and electrical functions, then identified specifically HCI-relevant qualities and means of creating them via weaving. The paper outlines those woven structures useful for HCI and advocates consistent weaving-related terminology, to improve knowledge transfer across disciplines. In addition, the results point to research opportunities involving haptic qualities, the ability to weave multiple layers, functionality integration, and tools and methods.

CCS CONCEPTS

• **General and reference → Surveys and overviews**; • **Hardware → Flexible and printable circuits**.

KEYWORDS

eTextiles, smart textiles, weaving

ACM Reference Format:
Emmi Pouta and Jussi Ville Mikkonen. 2022. Woven eTextiles in HCI — a Literature Review. In *Designing Interactive Systems Conference (DIS '22), June 13–17, 2022, Virtual Event, Australia.* ACM, New York, NY, USA, 20 pages. https://doi.org/10.1145/3532106.3533566

1 INTRODUCTION

Textile materials have long been used to extend the ways people interact with physical interfaces. Over nearly three decades, advances in functional materials and flexible electronics have enabled new means of integrating distinct electrical properties into textile materials. This development has opened new avenues for multidisciplinary research in which such fields as electrical engineering, material science, interaction design, computer science, and textile design come together. Recent years have witnessed the focus of that research move increasingly toward how functionality can be incorporated into the very structure of textiles, as opposed to textiles serving as a mere substrate for electrical and interactive elements' attachment. This shift has ushered in increased use of textile-oriented construction methods in smart-textile development, thus calling for fuller understanding of textile materials and fabrication techniques.

While thorough reviews of eTextile technologies are available [e.g., 15, 36, 104], summaries focused on the ways of utilising weaving, complex woven structures especially, in eTextiles for HCI remain absent. In addition, eTextile research is often driven by the engineering and HCI disciplines, and, although textile craft methods have been applied in smart-textile development for decades, publications have disseminated little of the textile-related knowledge. More specifically, descriptions of the insight related specifically to weaving and how textile knowledge unfolds during the weaving process have often remained vague.

Our aim with this literature review is to home in on *how weaving has been used in eTextile research in the various related research fields* and draw conclusions for advancing eTextile research in HCI. As complex weaving represents especially strong contributions to HCI-linked design opportunities, this paper pays particular attention to complex functional woven structures. To acknowledge the multidisciplinary nature of eTextile research, we approach this review from two perspectives: that of a textile designer and of an electronics engineer. We begin by delving into the literature to specify *what electrical functionality can be achieved through weaving* and *which woven structures and weaving techniques have been used in woven eTextile fabrication.* Then, to offer practical guidance as to how weaving can benefit HCI, we look beyond electrical properties and eTextiles' technical execution by examining *how woven structures and weaving techniques enable the integration of various electrical functions and sensorial properties suitable for HCI-affording eTextiles.* A multidisciplinary approach is reflected also in the body of literature our study reviewed. Our integrated review of 103 sources included both academic and grey literature from the HCI field and various related domains (e.g., material science, electrical engineering, and textile design), gathered through database searches and citation-tracing. The insight we extracted from the various sources brings more comprehensive answers to the above-mentioned questions.

Our literature review identified five elements that may be present in woven eTextiles: *electrical signalling*; *woven-in components*; and three electrically functioning elements – *woven sensors*, *woven actuators*, and *other woven components.* Furthermore, we found underrepresentation of complex multi-layer weaves in the eTextile landscape, suggesting a wide spectrum of remaining HCI research opportunities.

DIS '22, June 13–17, 2022, Virtual Event, Australia

ACM ISBN 978-1-4503-9358-4/22/06…$15.00
https://doi.org/10.1145/3532106.3533566

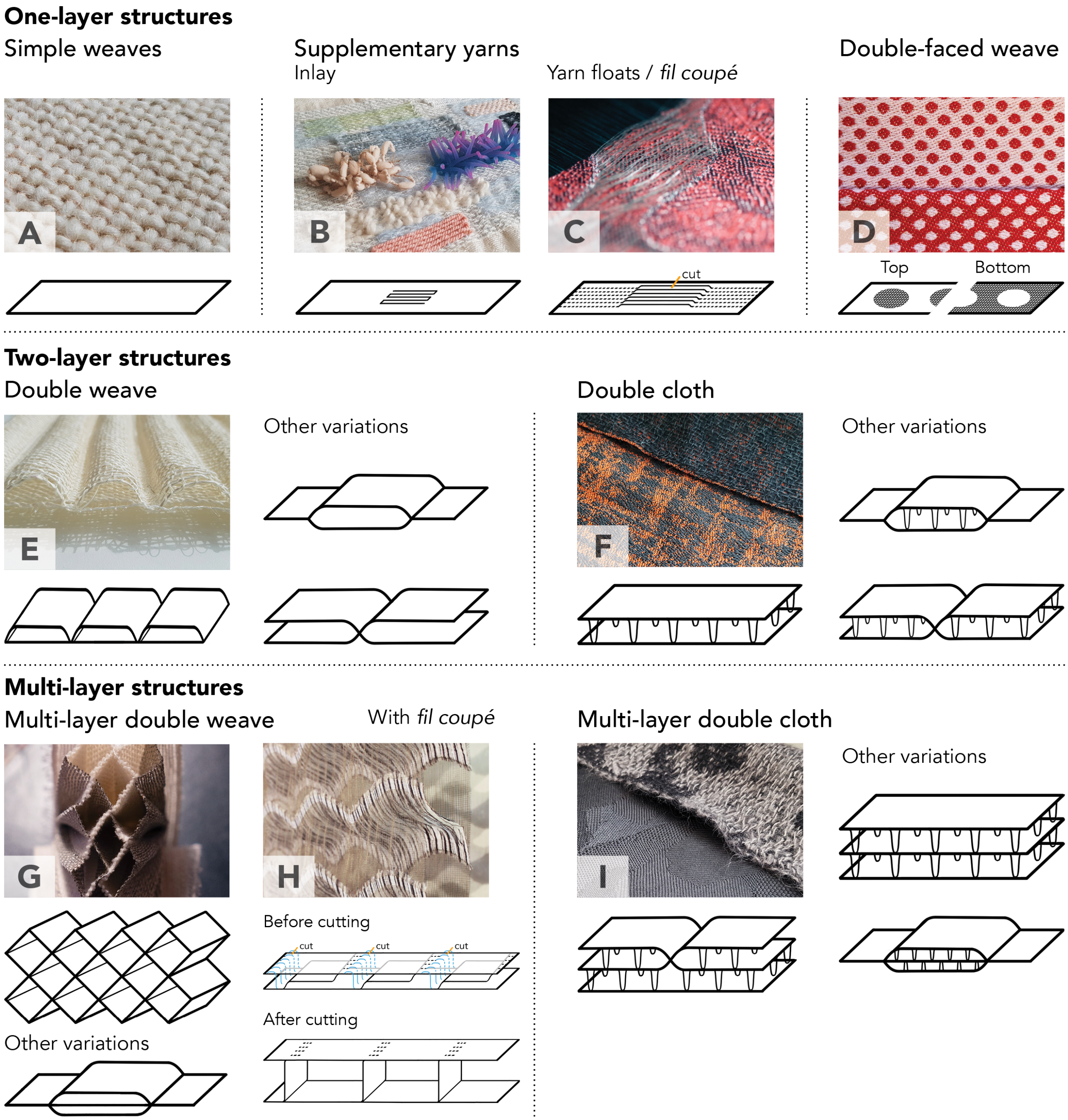

Figure 1: Woven textile structures, by increasing complexity. Pane H shows a *fil coupé* fabric design from the collection 'Floating and Clipping', created for an MA thesis by Tiina Paavilainen of Lodetex (reproduced with permission). Other images are from the authors' own repository.

1.1 Weaving

The literature discusses weaving from a multidisciplinary perspective, and the terminology and weaving techniques often are represented from perspectives other than textile design's. Therefore, we begin by applying uniform terminology in a brief discussion of weaving that draws together the various fields' understanding for HCI purposes. Weaving is one of the oldest textile construction methods. It can aid in producing the textile types most commonly seen in day-to-day life, encompassing clothing and fabrics for interior and industrial uses alike. As a construction method increasingly utilised in eTextile research, it also supplies a suitable foundation for integrating electrical and programmable functionality, such as various touch- and pressure-sensing capabilities, into textile-based tactile interfaces. The simplest method of producing woven textiles is to interlace two yarn systems, warp and weft, orthogonally to one another. Warp is the longitudinally running yarn set that is kept stationary under tension in a loom. In the weaving process, certain warp yarns get raised, on the basis of the intended weave structure, such that the weft yarns can be inserted horizontally across the warp before lowering. Various mechanisms can control warp yarns' lifting. These have a major impact on the complexity of the structure created and the pattern of the textile. Loom types differ in their capabilities of controlling the warp, with the two most commonly used mechanisms being dobby and Jacquard. Dobby looms follow a shorter sequence before the pattern's repetition, whereas Jacquard looms permit more versatile structures and larger woven patterns, even supporting full control of each individual warp yarn separately [25].

Thus, the textile's weave design determines how the yarns intertwine in the fabric, determining such properties as the length of 'yarn floats' (the stretches of yarn that run between intersection points), the density of the weft, and how the fibres ends up assembled. All of these factors influence the tactile properties of the textile's surface. Weave patterns display diverse structures, running the gamut from the simplest possible to complex multi-layer structures. In simple weaves, the woven structure is composed of one set each of warp and weft yarns. The simplest structure, wherein each of the weft yarns passes over and under every warp yarn, is called plain weave (see pane A in Figure 1). Any other way of interlacing the yarns creates the above-mentioned yarn floats, where warp or weft yarns pass over two or more yarns consecutively on either face of the fabric. The floats' alignment is the distinguishing factor in float-weave textures such as satin and twill [25, pp. 74–90].

Using more than two yarn sets in the composition increases the textile's complexity, thereby providing more possibilities for structural variations. An additional yarn set as a supplementary warp or weft element may provide decoration (e.g., an inlay, as in Figure 1, B), serve as reinforcement, or create floats (see the figure's pane C) [25]. In contrast, using multiple warp or weft systems provides more equal contributions, in which the woven structure's yarn systems complement each other. For example, complementary yarn sets are used for creating double-faced weaves, in which a warp system and two or more weft systems are interlaced to form a two-sided fabric. Typically, one of the weft patterns is visible from each side, and the two wefts sometimes form different patterns from each other (see pane D). Complementing such a weave with a further set of *warp* yarns enables fabricating double weaves, in which the two sets of warp and weft form two separate layers of fabric that are woven simultaneously. The pattern may keep the layers separate across the full width of the textile or, by switching the order of the layers, create pockets within a fabric (as shown in pane E). Double cloth uses the same yarn-system configuration but, in addition, interlocks the layers with a third weft system, or a binding weft (illustrated in pane F) [55]. Additionally, a more complex woven structure enables creating more versatile three-dimensional structures, also called 3D woven structures, with some examples being multi-layer double weaves (see pane G), double cloths (see pane I), and fabrics that use spacer materials between layers [48, 88]. Further opportunities, especially to increase the woven textile's volume, arise with versatile weaving techniques and structures such as *fil coupé* technique (see pane H) [81] and three-dimensional tessellation inspired by origami folding methods [76],

In summary, the loom mechanism and set-up imposes certain limitations on woven-textile fabrication, and the choice of weaves and materials determines the resulting fabric's texture. At the same time, for the textile's visual aesthetics, it is crucial to design appropriate colour combinations and attend to the figurative aspect of pattern designs. In-depth textile-design knowledge in these and other domains is vital for a well-designed functional combination of texture, patterns, and colour, not to mention electrical qualities.

2 THE METHOD FOR THE LITERATURE REVIEW

To understand how weaving can contribute to developing woven eTextiles suitable for HCI, we conducted an integrated literature review regarding woven structures' application in eTextile research, across various fields. The review protocol is depicted in Figure 2, and Table 1 presents the search strings and databases.

2.1 Search Procedure

The search process utilised two distinct phases. In Phase I, we sought initial understanding of how HCI-related eTextile research has applied weaving and of the terms it typically uses to describe woven eTextiles and their structures. For this, we targeted our search via the ACM Full-Text Collection database. With our preliminary searches, we identified the terminology employed in the eTextiles field as still evolving, with terms such as 'eTextile', 'e-textile', 'electronic textile', and 'smart textile' getting used interchangeably. Hence, we selected the generic keywords 'textile' and 'fabric' so that terms' inconsistency could not hide relevant sources from us. To specify the construction method, we coupled these keywords with 'weaving' and 'woven'. Searching for these keywords' appearance anywhere in the text yielded 1,060 papers, whose titles and abstracts we then screened. At the screening stage, we excluded all papers that did not exhibit a connection to eTextiles or that, while related to eTextiles, dealt only with other fabrication methods, such as knitting or sewing. The full-text analysis that followed covered both the relevant papers, whose title or abstract mentioned weaving and indicated a link to eTextiles, and also somewhat pertinent ones – pieces displaying a connection to eTextiles without presenting any specific textile-construction method.

Our full-text analysis yielded a corpus of 33 articles that mention weaving as a method of constructing eTextiles. We analysed the articles by considering the woven structures and weaving techniques as either described in their text or presented in figures showing textile samples or structure illustrations. Nine of the papers were excluded from further review for not providing sufficiently detailed information about the woven construction. To gain more comprehensive understanding of how woven structures have been applied in eTextiles suitable for HCI activities, we performed citation-tracing for all

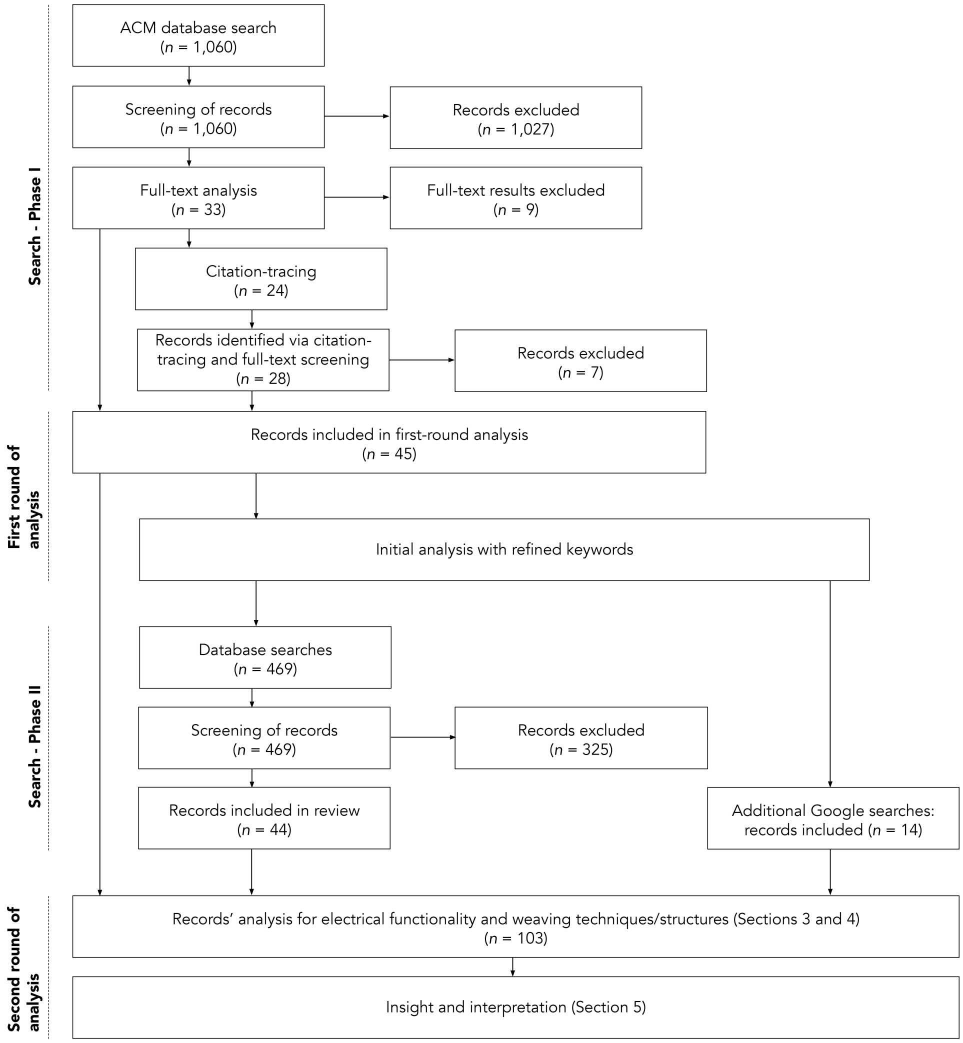

Figure 2: The literature-review protocol followed.

24 remaining papers, using a snowballing technique [119]. That pinpointed 28 additional sources (papers and Web pages) reporting on the use of weaving as a method for constructing eTextiles, of which we filtered out seven, which presented insufficient information on the woven structures. Thus, in total, our ACM database search and snowballing revealed 45 relevant sources for our literature review. At this point, we analysed the publications to pin down the terms employed for eTextiles and the woven structures applied in their construction. From this analysis, we obtained a set of more specific keywords to inform Phase II's database searches.

In the next phase, we used the refined terms to broaden the review with additional searches. Our initial analysis of the ACM and snowballing results pointed to grey literature as a possibly relevant source of information. We set out to access this material by searching literature via Google Scholar. In addition, for coverage ensuring a multidisciplinary literature review, we searched the Scopus database for suitable publications. The searches yielded, all told, 469 records. These underwent screening similar to that in the previous phase. Ultimately, our review covered 45 records. In addition, we augmented our set of sources in light of initial analysis revealing that the corpus developed in Phase I contained only three publications describing woven structures with multiple layers. We obtained greater coverage of complex woven structures by means of additional Google searches, with different keyword combinations. While this mechanism, using purposeful sampling, was not systematic, we continued until reaching saturation.

2.2 Analysis

For both reviews, we used ATLAS.ti software to analyse the papers. The first aim was to identify the electrical functions created via weaving and how they were achieved. We found three distinct functionality categories: electrically functional weaves [e.g., 95], woven-in components [e.g., 73], and electrical signalling [e.g.,

Table 1: Databases, search strings, results, and search dates

Database	Search string	Results	Date of search
ACM Digital Library	(AllField:("weaving") OR AllField:("woven")) AND (AllField:("textile") OR AllField:("fabric"))	1060	9th October 2021
Google Scholar	("double weave" OR "double cloth" OR "fil coupé" OR "tapestry weaving" OR "jacquard weaving" OR "multilayer weave" OR "multi-layer weave") AND ("eTextile" OR "e-textile" OR "smart textile" OR "electronic textile")	166	13th April 2022
Scopus	ALL ((("double weav*" OR "multi-layer weav*" OR "multi layer weav*" OR "fil coup*" OR "tapestry weav*" OR "multilayer weav*" OR "double cloth" OR "double faced weav*" OR "jacquard" OR "supplementary weft" OR "supplementary warp" OR "supplementary yarn" OR "complementary weft" OR "complementary warp" OR "complementary yarn" OR "tc2" OR "TC-2" OR "dobby")) AND (("etextil*" OR "e-textil*" OR "smart textil*" OR "electronic textil*")))	303	13th April 2022
Google	"woven" AND ("double weave" OR "double cloth" OR "fil coupé" OR "multilayer weave" OR "multi-layer weave" OR "3-layer" OR "three layer") AND ("eTextile" OR "e-textile" OR "smart textile" OR "electronic textile") ("double weave" OR "double cloth" OR "multilayer weave" OR "multi-layer weave") AND ("eTextile" OR "e-textile" OR "smart textile") "woven" AND "three layer" AND ("smart textile" OR "e-textile" OR "eTextile")	-	14th April 2022

The search was not sensitive to the accent mark in 'fil coupé'. In Google searches, the search engine recognises only alphanumeric characters and treats keyword sets such as 'three layer' and 'three-layer' as the same.

37, 97]. The first of these categories could be divided, further, into woven sensing [e.g., 95], woven actuators [e.g., 105], and other functional weaves [e.g., 33]. Secondly, we analysed the papers to understand how weaving contributed to the functionality described and which specific weaves, structures, and weaving techniques were employed. The structures were examined in light of what both the written descriptions and the photos and illustrations revealed.

3 WOVEN ETEXTILES IN HCI

Proceeding from our analysis, we grouped the woven eTextile structures in the HCI domain into three categories: electrical signalling [e.g., 37, 97], woven-in components [e.g., 73], and electrically functional weaves [e.g., 95]. Our categorisation, illustrated in Table 2, represents perspectives from both electronics and weaving. The subsections that follow (3.1–3.3) present these in terms of electronics, and Section 4 then addresses the weaving angle, by discussing woven structures for functionality (with subsections on simple-weave structures, one-layer structures with additional yarns, two-layer structures, and three-layer ones). Where a source falls under more than one category, it is discussed within the context of each applicable one. We should point out also at this juncture that some papers describe functionality without noting the mechanics behind the sensing. While these are included in Table 2, we give them less attention in this portion of the paper. Finally, worthy of particular note are a book by Cabral et al. [14], a chapter contributed by Kuroda and colleagues [59], and the doctoral dissertation of Veja [115], all of whom outline the basics and offer a broader set of example applications for woven eTextiles. Of the three, Veja's work offers by far the most extensive documentation of various woven structures, including switches, LEDs, battery-holders, resistive components, and others.

Alongside reports on individual projects and pieces discussing the same project from alternative angles, our survey identified nine **literature reviews** focusing on topics adjacent to woven eTextiles. While none of the reviews provide the depth of detail on the textile structures that some other sources do, each of these articles features some examples of woven eTextiles [1, 17, 29, 35, 58, 101, 102, 112, 126]. We include them here because they go into the links to woven-eTextile-related topics and present overviews of these, but they are excluded from our detail-level analysis since they lack the required depth. One review focuses on light-emitting textiles, which represent one of the matters quite frequently addressed in eTextile work [17]. In a somewhat similar vein, optical-fibre technologies [35] are examined from several perspectives, such as that of serving both for input and for output. The review of fibre-based devices [101] focuses on materials, fibres' processing, textile integration, and related topics, while also drawing a roadmap of future applications. To a similar extent, two articles found [102, 126] examine nanomaterials and nanotechnology, along with surrounding efforts, such as textile-integration work. Bus structures and interconnections for eTextiles have been reviewed also [1], as has the fabrication of eTextile devices and their power supplies [58]. The final two reviews attend more to the application level, with one focusing on the technologies enabling information-gathering garments [112] and the other considering robotics applications [29].

3.1 Electrical Signalling

Connecting components of different types or forming a network within the woven textile requires electrical signalling. This is significant for HCI in that signalling enables distributed electrical functionality for woven textiles and because the wiring and mechanical-connectivity choices influence the textiles' draping and feel. All papers surveyed address some form of electrical signalling or wiring: at minimum, electrical connectivity is needed for supplying power to the electronic components. When greater complexity is required, electronic-circuit design becomes relevant. Our survey found 15 sources putting focus primarily on electrical signalling [13, 23, 24, 38, 44, 45, 65, 67, 69, 85, 86, 92, 93, 114, 132] and 15 other sources in which the signalling or wiring plays a major role [3, 6, 37, 70, 72, 73, 82, 83, 94, 95, 97, 111, 115, 133, 134].

Table 2: Woven eTextiles' categorisation, inputs, outputs, other components, and systems

Woven structure	Electrical signalling	Woven-in component	Electrically functional weave		
			Woven sensor	*Woven actuator*	*Other woven component(s)*
Simple weave	[23, 24, 65, 67, 70, 134] [82, 93, 94, 111, 132, 133]	F-photodetector [16] F-temperature [16] Temperature and humidity [70] EL wire [56, 121] LEDs [16] Capacitive yarn [16, 50] PCB [132, 133]	F-biosensor [16] Optical fibre [42, 98, 105] Plate capacitor [129] Pressure sensor [16, 26, 77, 87, 89, 90] Touch pad [89] Pressure sensor [28]	Artificial muscle [71] Optical fibre [9, 42, 49] Thermochromic heat [116, 120] Thermochromic yarn [28]	Electrode [2, 131] Inverter [11] Memory wire [68] Piezoelectric generator [66]
Simple weave and supplementary sets of yarn	[44, 45, 69, 95, 114]	Shape-memory alloy [14]	Capacitive grid [95] Capacitive touch function [125] Moisture sensor [5] Stroke sensor [89] Touch potentiometer [124]	Thermochromic yarn [21, 28]	Antenna [62] Coil [128] Electrode [43]
Double-faced weave	[85, 86]	–	Capacitive touch function [96] Moisture sensor [84] Tilt switch [89]	Optical fibre [30] Thermochromic heat [91]	Electrodes [89]
Double weave	[37, 82, 97, 115]	Soft potentiometer [18] Strain sensor [64] EL wire [56] LED(s) [5, 96, 105, 115] Shape-memory alloy [105] Capacitive yarn [50] PCB [63] Solar cell [118] LED yarn [57] PCB [19, 28, 57]	Capacitive touch [105, 108] Optical fibre [37, 82] Pressure sensor [34, 96, 105] Switch [20, 89, 97, 115] Thermocouple [54] Touch sensor [79]	Optical fibre [8, 31, 32, 99, 108, 110] Thermochromic heat [78, 80, 105] Thermochromic yarn [20, 60]	Battery-holder [115] Electrode [43] Resistor [115] Triboelectric generator [39] Electrode [19]
Double cloth	[3, 83] System [72]	LED yarn [41] Hall-effect sensor [72] LEDs [72]	Plate capacitor [129]	Optical fibre [31, 32, 99, 108, 109]	Electrode [103, 130]
Multi-layer double weave	–	Solar cell [118]	Switch [4, 89]	–	Electrode [43] Plate capacitor [27]
Multi-layer double cloth	[22, 92] System [73]	Strain sensor [46] Battery [73] LEDs [73] Processor-yarn [73]	–	–	RFID antenna [33]
Unspecified woven structure	[6, 13, 38]	LEDs [61] Optical fibre [51] RFID [113]	Thermocouple [107]	EL wire [33] Thermochromic heat [7]	Electrode [6]

Since the yarn components are tailored specifically for weaving, their use is distinct from others in the relevant category; PCB woven-in components include both rigid and flexible printed circuit boards.

Conductive yarns and wires, in both weft and warp, have been used for constructing signal traces, to which components are connected. The network structures often utilise the natural orthogonal grid structure of woven fabric, with weft-patterning techniques having been applied also. A key concern is the components' connection to the signal traces, which is affected by the selection of wires or conductive yarns. We identified four distinct types of yarns or wires used for electrical signalling. These are pure metallic yarns, insulated wires, blended or twisted yarns, and coated yarns. We discuss them in a bit more detail here because of the part they play in constructing electrically functional weaves.

Pure metallic yarns are made from thin filaments of conductive material, such as steel, copper, silver, or some combination of these. The yarns are not coated, and they contain no additional materials. Stainless steel was used in five projects reported upon [24, 38, 82, 97, 105], copper in six [13, 23, 24, 82, 111, 133], and a silver–copper mix for one [114]. Yarns of these types have played a role in creating electrical and electromagnetic shielding, while also serving in a decorative capacity. One drawback is that uncoated metallic yarns are prone to oxidation, which may lead to unusual signal behaviour.

Insulated wires are conductors with insulation on the exterior surface. The insulation, which one must remove prior to soldering or other electrical connection, confers these wires' main benefit – prevention of short circuits when the textile moves and yarns in its structure cross. Our review identified use of Litz wire and other enamelled wires [44, 45, 72], plastic-insulated wire [23, 24, 65] and tinsel-wire [69], and wire-wrapped wire [67, 82]. Litz wire, normally used for creating transformers and coils, consists of individually enamelled copper filaments bundled together. Employing enamelled single-core copper wires similarly, magnet wire is used for creating electromagnets. In both types, the enamel must be removed via physical abrasion or burned away with high heat before the wire can electrically connected. Insulated tinsel-wire, utilised for high-flexibility applications such as telephone handset wiring, comprises multiple thin uninsulated copper fibres housed in a flexible plastic coating that can be easily stripped away. Finally, wire-wrapping is used for prototyping circuit boards. It employs slightly rigid single-core wire with a plastic coating that can be sheared away. With the exception of wire-wrapped wire, the wires reported upon were chosen for being thin, and hence suitable for weaving, yet able to withstand mechanical movement. A fundamentally different application of insulated wire, mentioned in two publications [37, 82], is poly-acetylene fibre. Its wires, as conductive polymers, appear to be the only non-metallic conductors in the work described.

Blended wires and conductive yarns typically have a flexible core of one or more non-conductive fibres or polymers, which is twisted with or wrapped in conductive metal. These permit soldering of electrical connections without preparation, and the wires are generally durable. To create a structure more amenable to textiles, some work has used natural materials – for instance, spinning strands of steel and cotton together [70, 94, 132, 134]. Non-insulated tinsel, consisting of thin strips of copper foil wrapped around a core of plastic fibres [93, 94, 111], is similar to a copper–polyamide-fibre blend sometimes used [85] and to the silver blends reported upon [73]. Related to these is Jacquard yarn, created by surrounding several strands of thin insulated copper with a twisted or braided silk yarn, with a yarn layer optionally on top [95]. While the other yarns are fruit of creating durable wires for highly flexible cabling, Jacquard-yarn variants were developed specifically for eTextiles.

Metal-coated polymers have served various purposes, such as creation of electrodes, decoration, and electromagnetic shielding. Coated yarns have served several projects [3, 72, 82, 92, 94, 111, 115]. They are made from a plastic, such as nylon, that has been copper- or silver-coated for a conductive surface. The downside of this material is proneness to mechanical wear over time.

As noted above, **how the electrical connections are made** is a key concern in the eTextiles domain. From those electrical-signalling-oriented sources with clear discussion of attachment methods, we identified several techniques. 1) Eleven pieces mention soldering the connections to the woven structure [6, 44, 45, 69, 85, 86, 94, 95, 111, 133, 134]. This method, which requires access to the electrical connection, uses heat to melt solder to connect the yarns together. 2) Welding too uses localised heating, but it melts the material itself to form a connection. Two sources refer to it [24, 82]. 3) Four pieces report on weaving the electrical connections together [72, 73, 92, 97]. Here, the connections utilise textile materials and woven structure to establish the contact. 4) Similarly, knotting uses only textile materials to form the connection. Mention of it appears in only two sources [3, 83]. 5) Four projects relied on forming connections through mechanical pressure, applied by crimping or by means of insulation-displacement connectors [67, 69, 94]. These are susceptible to mechanical failure, since the connector is attached through physical stress and force, deforming the connector and the wiring. 6) Finally, two types of conductive adhesives are mentioned: some teams used conductive glue to attach conductive yarns, circuits, or flexible thin-film PCBs [65, 70, 82, 92, 111, 132], and an anisotropic conductive adhesive connected parallel bus signals to a flexible electronic circuit in one project [114].

3.2 Woven-in Components

When electrical functionality constitutes an additional element of the textile structure, the components can be part of the textile's weave. This portion of the paper deals with work in which the integrated component was woven in but not part of the textile's fundamental structure. Woven-in components, defined here as electronic components integrated into the structure of woven fabric, contributed to the work behind, in total, 26 sources [5, 14, 16, 18, 19, 28, 41, 46, 50, 51, 56, 57, 61, 63, 64, 70, 72, 73, 96, 105, 113, 115, 118, 121, 132, 133]. Five of these address systems in which all functionality except power is contained within the woven textile [19, 28, 57, 72, 73] (these sources discuss other components and structures also). Sensors created via woven-in components are the principal subject of five papers [16, 18, 46, 64, 70], and 10 papers discuss outputs or actuators woven into the textile structure [5, 14, 41, 51, 56, 61, 96, 105, 115, 121]. We found descriptions of woven-in inputs *and* outputs in only one paper, for which LEDs and an ultrasonic sensor were integrated into the textile structure [61]. Likewise, a single paper describes energy-harvesting using solar cells [118]. Other woven-in components reported upon are PCBs [16, 63, 132, 133], RFID chips [113], and capacitive yarns for temporary power storage [16, 50].

Woven-in sensing, characterised in sources discussing both systems and inputs, makes use of external modules or components that measure some physical quality that can be translated to useable input for a microprocessor. This translation requires additional electronics and/or an electrical connection, which may reside either in the textile or outside it. For larger components, the textiles commonly have a pocket, with examples being soft potentiometers with soldered wiring from the textile to detect the reclining wearer's posture on a mattress [18] and an ultrasonic sensor encased within a wall-hanging textile so as to detect viewers [61]. In contrast, smaller and thinner components similar to wires/threads or components specifically prepared for weaving can be woven directly into the textile's structure. This preparation generally entails modifying the component into a long wire or yarn that can then be treated as part of the weft. Some components of this sort are simple material-based sensors, such as temperature-sensing-fibre yarn [16] and mechanical strain-sensing filaments [46], while others are 'smart' ones with integrated functionality, such as a Hall-effect sensor for detecting magnetic fields [72].

Sources dealing with **woven-in actuators or feedback components**, including those presenting systems, describe utilising either individual components or sets of them to create a physical effect in the textile. These most often employ light-emitting components, but some change the textile's shape by using pre-treated shape-memory alloys integrated into the structure [105]. Light emission for textiles is implemented either with LEDs [5, 61, 105, 115] or by weaving strands of electro-luminescent wire into the textile structure [56, 121]. The components featuring most commonly in our corpus are LEDs, prepared with soldered wires or yarns that specifically enable weaving [41, 57, 72, 73, 96, 105, 115]. As of this writing, the most advanced example involves creating a cycling jacket with LED yarn designed especially for weaving [41].

Finally, **fully functional woven-textile systems** (with or without an integrated power supply) typically either include a processor or have a sensing element directly controlling the outputs. The only fully integrated textile we found in woven form featured a weavable processor implemented as a wire, a LiPo battery, and three LEDs [73]. An earlier report by the same researchers describes using a Hall-effect sensor with associated LEDs [72]. They sandwiched the components attached to Litz-wires between woven layers. Other papers report using thin, flexible circuit boards and surface-mounted components, enabling thin structures and nearly undetectable integration of programmable electronics [57]. Textiles with a hard circuit board were woven inside a larger pocket, then connected to other components via weaving [19, 28]. These textile structures enabling woven-textile systems are described with more detail in chapter 4.

3.3 Electrically Functional Weaves

An electrically functional weave is an electronic component formed by combining structure and different materials during weaving in such a manner that the resulting component is an inseparable part of the textile structure. Such components thus cannot exist separately from the textile. The requirement is that the materials can be woven and integrated into the textile structure.

Electrically functional weaves account for the largest category in our results by far. They are described in 61 pieces. Several papers (such as those by Berzina and Veja [6, 115]) address several types of component or functional weave, so we identified the primary focus of each and organised the results accordingly. Woven sensors constitute the primary focus of 14 sources [4, 26, 34, 54, 77, 79, 84, 87, 90, 98, 107, 124, 125, 129], and woven actuators and outputs are the main contribution described in 17 [7–9, 21, 30–32, 49, 60, 71, 78, 80, 91, 99, 109, 116, 120]. Three works focus on both inputs and outputs [20, 42, 108]. We found 13 sources describing other woven components (electrodes or other discrete components) and antennas and coils [2, 11, 27, 33, 39, 43, 62, 66, 68, 103, 128, 130, 131]. In addition, six sources address woven components in combination with woven-in ones [5, 16, 19, 28, 89, 96], and five discuss the former in conjunction with electrical signalling [37, 82, 95, 97, 105].

Woven sensors, most often based on *measurement of resistance*, constitute the most commonplace technique. Represented by 16 pieces in our corpus, they have seen use for various types of sensors and input devices. The most extreme form involves contact switches, in which the resistance varies between extremely high (no contact or high-resistance contact) and low (strong contact). Corresponding structures are presented in seven sources [4, 20, 28, 34, 89, 97, 115], with Balgale offering a good demonstration of a woven structure's use for switch-bounce mechanics [4]. An interesting variation of the contact switch is described in 'Involving the Machines': sensing stroking by means of several conductive threads in a clustered tuft that deviates from the surface of the textile [89]. When a hand strokes the conductive-thread hairs, their mutual connection creates a signal whereby the stroking direction can be determined via interpretation. Apart from a report that leaves the type of conductive yarn unspecified [28], all sources mention using stainless steel [4, 20, 34, 97, 115]. Also, one lists magnet wire, Litz wire, and copper wire in addition [20].

Pressure sensors are similar to contact switches but have a continuous range for the resistance change. Therefore, one can use them for measuring mechanical force. They operate either from direct contact between resistive electrodes/yarns or via a piezoresistive intermediate material, such as Velostat, or a spacer material, such as tulle [16, 34, 77, 87, 89, 90, 96, 105, 124]. The sensor set-up can be created as individual sensors enabling interaction at a specific location, by means of Velostat and silver–nylon yarns [96]; in grid form to create an interactive surface with carbon-particle-coated copper wires [87]; or with overall-sensing functionality as seen with a soft potentiometer [124]. Also, researchers have applied resistance-based sensors to sense moisture, using copper [84] and steel [98] yarns.

The second most common form of sensing is based on *measuring capacitance*. Seven sources present it, with the typical implementation being to weave an electrode to create an interaction location for the textile, either to one side by using silver–nylon yarns [96, 108] or on each side separately with an insulated bespoke copper–silver alloy [125]. Also, capacitive grids and lines have been used to create larger interactive areas suited to whole-body measurement [26], smaller grids [95], sliders [105], or just a sensing area in the form of a plate capacitor [129]. Beyond resistive and capacitive sensors, two papers discuss woven thermocouples made from metallic wires, applied for measuring temperature in a shirt [107] and at the legs [54]. Finally, four sources describe the use of optical fibre for sensing. Optical fibres have aided in detection of a bullet impact [37, 82], informed of a joint bending [105], and served in input-mechanism capacity as part of a display [42]. A special case of a sensor utilising the weave's structure is the F-biosensor [16], used for detecting heartbeat. Combining a woven-in component with the woven structure to complete a transistor amplifier, it makes the weave fundamental to the solution's functionality.

Twenty-four pieces discuss **woven actuators and outputs**. Of these, 10 describe thermochromism [7, 20, 21, 28, 60, 78, 80, 91, 116, 120], with one specifying the dye for the colour change as liquid-crystal-based [116]. The heating elements required for this heat-based change were provided by resistive yarns that grow warmer when current is flowing. Two distinct approaches to using thermochromics emerged from the literature. The first one is to weave in ready-made yarn that includes both heating-element and colour-change fibres [20, 21, 60]. The second approach involves weaving in the heating element as a yarn [7, 78, 80, 91, 120] or as a soft cell [116] and then printing on top of this (e.g., via screen-printing) with a thermochromic dye. In another visual-feedback element, which utilises fibre-optics to emit light, the optical fibre is a woven part of the textile structure [8, 9, 30–32, 42, 49, 99, 108–110]. In one setting described, the optical fibre interacts with an external light source, and the two together create a colour-change effect by means of photonic bandgap fibres [99]. Another source discusses electro-luminescent wires as a part of the textile structure [33]. The literature presents physical actuation as achievable via shape-memory alloys [34] and polymers [71].

Several **other woven components** and electrical structures have been documented. Seven of them involve on-skin electrodes for measuring biosignals. The researchers reported on silver-coated yarns [2, 19], silver–silver-chloride yarns [130, 131], stainless-steel yarns [2], a combination of stainless-steel and Litz-type wires [43], and silver-polymer twisted yarns [103]. Electrode-like structures featured in the 'Involving the Machines' work too, with the team testing various types of conductive yarns [89]. We also found a source discussing the development of electrodes suitable for sensing static electricity [6]. In addition, seven papers present other types of electrical components, used to create a resistor [115], a plate capacitor [27], an inverter-structure [11], an RFID antenna (several metallic treatments of silver-coated polyamide monofilament were tested) [33], various microwave antennas [62], a power-transmission coil using copper yarns [128], and a magnetised thin-film wire used as a memory element [68]. Finally, two energy-generation mechanisms were identified – a piezoelectric generator using PVDF microfibres with a conducting core [66] and woven triboelectric generators utilising various non-conductive materials and silver-plated copper–nylon yarns [39].

4 WOVEN STRUCTURES FOR FUNCTIONALITY

Many aspects of woven structures render them suitable for eTextile prototyping. As our categorisation in Table 2 attests, the varieties of woven eTextile structure range from simple weaves to complex structures in which several sets of warp and weft yarns make up textiles with multiple intertwining layers. We examine the major woven eTextile structures below. Figure 3 provides an overview of them. We remind the reader that nine sources [6, 7, 13, 33, 38, 51, 61, 107, 113] were excluded from the structure-related analysis presented in this section, as they did not provide enough information about the woven structures used in integration of electrical functionality.

4.1 Simple-Weave Structures

Simple weaves are used to form a stable one-layer structure within which functional and traditional textile yarns contribute equally to the textile. We found 36 sources [2, 5, 9, 11, 23, 24, 26, 28, 42, 49, 50, 56, 65–68, 70, 71, 77, 82, 87, 89, 90, 93, 94, 98, 105, 111, 116, 120, 121, 129, 131–134] presenting woven eTextiles based on simple weaves. The simplest woven structure, **plain weave**, can be used as-is to interweave purely functional yarns, thus creating functional weave elements such as memory units [68] and sensors [129]. Plain weave also provides a stable base and organised yarn arrangement for various combinations of functional and traditional textile materials (e.g., for constructing electrical signalling). Plain weave has provided a foundation for integrated signal traces [23, 24, 93, 94] and for embedding a network [65, 67, 82] in which the conductive weft-yarn organisation is supported by the woven structure and can be designed to match the pin order of components attached to the textile after weaving. Tao et al.'s work [111] included conductive yarns for signal traces in both warp and weft for attaching an LED array to the textile surface. The capacity to include functional yarns in both directions opens possibilities for constructing woven circuits – for example, integrating narrow thin-film PCBs [132] and components [70, 133] into the plain weave. One can weave flexible plastic strips within the structure as weft yarns and connect these to the woven circuit via conductive warp yarns. An orthogonal yarn arrangement is suitable also for forming functional weave structures. The woven plain-weave structure in one project [11] employed three distinct fibres in the warp and weft – conductor fibre, spacer fibre, and transistor fibre – to form a thin-film inverter. In Joshi's work [50], in turn, the warp and weft systems utilised supercapacitor e-yarns to fabricate a woven energy-storage device. Using conductive warp and weft yarns also enables creating grid structures capable of sensing touch and pressure [16, 26, 87, 98]. For the pieces exemplifying this category of work, functional materials were incorporated into both warp and weft, with the resulting structure being able to sense the textile's deformation at the intersection points of functional yarns, whether these used conductive yarn [16, 26], resistive yarn [87], or optical fibre [98].

Plain weave is suited to constructing illuminative textiles also [9, 42, 49]. Bigger and Fraguada [9] employed optical fibre in both warp and weft to create a visible criss-cross pattern, whereas Hashimoto et al. [42] chose optical fibres exclusively in the weft to fabricate a uniform display surface for illumination based on bi-directional data communication. Similarly, Jing's [49] weft system applied solely optical fibres in forming an illuminative textile for phototherapy. Heating elements too function to activate woven displays [14, 116]. The heating element is woven with conductive weft, and the resulting textile is coated either with thermochromic pigments [14] or with liquid-crystal ink [116] after weaving. In these examples of textile-based displays, plain weave provides a solid base structure for the integration, with minimal visual interference.

Alongside plain weave, the literature offers examples of **other simple weaves**' utility in eTextile construction. In waffle-weave pressure sensors [28, 89, 90], the yarn arrangement increases the volume of the porous structure and, thereby, the distance between yarns. When the textile is pressed, the resistive yarns' denser connection decreases the overall resistance of the structure. Also, one can create a resistive sensor by allowing parts of the conductive warp and weft yarns to float at certain locations for insertion of Velostat within the float span [77]. Kisand [56] used satin weave to integrate electro-luminescent wires into a textile and, thereby, create a curtain with an ambient light source. The base textile is woven with weft- and warp-faced satin weaves arranged in stripes, and the varying tension on the warp and weft yarns in the individual regions causes the fabric to undulate. The resulting pleated structure is utilised to control the visibility of the EL wires within the textile. Similarly to satin, twill has longer weft and warp floats, for opposite sides of the textile. This type of weave has facilitated, for example, integration of signal traces [134].

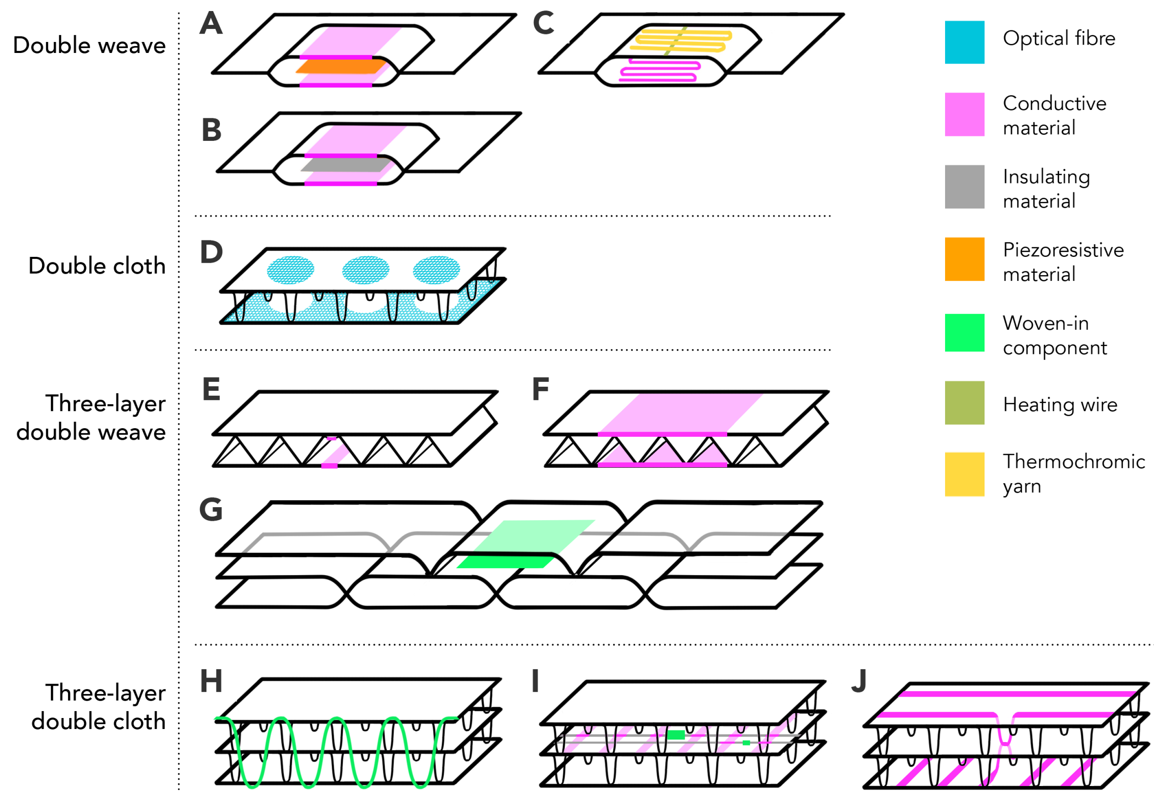

Figure 3: A sampling of the two- and three-layer structures identified in the literature review. The corpus provides examples in classes A [20, 34, 96], B [115], C [105], D [99], E [4], F [27], G [118], H [46], I [73], and J [92].

Several authors have noted how **differences between simple-weave structures** influence the resulting eTextile's electrical properties. Their comparisons have addressed such applications as woven sensors. Parzer et al. [87] examined how increasing the length of resistive yarn floats influences the sensitivity of the sensor structure. They found that the intersection points' density in a plain-weave setting reduces the sensitivity range of the resistive sensor as the functional yarns get compressed by the structure. Reducing the yarn tension at dense intersection points can address this issue (e.g., the yarns in Panama weave are in a more relaxed state). Also, optical fibre has been integrated with an elastic twill base for creation of a stretch sensor [105]. The authors made an observation similar to Parzer et al.'s with regard to the influence of yarn floats' length: the twill weave has fewer intersections than plain weave, thereby letting the elastane and optical-fibre wefts stretch while maintaining structural stability.

Arquilla et al. [2] and Zhang and Zhong [131] have compared how various simple weaves influence the performance of electrodes for electrocardiogram. The results suggest for example, that creating shorter yarn floats improves performance, as it lessens yarn movements within the electrode, whereas longer floats provide better skin contact. Differences among simple weaves (namely, plain weave, weft rib, and twill) have been compared also in the context of piezoelectric textiles [66]. The research indicates that the balance of weft and warp coverage between the two sides of the textile is an important factor in its piezoelectric properties.

4.2 One-Layer Structures and Additional Yarns

Additional sets of weft and warp yarns have been used to enhance woven eTextiles' structural versatility and electrical properties. We identified 22 sources that address this in terms of a one-layer structure comprising at least three separate yarn sets [5, 14, 21, 28, 30, 43–45, 62, 69, 84–86, 89, 91, 95, 95, 96, 114, 124, 125, 128]. These include structures woven with either supplementary or complementary yarn, presented in the following two subsections, respectively.

4.2.1 Simple weaves and supplementary yarns. In all, 16 sources mention supplementary yarns in simple-weave-based textiles [5, 5, 14, 21, 28, 43–45, 62, 69, 89, 95, 114, 124, 125, 128]. The normal use of supplementary yarns in simple weaves is to add functional elements to specific areas of a textile and to position functional yarns on the designated side of the fabric. Several weaving techniques suit these purposes. Among them is **inlay**, a technique for inserting a continuous additional weft yarn in a solid base woven textile. The additional weft may be embedded either within the weave structure of the base fabric [5, 28, 62, 124] or by means of another weave structure for the supplementary yarn [21]. In the corpus's examples, inlay afforded creating figurative colour-changing areas with yarns coated in thermochromic pigments [21, 28], antenna structures [62], a moisture sensor [5], and a potentiometer embedded within a textile item woven with tapestry weave [124]. Somewhat resembling the inlay technique is **serpentine lace**, a method that has served the creation of flexible structure for signal traces [44, 45]. Also, Huang et al. [45] used **tapestry weave** for creating well-separated areas to form a 3D shape. The same weave has been used to situate electrodes within a wider textile surface for electrocardiogram measurements [43].

Fil coupé, in turn, is suitable for weaving several separate supplementary weft and warp strands. This technique entails integrating conductive yarns of specific lengths into the base fabric to form coil structures for antennas [128]. Poupyrev and colleagues [95] coated conductive core yarns with textile fibres and embedded these in warp and weft to form a capacitive grid structure on the textile surface. Their paper does not describe any particular structure for the base fabric, yet it is a good example of how supplementary yarns can be added to a range of base textile structures from simple to complex weaves. The *fil coupé* technique can be utilised to create a hairy surface texture at specific locations [89]. With supplementary conductive-yarn clusters connected to conductive paths in the structure, long floats get formed on the textile's surface and are cut after weaving. The textile can function as a stroke sensor in the above-mentioned fashion (stroking the conductive tuft creates connections between separate yarn clusters).

With supplementary yarns, one also can situate functional yarns on the relevant side of the fabric. This approach has been applied [114] for weaving additional conductive weft yarns on one side of the textile, where components can be attached. In other work [69], floats at the top of both warp and weft have served a similar purpose. In another application, conductive yarns are situated in parallel on both sides of a woven textile, to form a sensing element that enables double-sided interaction [125]. With shape-memory alloys integrated via supplementary weft on the underside of the textile, Cabral et al. [14] created shape deformations based on origami folding.

4.2.2 Double-faced weave. **Double-faced weave** structures, mentioned in seven pieces [30, 84–86, 89, 91, 96], introduce structural variations in one-layer woven eTextiles. Adding complementary sets of weft lets one fabricate two-sided woven textiles, in which, for example, one side makes the functional properties available while the other side of the textile provides insulation, as in Perner-Wilson and Satomi's work [91] and Parkova's [84]. The woven 'heat fabric' developed by Kobakant [90] provides a heating element, woven with double-faced satin weave, for use in screen-printing using thermochromic pigments. On the underside of the textile, every eighth weft yarn is copper yarn, whilst the top side is white cotton. The double-faced weave ensures that the copper yarns are near the upper surface while the cotton weft supplies a blank base for screen-printing and isolates the pigment from the copper yarns. Gauvreau et al.'s article [30] presents another example of double-faced structure for textile display. Here, a complementary set of optical fibres is woven within a plain-weave base fabric, with its longer yarn floats on the upper surface of the display, for maximal illumination. Parkova [84] used double-faced twill similarly, to construct a two-sided moisture sensor by integrating copper yarns into warp and weft, with cotton yarns on one side and insulating cotton on the other.

Increasing the number of further weft-yarn sets enables the added yarns' use to, for example, weave patterned **jacquard** fabrics. Each individual yarn set can have its own properties, such as distinct colours or materials, as introduced in work by Parkova and colleagues: the authors used multiple weft systems to weave a figurative textile with conductive yarns for signalling in weft [86] and in both weft and warp [85]. The conductive yarns float on opposite sides of the fabric, either in parallel [86] or at the weft/warp junctions [85], and LEDs are attached to the floats. The LED arrangement meshes with the pattern design, and the base textile's weave is designed to support hiding the LEDs while still enabling light penetration.

Other work [96] interwove conductive weft within figurative double-faced jacquard fabric, forming capacitive sensors for measuring touch.

In the 'Involving the Machines' [89] design, a loop of an additional conductive yarn is pulled above the surface of a double-faced jacquard pattern. The figurative pattern places conductive weft-faced areas within reach of a metal bead attached to the loop. This touches the conductive sections when the fabric tilts.

4.3 Two-Layer Structures

Two-layer structures (namely, double weave and double cloth) have been applied frequently in woven eTextile construction. As multiple sets of yarns constitute the textile, these structures enable more complex structural hierarchies and versatile material combinations, thus expanding the range of properties possible for woven eTextiles.

4.3.1 Double weave. **Double weave** (shown in Figure 3, A–C) is the complex structure appearing most often in the woven eTextile literature we reviewed. They are mentioned in 32 pieces [5, 8, 18–20, 28, 31, 32, 34, 37, 39, 43, 50, 54, 56, 57, 60, 63, 64, 78–80, 82, 89, 96, 97, 99, 105, 108, 110, 115, 118]; however, four of these [43, 78–80] were excluded from analysis because they do not describe how the functional structure is constructed. The capability of weaving two separate textile layers simultaneously has served the creation of pockets, tubes, and fully separated textile layers for integration of various functions.

Pocket structures allow for such uses as location-specific housing of hardware components inside a textile. Pockets permit situating a PCB at close proximity to other functional elements while also protecting against damage to integrated electronics from outside [19, 28]. Pocket structures offer many possibilities also for constructing functional weaves for sensing. Three sources describe a pocket structure consisting of conductive yarn woven in both layers, with a sheet of piezoresistive Velostat foil placed between the two [20, 34, 96]. Additionally, Pouta and Mikkonen's paper [96] describes using a double-faced structure for each separate layer and employing conductive weft for the inner surfaces of the pocket's layers while colourful cotton yarns provide facing for the exterior surfaces. This yarn arrangement can improve the conductive-yarn–Velostat contact. Besides Velostat, one can place a piece of tulle within a double-weave pocket of this type [34]. The tulle enables contact to be formed through the mesh structure while it is pressed. This exemplifies the principle that different materials between the pocket layers permit obtaining differing electrical functionality. One application [89] filled a double-weave pocket with conductive weft floats. As Devendorf et al. [19] demonstrated, the material can serve non-electrical purposes too. Their paper presents a headband in which a soft and porous fill material in the pockets gives wearers of the textile device a better fit for its electrodes. Separated pocket layers can provide switch functionality even when no material is between them – for instance, in a pressure-sensitive structure wherein conductive warp and weft yarns cross in the overlapping layers [97]. Researchers have followed a similar principle to craft a multi-function double-weave structure [20, 28]. The underlayer uses conductive weft yarn, and the top layer features two types of additional conductive yarn: embedded heating yarns and yarns coated with thermochromic pigments. Pressing the structure triggers a colour change. Another paper presents a double-weave structure of this general nature for thermochromic actuation but without a pressure sensor [60].

Weaving two layers to remain separated over their full width forms **tubes** in a woven textile. Tube structures have been used to insert components (such as solar panels [118] and circuit filaments [57, 63], strain-sensing yarns [64], supercapacitors [50], potentiometers [18], and LEDs [5]) and routing wires [20] between the textile layers. They have seen use also for fabricating a two-layer optical-fibre display that changes colour in response to hand gestures [110]. Optical fibres are woven into the tubes' upper layer, and a camera module resides within the tubes for computer-vision-based gesture recognition. The corpus describes using double weave also in illuminative textiles [31, 32, 108].

Alternatively, one can keep the two layers entirely separate. **Separated layers** permit, for example, the wearable motherboard [37, 82]. Among the very first eTextile research endeavours, it laid the foundation for further research in this field, and it remains one of the few examples of applying weaving to construct 3D shapes for fully fashioned woven eTextile garments. The tailored outcome is obtained by constructing a tubular structure via double weave. By means of individual continuous weft yarns helically interlaced in both layers, the layers become connected from the edges. The weave contains several materials, each serving a distinct purpose. In the weft direction, polypropylene yarns complemented with spandex fibre for better fit form the base tubular structure, and two distinct sets of optical fibre are woven in at each side for detection of bullet penetration. Conductive yarns in both warp and weft support a bus structure. The warp contains, alongside these, polyester- or nylon-coated trilobal conductive core yarn, for releasing surface electrostatic charge. For arm holes, the layers are separated, and both layers are woven with designated weft-yarn sets. Using separated layers has shown potential likewise in constructing triboelectric textile structures [39], providing an air gap between two layers' woven thermocouple temperature sensors [54], and controlling light penetration in an ambient EL-wire-based light source [56]. The separate layers may differ in width. For switch fabrication, Devendorf and Di Lauro took this approach [20]. The warp set for an additional layer covers a portion of the fabric's width, and weaving uses either a single weft or multiple two-layer areas woven in parallel with one weft that floats between the regions.

In smaller-scale textile fabrication, a structure with two, separated layers supports crafting multi-function on-skin interfaces. Sun et al. [105] have presented three examples of **multi-functional double weaves**, which combine different types of sensing and actuating capabilities. One of them implements a top-layer seven-segment display woven with thermochromic yarns and heating wires in conjunction with a bottom layer of conductive yarns for capacitive sensing. For the second, the authors combined a smart-memory alloy in the top layer with Velostat enclosed within a conductive-yarn pocket, for pressure sensing and haptic feedback. The final example showcases a double-weave structure providing an SMA spring for haptic feedback (interwoven into the underlayer) and a woven-in LED for visual feedback (partially interwoven with both layers). Interconnecting the layers renders the structure more stable and secures the connection points between the LED and the spring. Furthermore, multi-function eTextile elements can be integrated into fully woven circuitry. The literature offers diverse examples of integrating signalling, woven-in components, and functional weaves into double-weave-based structures [115]. Our corpus introduces three prototypes (an RGB colour mixer, CPLED v. 2, and BHM v. 4), which represent the range of structures comprehensively. Here, the circuits rely on a conductive-warp set connecting the distinct functional weaves and woven-in components to form a single system. The structures use, for example, double-weave pockets for housing LEDs and coin batteries, which signal traces in both warp and weft connect to woven circuits, while pockets or tubes filled with cotton fabric provide insulation. The researchers wove the samples with a dobby loom with two warp beams, so as to implement pleat structures for switches. The structures also use magnetic connections for attaching various eTextile modules to the same circuit. The battery-holder demonstrates another feature: after a coin battery is inserted between the layers, the textile is folded to form a casing, and magnet connections handle the contact between the battery and conductive areas within the textile.

4.3.2 Double cloth. The literature presents 10 examples of employing **double cloth** (see Figure 3, pane D) to construct woven eTextiles [3, 41, 72, 83, 99, 103, 108, 109, 129, 130]. Relative to double weave, double cloth acts as a firmer base for integrating functional elements, thanks to its interconnected layer structure. Hence, double cloth is typically used for sealing supplementary functional yarns or yarn-like components inside a textile, isolating them from external exposure and protecting the wearer from the system both. The corpus presents LED yarns [41] and Hall sensors and LEDs (attached to wires) [72] interwoven within the structure as yarns constituting the fabric, and sandwiched between the layers. Bahadir et al.'s work [3] wove conductive yarns between the layers, for signal traces, and lifted a loop of the conductive weft to the top of the surface, for attaching external components. A sturdy double-cloth structure is suited also to insulating conductive materials woven into the opposite layers of the textile. Parkova [83] presented an LED matrix based on a grid structure woven with copper yarns in weft and warp. In this design, the LEDs are partially connected to copper weft yarns before weaving and woven in the top surface of the textile. After weaving, the LEDs are attached to conductive warp yarns in the bottom layer. Both layers have either weft- or warp-faced satin weave, with outward-facing floats at the surface, and the textile's structure naturally prevents unwanted contacts between conductive yarns.

Also, double cloth has been used directly to construct functional weave elements. For example, two-layer structures provide visual versatility for woven fibre-optic displays. Both double cloth and double weave are unlike simple-weave-based displays in allowing figurative patterns' inclusion within a textile surface woven with optical fibres. Two works [8, 99] address a two-layer structure consisting of a cotton warp divided for two layers and a weft set of both cotton and optical fibre. The research explored the use of both double-weave and double-cloth structures, alongside the capability of switching the order of the layers (woven with either cotton weft or optical fibre) in accordance with the figurative pattern. Optical-fibre thickness influenced the choice of weave structure: thicker fibres were used with double weave because the fibre provided sufficient rigidity, whereas interlocked layers provided support for a textile woven with thinner fibres. With the stiffer interconnection structure, the optical fibres bent at the point where the layers crossed. Tan et al. [109] used double cloth similarly to provide surface texture and visual versatility for woven displays. Double cloth has functioned in the construction of capacitive sensing elements too. Zhang et al. [129] presented a study of various weaves' influence on the behaviour of a capacitive sensor structure. Comparing plain weave to double cloth, they found that, since a double-cloth structure increases the volume of the textile and subsequently increases capacitance, double cloth is more appropriate for detecting external pressure on fabric. Double cloth can be applied also for fabricating electrodes for biosignal measurement [103, 130]. It enables positioning the electrodes in the top layer, which is worn against the skin, and the cotton warp yarns' density can be reduced in the electrode areas, for better skin contact [103]. Scholars have examined optimising the material selection for wearer comfort – Zhang and Zhong [130] took advantage of polyester yarns' water-absorbing properties to create a top layer that absorbs sweat, for greater moisture-related comfort.

Three sources refer to using **double-cloth and double-weave structures within the same woven eTextile** [31, 32, 108]. Tan et al. [108] took this approach for constructing illuminative pillows with a touch-sensitive figurative pattern. The base fabric – woven with optical fibres and elastic yarn – is a firmer double cloth, while double weave is used for areas where capacitive sensors are located. A supplementary conductive weft is woven for the upper layer of the sensor structure, otherwise floating on the underside of the textile to be cut or connected to electronics after weaving. The use of different weaves and elastic yarns renders the capacitive buttons visually distinct, and their protrusion from the surface provides haptic feedback that supports interaction. Finally, researchers [31, 32] used a combination of double-weave and double-cloth structures with elastic yarns to create stretchable illuminative textiles and various 3D surface textures.

4.4 Three-Layer Structures

The eTextile literature offers a few examples involving three-layer structures. Of the 10 projects applying these in woven eTextile fabrication [4, 22, 27, 33, 43, 46, 73, 89, 92, 118], the reports on five mention using a **three-layer double weave** (refer to Figure 3, E–G). Eriksson et al. [27] and Balgale and Baltina [4] described a sensor structure that utilises two warp beams and the ability to weave layers of different lengths with various proportions of weft yarn to achieve a more voluminous textile. For creation of a 3D structure, the middle layer is repeatedly woven longer to form a spacer layer with alternating connections to the outermost layers (the upper and lower layer). Eriksson et al. used this technique to construct a woven capacitor with uniform areas of conductive yarn in the top and bottom layer. In Balgale and Baltina's design, in contrast, the middle layer forms hollow sections at specific locations, and compression connects conductive materials woven within the opposite layers of a switch. A three-layer construction can provide additional means of creating visually elaborated textiles for integration of woven-in components, as Wirtanen has attested [118]. Such applications dedicate the middle and bottom layer to the figurative pattern. They intersect in accordance with the given jacquard pattern. The top layer, which is woven with transparent fishing line, for maximal light penetration, intersects with the layer below to form a tube for solar-panel insertion. Finally, two sources describe functional structures' fabrication via a three-layer double weave (for a switch [89] and electrodes [43]), but lack of information precludes more detailed analysis.

Five papers address the final mechanism, making use of **three-layer double cloth** (per Figure 3, H–J) [22, 33, 46, 73, 92]. These explore the weave structure's use for woven-in components' integration and to insulate conductive warp and weft yarns in either signalling or functional weave construction. Studies have integrated carbon-fibre-based strain sensors into three interconnected layers to investigate various binding patterns that could stimulate increased sensor-fibre undulation [46]. While resulting in lower sensitivity and linearity, increasing the undulation reduced hysteresis. Mikkonen and Pouta [73] found that a three-layer structure provides insulation and protection when the system is interwoven with a middle layer that is interlocked with the outermost layers. The warp included 11 lines of conductive yarn, each connecting to a conductive counterpart in processor wire, as well as to LEDs and a battery. All components took a modified, yarn- or ribbon-like form that enabled interweaving them in the weft of the middle layer's functional plain-weave structure. Three sources [22, 33, 92] deal with a middle layer insulating the top and bottom layer, which comprise conductive materials, from one another: Dhandhania's paper [22] presents a signalling structure suitable for attaching LEDs to the woven-textile substrate. Pieterson et al. [92], in turn, constructed grid-based signalling by situating conductive warp and weft yarns in opposite layers, with these being drawn to the middle layer at selected intersection points to form a galvanic connection. Similarly, Gimpel et al. [33] formed a coil structure for an antenna by positioning lines of conductive weft and warp in the top and bottom layer, which were interconnected at specific locations in line with their design.

5 INSIGHT FROM THE LITERATURE REVIEW

The body of literature reviewed attests to great diversity in the weave structures and weaving techniques that have been used to construct woven eTextiles, across a wide spectrum of purposes. From cataloguing both electrical and structural characteristics of woven eTextiles as presented by sources across various fields of research, we are able to conclude that merging electrical functions via encapsulation in traditional textile materials at structural level provides a solid foundation for fabricating woven textiles with interactive qualities. With the discussion below, we examine those characteristics in depth and then offer our suggestions for ways of considering them more holistically, to advance research in this multidisciplinary field. Finally, we propose some concrete actions that hold potential to take research in this field further.

5.1 What Enables Interactive Functionality in Woven eTextiles

Three core characteristics of weaving together enable construction of versatile woven eTextiles. Firstly, the orthogonal arrangement of their warp and weft yarns makes woven textiles structurally stable, providing a suitable base for eTextile construction [77, 92, 97, 103, 118, 129]. Second is the facility of precise control over how the weft and warp yarns intertwine within the woven structure [21, 43], from utilising a Jacquard loom and/or techniques such as weft and warp patterning. Thereby, researchers and designers can bring together a vast array of conventional, functional, and digital materials in an integrated weave structure, thus expanding the sensorial, electrical, and interactive capabilities of woven eTextiles. With precise yarn control, one can construct complex structures at minute scale, even down to micrometre level [33]; control the density of multiple sets of warp and weft yarns [118]; and design textile-area-specific layouts [4, 95]. Thirdly, because several fibre types can contribute to the woven textile, the resulting construction may take advantage of multiple individual materials' characteristics. Those numerous characteristics have a wealth of implications for how we approach woven eTextiles as multi-material composites, construct complex circuit topologies, and design the aesthetic and tactile properties of woven eTextiles. We examine these next.

5.1.1 Precise yarn control for multi-material combinations. First of all, precise yarn control enables mutual integration of many types of materials, over a wide spectrum – from traditional textile fibres to versatile functional materials – within the same construction. The material combinations can provide versatile haptic experiences [e.g., 105], serve multiple functions simultaneously [e.g., 28, 56], incorporate materials with various electrical properties [e.g., 33, 39], and bring together several digital and physical characteristics [e.g., 16]. One can employ the functional materials in various combinations both in warp and in weft [73, 87], with their presence ranging from single supplementary yarns [e.g., 5, 64] to entire complementary yarn sets [e.g., 32, 110]. The ability to construct functional elements for multiple properties by means of a single textile-construction process has been cited as one of the key benefits of weaving in eTextile development [4, 27, 37, 39, 43, 73, 85].

The repertoire of yarn-like functional materials suitable for weaving is broadening rapidly as material science and flexible electronics advance in leaps and bounds. This development is reflected in the literature reviewed. Today's toolbox contains far more than conductive yarns and fibres. Functional materials for woven eTextiles can react to physical changes and produce a corresponding electrical change, as piezoresistive materials [e.g., 46, 77, 103] and strain-sensing yarns [64] do; change colour in response to temperature variations [19, 21]; form embedded weaving-specific semiconductor-devices [41, 73] and narrow flexible circuit boards [e.g., 57] in yarn-like form; and transmit light signals, for sensing [37], lighting [99], or both [42]. It bears repeating that not just the electrical capabilities but also the textile materials' properties contribute to the functionality of the eTextile. Material combinations can utilise properties specific to certain textile fibres, such as transparency, for making sure as much light reaches solar cells as possible [118]; shrinking, which can increase structural stability [86]; absorption of water, to increase user comfort [130]; and elasticity, to improve sensing [64], the wearer's comfort level [19, 69], and skin contact [19].

5.1.2 Yarn control to facilitate complex circuit topology and multi-component interfaces. Secondly, precision in the control of yarns allows the integration of *complex circuit topologies and multi-component interfaces* at structural level [44, 45]. Designs may include signal traces, vias, input and output components of various sorts, and processing power [e.g., 73, 105]. Woven structures seem to share some characteristics with constructions familiar from electronics, such as multitouch sensor panels [95] and multi-layer PCBs [73]. They can also provide a structurally stable base for interwoven connections [92, 103], a network [97], construction of resistive [77] and capacitive elements [129], and components' mutual integration [118]. Authors addressing component integration typically identify the interface between the hard and the soft structures as one of the main issues in woven eTextile fabrication [e.g., 46, 73, 85, 95, 99, 115, 128]. Also advantageous is structural variation of woven multi-layer textiles for purposes of supporting the desired electrical properties – e.g., greater distance between capacitive layers [27] or yarns [129] and undulation of functional yarns [46]. Another feature in the electrical domain is how complex weaves enable mutually distinct designs for the two sides of a woven textile, thus affording double-sided capacitive sensing [125]. In addition to possessing conductive, capacitive, and resistive capabilities, woven structures are used for isolation in various ways. Multi-layer structures sealing the conductive yarns within the structure isolate it from external exposure while also protecting the wearer from the system [3, 73, 85]. Complex weaves can help isolate the conductive yarns within the structure and protect it against short circuits [27, 86, 97]. With simpler weaves, one can still isolate particular conductive areas of a textile surface from each other, by means of weaving techniques such as inlay [21] and yarn floats [89]. Larger components too can be protected: sealing electronics inside woven structures – e.g., sandwiching components between the layers of a double-cloth structure [41, 72, 73] or housing hardware in double-weave pockets [19, 57] – protects integrated electronics from external damage etc.

5.1.3 Visual and tactile surface characteristics. Furthermore, the material combinations and yarn arrangements determine the appearance and tactility of woven eTextiles. In various writings, researchers identify woven textiles' aesthetics potential as a crucial contributor to eTextile construction [20, 20, 28, 32, 43, 73, 85, 86, 89, 95, 96, 105, 109, 118]. This aspect often ties in with a textile-design-driven research orientation. Authors often emphasise the seamless integration supported and the capacity to hide the functional elements inside the woven structure. For example, when the lower layers in a multi-layer structure supply the functional characteristics of the eTextile, the top layer may become a site for textile design expression that considers the feel and look of the fabric [see, for instance, 20, 105, 118]. The functional elements can be either wholly merged with the visual and tactile properties of the woven textile [e.g., 39, 41, 57, 95] or made a distinct part of the pattern design [e.g., 7, 28, 85, 86, 96], becoming an element of the product's aesthetics. Moreover, designers can exploit distinct visual cues to support user-interface design. For example, they might denote the location of touch-sensitive elements [96, 110].

Besides visual aesthetics, the materials and surface textures determine the haptic properties of a woven textile. They can, accordingly, give tactile cues that support surface gesture-based interaction. Distinct textures' tactile feedback could provide readily distinguishable haptic experiences via a textile interface capable of recognising specific hand gestures, and it could facilitate identifying the functional portions of the textile's surface [89, 95].

5.2 What Is Missing and How Weaving Can Advance HCI

The clearest gaps found in current eTextile research are visible directly from Table 2. We acknowledge that our focus on complex woven structures in eTextile construction left descriptions of simple weaves beyond the scope of our supplemental database searches, and the literature's inconsistent eTextile terminology may have led to relevant records' omission from the search results. However, we are confident that our inclusion criteria yielded a good representation of the multidisciplinary woven eTextile research relevant for HCI. Several categories articulated have seen very little or no HCI-related research. For example, many research possibilities related to multi-layer structures' use remain uncharted. Studies have explored three-layer structures quite sparingly, though their potential has been discussed by several authors, who envision multi-layer weaving as an avenue for constructing structures equivalent to multi-layer circuit boards [20] or more versatile sensor structures [35]. In addition, as noted in the literature, double-weave and double-cloth structures can be combined in a single textile [31, 32, 108], although multi-layer structures have not yet done so. Exploring such integration could shed light on how a stable double-cloth base might support circuitry integration analogous to that suggested with WovenProbe [45]. Likewise, flexible circuit boards could be integrated within double weave, as Komolafe et al.'s work suggests [57]. It is worth noting also that work on multi-layer weaves has not gone beyond three-layer structures, even though the only restrictions to the potential layer count are those imposed by the loom. On the other hand, a broad base of reports on woven 3D textile composites attests to thriving work on multi-layer structures [e.g., 10, 12]. These sources could stimulate exploring the possibilities of multi-layer structures in woven eTextiles further.

5.2.1 Research on sensoriality and woven eTextiles. We have noted that researchers extol the sensorial potential of woven eTextiles and that scholars have identified the ability to fabricate visually and tactually pleasant eTextiles as one of the major gains that complex weave structures and material combinations enable. However, the full spectrum of interaction that the various visual and tactile surface characteristics could afford has only been briefly noted by a few authors [89, 95, 96, 108], no matter how much promise they hold for the materiality of interaction [117]. Variations in textile stiffnesses, yarn densities, material textures and colours, structures, figurative patterning, and component-placement options are all ripe for research. Surface textures and tactility alone provide a vast area to attend to, before one even considers the context of use. Work that considers several textile-design variables (such as visual and tactile characteristics) in combination with embedded functional structures would provide an interesting bridge, for establishing a design space for tactile interaction in woven eTextiles. For instance, work investigating surface texture for informing users of gestural interaction could take direct inspiration from Mlakar et al.'s studies [74, 75], thus yielding an immediate step forward. Double-faced weave represents another research gap. Not yet charted in the current literature, it could offer further means to construct visually and tactually versatile surface characteristics while embedding functional materials within the inner structure of a multi-layer weave. Its capacity to create two-sided textiles can serve multi-layer structures by forming layers with distinct sides [96]. In addition, 3D weaving allows fabrication of clear relief patterns on the textile surface [122]. It could offer interesting directions for combining complex functional weaves and surface textures in touch-based interface layouts.

Furthermore, most textiles considered in the corpus were flat or exhibited minimal shape variations, yet truly 3D structures and shapes that extend from the textile present interesting unexplored opportunities for HCI. Work involving interactions similar to those with Karrer et al.'s Pinstripe [53] could pay dividends in combining multi-layer double cloth with multi-layer double weave. In another 'quick win', the fully fashioned woven objects enabled by weaving could be directly exploited within tangible user interfaces [47]. Nonetheless, the wearable motherboard, which is based on a relatively simple double-weave tube structure, is the only example of fully fashioned eTextile garment presented in the corpus. Multi-layered 3D weaves enable the fabrication of far more intricate fully fashioned objects, exemplified by a 3D woven shoe [123]. In our view, this path holds promising opportunities for research into 3D textile interfaces. Finally, we see a great opportunity in work focused on material-specific eTextile interaction design [40] and on how the textile deformations occurring in the interactive textile objects' real-world use contexts could inform designing the forms of interaction for these interfaces.

5.2.2 Fully woven eTextile systems' benefits for research and commercialisation. Finally, we detected a lack of fully woven eTextile systems for HCI. Most sources we investigated approached woven eTextiles as swatches, with focus on constructing or integrating some specific components, for later connection to an external box of electronics. Clearly, filling this void would advance eTextiles not as mere research objects but as commercial products as well. From the standpoint of fashioning an interactive product, the interface layout must be designed to match the weave structures [e.g., 19, 105] and the sewing patterns or form of the final product [e.g., 43, 96], but also the eTextile has to be scalable and otherwise prepared appropriately for production [27, 57, 95]. The scalability goal for independent woven eTextile systems is a two-pronged one. Firstly, scaling for production must be rendered reliable, to ensure that the industrially produced woven system behaves similarly to the prototype developed for research and development purposes. Secondly, reliable methods must exist – and be in place – for scaling both the functional weave structures and the woven circuitry's layout in the sewing patterns, in terms of physical dimensions and location. While the fashion and clothing industry employs set specifications for grading the patterns for particular sizes [100], taking a similar approach for scaling the electrical functionality integrated within textiles is impossible. Scaling it introduces several issues, including how the electrical signalling or the interactive/measuring elements scale. Resolving these issues promises great rewards, however. Finally, with scaling come opportunities to produce woven eTextiles not only for wearable applications but for industrial and commercial textiles far beyond direct human interaction. We see vast potential in industrial applications such as tarpaulin, textiles for building-façade elements such as awnings, rigid woven structures (e.g., carbon-fibre plates and vehicle covers), and protective textiles.

5.3 Propelling Woven eTextile Research and Practice

We appeal for action to advance woven-eTextile-related research and practice. Below, we offer both short- and long-term suggestions accordingly.

5.3.1 How woven HCI can be advanced immediately. Our primary concern is the lack of documentation in the reports. Authors should strive to make all relevant design files, schematics, layout drawings, and (especially) weaving patterns accessible. Furthermore, the information should note the specific yarns (or, at minimum, their material) and the material's age. For example, stainless-steel fibres are likely to form a semiconductive layer due to ageing, which changes these yarns' electrical behaviour [127]. If specific machinery is used, details of it and the setting help lower the barrier to reproducing the results. We hereby issue a call also for improving the terminology and using correct definitions and names for the construction methods and woven-textile structures. Current use of woven eTextile nomenclature shows large fluctuations and, at times, imprecision, with terms such as 'double weave' and 'double cloth' getting used interchangeably. Also, the details of the electrical functionality should be stated explicitly, not confined to vague mentions that describe only an interaction. Because eTextiles represent a relatively young field, establishing consistent documentation is especially vital for reproducibility.

5.3.2 The need for tools, design methods, and new disciplines. Our literature review shows that the disciplines intersecting in the eTextiles field contribute to the research through their distinct perspectives. For example, material science constantly introduces novel materials suitable for integration of particular functions whereas electrical engineering pushes the boundaries of flexible circuit boards and yarn-like components adaptable to textile-production methods. Textile designers, in turn, provide access to a vast body of knowledge of textiles' design and construction, illuminating, for example, how to employ complex structures in eTextile fabrication and take certain textile materials' look and feel into account. To reap the most from these many angles and, thereby, move toward holistic woven eTextile systems, the various fields' distinct characteristics should be interwoven within interdisciplinary research processes.

For example, the methods of designing and crafting textiles ought not be regarded merely as construction techniques. They are vital for the analysis too. It is clear that researchers must be more aware of how the structural characteristics of the selected weaves influence electrical (and therefore also interaction) behaviour, something noted in only a few pieces [2, 46, 66, 87, 105, 131]. One long-term goal should be to map this uncharted area, by expanding the methodology via textile-evaluation methods to be employed alongside the electrical and interaction evaluations. Including analysis of structural hierarchies of woven structures (see, for instance, Kapsali and Vincent [52]) and complementing the resulting perspective with, for example, subjective sensory assessment [e.g., 106] could form the heart of such assessment. Involving textile designers as equals in research collaboration has already shown a much-needed step in a positive direction [19]; however, much work remains.

In general, eTextile evaluation needs to grow more detailed, transparent, and holistic. As all advanced disciplines do, textile design takes several years to learn, and an individual seeking mastery of both electrical engineering and textile design would require an interdisciplinary double degree. While supporting interdisciplinary education is one way to improve eTextile research and practice, CAD tools might facilitate reducing the barrier on the design side. Indeed, some such attempts at rendering woven eTextile design more accessible already exist, with tools such as AdaCAD [28]. That said, because numerous variables related to electrical functionality, circuitry layout, material-specific properties, and textile structures influence the outcome of development efforts in this field, interdisciplinary research would benefit from AI-supported design software. While intended to assist researchers with no prior background/expertise in any specific field to deal with those complexities, software of this nature could also aid in scaling the physical dimensions, ultimately for commercial production, in roughly the way CAE programs do.

6 CONCLUSION

The literature review helped us identify how HCI-related eTextile research has approached weaving, complex woven structures in particular. We can sum up the resulting insight thus: researchers and designers have been presenting various ways to integrate bus structures, woven-in components, and functional weaves into the very structure of woven textiles, thereby creating complex circuit topologies and multi-component interfaces that intertwine electrical, aesthetic, and interactive properties of functional and conventional textile materials. Enabling all this is the ability to control the yarns constituting the textile precisely and combine diverse materials in a single structure. Pinpointing five categories of woven eTextile applications in the HCI field (electrical signalling; woven-in components; and three electrically functional weaves: woven sensors, woven actuators, and other woven components) aided in characterising the landscape.

Shortcomings pinpointed via the literature review have vital implications for the field's future development. The eTextile literature's discussion of how multi-layer structures can be implemented in woven eTextile prototyping is quite sparse. Double-cloth structures have received especially little investigation, and the study reports do not provide clear guidance as to how eTextile prototyping can make use of these structures. Hence, we have offered several suggestions for future HCI research in this area, and it is our hope that the proposed actions contribute to improving the woven eTextiles field.

ACKNOWLEDGMENTS

This research has been supported by the Finnish Cultural Foundation (grant 00180873), as well as Academy of Finland (grant 330124). We thank the anonymous reviewers also, for their insightful comments that enriched our contribution.

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