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Between yarns and electrons: A method for designing electromagnetic expressions in woven smart textiles

ABSTRACT

The design of woven smart textiles presents a discrepancy of scale where the designer works at the level of structural textile design while facets of the material express at scales beyond one's senses. Without appropriate methods to address these unknown (or hidden) material dimensions, certain expressional domains of the textile are closed off from textile design possibilities. The aim of the research has been to narrow the gap that presents when one designs simultaneously at the scale of textile structure and electron flow in yarns. It does this by detailing a method for sensing, visualizing, and discussing expressions of electromagnetism in woven smart textiles. Based on experimental research, a method of textile surface scanning is proposed to produce a visualization of the textile's electromagnetic field. The woven textile samples observed through this method reveal an unknown textural quality that exists within the electron flow – an electromagnetic texture, *which emerges at the intersection of woven design and electromagnetic domain variables. The research further contributes to the definition of specific design variables such as:* field strength *and* diffusion *expanding the practice of woven smart textile design to the electromagnetic domain.*

KEYWORDS

textile design
textile thinking
design methods
visualization methods
electromagnetism
weaving

INTRODUCTION

The practice of smart textile design can be understood as the design of textiles that are composed of computational, electronic and emerging materials (Berzowska 2004, 2005; Berzowska and Coelho 2005; Beauchly and Eisenberg 2008; Kettley 2016) such as piezoelectric yarns and coatings (Ryu et al. 2022; Honnet et al. 2020), electrochromic inks (Eom 2022) and phase-change materials (Iqbal et al. 2019). These textiles are able to sense and convey environmental changes, as well as transmit and receive power and data to and from external electronic and computational devices. As a research field it dates back some twenty years, and through this time it has matured and diverged along new trajectories (Schneegass and Amft 2017; Tao 2015; Berglin et al. 2005; Gopalsamy et al. 1999). Research into smart textiles now spans many disciplines including material science, various practices of engineering (electrical, computational, wireless technologies), human–computer interaction, health sciences, military research, social science, humanities and more. Each prioritizes the principles and practices of their discipline and researches through these perspectives to contribute to the broader body of smart textiles research. This article takes the perspective of smart textile *design*, a small yet vital discipline within the broader scope of smart textiles' research that prioritizes the textile design process, its techniques and its methods. This article focuses in particular on woven smart textile design.

The design of smart textiles involves interdisciplinary knowledge found in seemingly contrasting fields, across diverse materials and techniques, and works through the translation of concepts, notions and terminologies across disciplines (Townsend et al. 2017). As an example, the supporting text for a smart textiles exhibition entitled 'The Enchantment of Textiles' in Montreal identified fifteen different roles involved in the design process of a series of garments with embedded textile antennas and flexible LED circuits (Layne et al. 2019). The team involved an embroiderer, a fashion designer, a pattern cutter, a technical developer of the antenna system, an antenna engineer, a technical supervisor, an industrial designer, a flexible LED system designer, a circuit designer, two programmers, a cultural researcher, an archiver and a research lead. Similarly, an electronic textile entitled 'The Embroidered Computer', designed by Ebru Kurbak and Irene Posch in 2016, required a team of sixteen people across seven different roles, including a computer circuit and software designer, generative routing designer, embroidery consultant, metal thread consultant, multiple crafting assistants, and two researchers/designers (Posch 2019). The interdisciplinary nature of designing and researching smart textiles means that any contribution to the practice such as methods and terminologies influences not only the work of smart textile designers themselves but also these collaborative relationships.

The research points to the topic of scale in smart textile design and suggests that smart textile designers manage multi-layered and multi-scaled approaches to their work in highly complex and 'entangled' spaces with 'technological compositions', and that they do so 'without ever losing sight of the expressive potential of the work' (Kettley 2016: 145). As a demand of the complexity of the design, smart textile designers are required to hold a multifaceted view of the textile and its scales as a combination of materials, structure and surface, and in addition, the energetic dimensions of the textiles such as the forces of intangible materials, the electronic and computational dimensions, and the various design skills and tools needed to access and work within these domains.

Conductive yarns used in woven textile structures are further discussed, and as design is concerned with expression, the article suggests that the electromagnetic field that the conductive yarns produce can be considered an expressive domain in itself. In addition, conductive yarn can have a limited visual appearance and tactility in textiles that can be a challenge for designers to work with. The revealing of its hidden electromagnetic properties may spark interest from designers to continue exploring its potential for textile designs. Currently, the use of electromagnetism as a material in the smart textile design field is under-represented in part due to these limited expressions, and also due to a lack of tools and methods for how to access and design with its extrasensory and intangible qualities (Lewis 2021; Townsend and Mikkonen 2017). While methods of detecting and sensing electromagnetic fields are available within practices of science and engineering, they often involve specialized laboratory tools and skills that can be beyond the reach of the smart textile designer. There is therefore a need for sensing methods that are 'agile, visual, and adaptable' in order for designers to engage with the properties of the phenomenon (Mikkonen and Townsend 2019). Townsend and Mikkonen (2019) have introduced *Teksig*, a visualization method for detecting electrical changes due to micro-interaction in conductive textiles. The method is an Arduino-based system that draws Lissajous figures on a computer screen. Lissajous figures are conventionally drawn on oscilloscopes, which is a measurement tool that is high cost and that requires specialized knowledge to use. The Lissajous figure itself is an emerging circle that forms in relation to the frequency response of the textile. This could relate to a change in phase, for example, or a change in the proximity of the conductive yarns in a textile structure. Teksig can identify micro-interactions with the textile in the form of pinching, rolling, folding, wrinkling, hanging and placing the hand on, over, or under the textile. While the smart textile design field tends to address the non-frequency domain of electricity (DC, or direct-current), Teksig opens up the frequency domain as an area of design exploration where smart textile designers can measure and qualify interactions with electronic textiles in the frequency domain, potentially leading to novel textile interactions and expressions. The aesthetic potential of this approach is that e-textile designers are equipped with a method and tool that allows the designer to engage with the frequency-based behaviours of a textile, a perspective of the textile that was previously inaccessible to designers.

Friske et al. (2019) have designed *AdaCAD*, a software that simulates electronic pathways in weave drafts. The software allows textile designers to design weave drafts and electrical connections in tandem in order to achieve fully integrated, complex embedded electronic circuitry while providing immediate screen-based visual feedback regarding the placement of conductive yarns in the textile (Friske et al. 2019). Circuit simulation software is a common tool in electronics engineering, and graphical user interfaces (GUIs) are common to both practices of electronics engineering and textile design. Where this software innovates is that it allows for complex, multi-layered electrical circuits to be designed in such a way that they are insulated and secured within the structural design of the textile itself. Further, AdaCAD allows the designer to exercise the dual perspective of the electrical current flow in relation to bindings, layers and weft passes, thus narrowing the gap between the tangible and intangible domains of the textile early on in the design process. The software affords a new workflow for woven electronic textiles that allows the designer to anticipate the electrical behaviour of the textile before it is woven. The designer is able to adjust and adapt designs before the weaving process begins, potentially saving the designer significant time and frustration. Conventionally, textile designers use patterning for aesthetic purposes that bridge visual and haptic experiences of the textile, though AdaCAD patterning can be used for aesthetic embedding of electronic circuitry, and thus the role of patterning in the textile design process is expanded. This becomes invaluable where conductive yarns can be decisively placed in a structure in such a way that they are insulated by dielectric yarns in the structure, thereby allowing for complex and fully embedded electronic functionality that is both functional and aesthetic.

The article proposes an experimental method that has been developed for textile designers, and which can be used within their design process to enable the exploration of the electromagnetic qualities of woven textiles. The aim of this method is to provide a way of understanding the impact of design decisions when it comes to electromagnetism's intangible qualities, i.e. where the density of conductive yarns in a woven textile structure can have significant effects on the shape of electromagnetic field it produces. Just as with media, sound and transmission arts where electromagnetic fields are used for expressive purposes (see Kubisch n.d.; Hinterding n.d., as examples), so can they be used in woven smart textile design as a material to be designed with and through – if methods and terminologies exist.

The method, called *textile surface scanning*, visually communicates the presence and form resulting from the electromagnetic field generated by current carrying yarns in a woven structure. The method outputs a graphical plot that illustrates an electromagnetic field shape that results from the placement of conductive yarns in a woven textile structure. It has accessible tool requirements and does not demand specialized knowledge or skills to interpret the results. The method introduces a key notion of *electromagnetic texture* and its related sub-notions of *field strength* and *diffusion.* These are discussed in detail further in the sections that follow. That electromagnetic expressions reside within a woven textile at the yarn level suggests that decisions regarding textile design variables, for example technique, structure, density, scale and overall formal qualities, will subsequently affect the electromagnetic textural quality. Moreover, it opens a space for textile designers to design with electromagnetic textures by exploring the relationship of material, structure and dynamic expressions, thereby broadening the range of design possibilities of smart textiles. It further answers a long-standing call by smart textiles designers for new methods and terminologies to better understand and work with the new material dimensions that smart textiles engage with (Berzowska 2004, 2005; Berzowska and Coelho 2005; Hallnäs 2008; Worbin 2010; Kettley 2016).

Woven textile design and textile thinking

Conventional woven textile design regards placing yarns in horizontal and vertical arrangements (as weft and warp, respectively) on a weaving loom in order to build the textile plane. While the vertical warp yarns are affixed to the weaving loom during the weaving process, the weaver inserts the horizontal weft yarns row by row, building the textile material by interlacing warp and weft with each pass. Structure and patterning are changed as certain warp yarns are lifted and released, causing variation in the interlacements. Qualities of fibre type (e.g. cotton, wool and polyester), yarn type (e.g. ply, twist and thickness) and the arrangement of the yarns in a structure are variables that, through manipulation, result in different textile designs (Sinclair 2014). Visual aesthetics emerge from material and structural decisions made regarding colour, pattern, sheen, visual weight and visual texture, while tactile aesthetics emerge primarily from surface texture, weight and fibre properties. In the process of weaving, textile designers must be attuned to the effects of fibres, yarns and interlacements on the overall expression of the textile. Textile designers are trained to be highly sensitive towards, to manipulate, to regulate, and otherwise surrender to the material forces that present when fibres and yarns are suspended in textile structures. In doing so, designers learn to identify patterns of behaviours, emergent properties and tendencies of material and structural combinations. They give form to matter through the manipulation and regulation of materials that lead to the final woven textile design expression. Thus, textiles may be considered assemblages of materials and forces combined with structural logic that demonstrates a particular expression inseparable from its constituting elements where the material and immaterial spaces of the textile conjoin (Lee 2020).

Yet aspects of the textile are present before the textile-making process has begun, as a form of impetus on part of the designer. This draws on the experienced hand of the weaver, conceptual thinking and the deep knowledge of working methods and diverse material experience acquired (Steed and Stevenson 2020). *Textile thinking* frames this space as an expanded notion that enfolds the textile design process of making, where the 'thinking, making, knowing with, in, and of itself (is) bound up within the agencies of the materials themselves' (Igoe 2018). This builds on the legacies of Anni Albers (1965) and Tim Ingold (2010) who, among others who argue for the submission to materials in the process of designing (Igoe 2018: 42), the used of the knowledged hand, and a shift in focus from the final tangible object to the process of making and knowing. Textile thinking has influenced the development and design of the *textile surface scanning* method as it has created a conceptual and exploratory space to work within to begin to articulate this material dimension, without prioritizing the textile object as a result (Dumitrescu et al. 2018; Valentine et al. 2017). It uniquely conjoins experimental knowledge of electromagnetics in textiles, combined with the design practice of textile weaving.

Scales of woven smart textile design

In woven textile design, designers must simultaneously regard the broader expression of the textile while addressing nuances at the scale of yarns. Expressions of texture, surface and visual aesthetics (e.g. colour and patterning) are determined by yarn properties such as fibre type, yarn thickness, yarn number and twist. Yet for smart textile designers, the design variables increase. While the focus on structure, material and expression are maintained, further variables are introduced: time-based, state-changing and recursive and recurrent behaviours (Worbin 2010; Kettley 2016; Heinzel and Hinestroza 2020). These behaviours expand the textile design space to include computational and electronic states that are incongruent with the natural passage of time, and that change under certain conditions as a result of external triggers. Materials often used in smart textiles introduce elements of scale that require designers to move deeper into the properties of the materials. For example, the use of conductive yarns requires an understanding of electron flow and polarity in relation to their placement in a textile structure. Disregarding this can result in non-functioning circuits, short circuits and erratic and unwanted computational behaviours. The type of alloys in the yarn, whether they are spun or extruded, the yarn gauge, its resistance per centimetre and its current rating all require textile designers to design not at the scale of the tangible material, but at the scale of the electron flow within the tangible material (Lewis 2021). Designers work indirectly with electrons through the components within which they flow (Kettley 2016).

The use of conductive yarns in a textile implies the designed behaviour of the yarns within a larger electronic or computational circuit that may involve sensors, actuators, power and signal connections. Sensing and actuating behaviours require programming, which suggests that the computational code and algorithms that drive the behaviours are also a form of material that builds the textile. This combination of computation, electronics and tangible matter has been referred to as 'computational composites' as an expression of matter that hybridizes the tangible with the intangible (Vallgårda and Redstrom 2007). When conceiving what a smart textile might do, the textile designer needs to think about the programmatic states and computational expressions of the work. These behaviours transfer as electric pulses through conductive yarns and into the structure of the textile to facilitate their actions. They are thus temporal electrical expressions that navigate the electron flow within conductive yarns, and which textile designers must also regard in their process of making.

All smart textiles designed with conductive yarns interact with electromagnetic fields. These fields are beyond human sensing capabilities though they can be detected, measured, formed and directed using specialized tools and technologies. Smart textiles that generate electromagnetic fields, or *electromagnetic textiles*, are designed matter in active states of doing, independent of human subjectivity. They express energetic bursts through their coupling and decoupling of electromagnetic fields, and the minute interactions that occur in the interstices of the conductive yarns suspended in their structure. The sensing of the electromagnetic field is a snapshot in time of this coupling behaviour that causes dynamic intensities across the surface of the textile.

The following three examples demonstrate design approaches to working with electromagnetism in textile designs and materials, across varying methods, scales and expressions.

Example 1: Embroidered computational logic using electromagnetic flip-dots

Designers working with electromagnetic expressions in woven textiles are few, and works produced have been mainly focused on frequency-based electromagnetism (e.g. sound and radio-based works), though some non-frequency domain examples do exist. Some may be designed using other techniques such as knitting or embroidery. In example 1 (Figure 1) design researchers Ebru Kurbak and Irene Posch have designed an embroidered electromagnetic textile that functions as an eight-bit computer (Kurbak and Posch cited in Kurbak 2018). The textile contains a matrix of magnetite beads encircled by the ornate stitches of embroidered conductive thread (Figure 2). A gold coil relay switch is attached to the magnetite bead, and when an electromagnetic field is generated in the yarns, the relay coil flips its position, thereby expressing different logic structures. Participants are invited to program this textile computer and witness the different logic structures expressed through

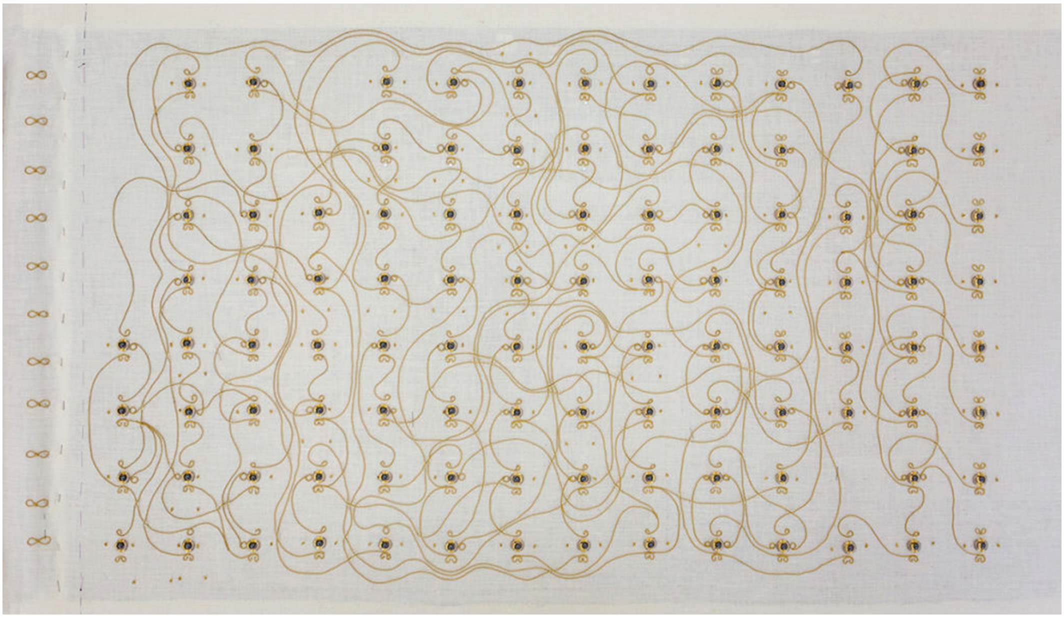

Figure 1: Ebru Kurbak and Irene Posch, The Embroidered Computer*, 2018. Woven textile, gold embroidery thread, magnetite beads. © Irene Posch (2019).*

Figure 2: Ebru Kurbak and Irene Posch, detail of The Embroidered Computer*, 2018. Woven textile, gold embroidery thread, magnetite beads. © Irene Posch (2019).*

the textile materials. In this work, the two have greatly enlarged the scale of matrixial computational logic gates, visually revealing the basic material interactions that are normally intangible, miniaturized and embedded within integrated circuits. The designers have utilized a quality of the gold yarns that, when stitched together to create a dense spiral, are able to produce an electromagnetic field that is strong enough to cause the magnetite bead reverse its magnetic poles. Here, they highlight the kinetic energy potential of electrons that are contained within the gold yarn, and creating a visually stunning aesthetic of computer logic flows across the surface of the textile.

Example 2: Accessing the magnetic properties of conductive yarns for voice recording

Kurbak has worked with So Kanno to design a magnetic yarn voice recorder (Kanno and Kurbak cited in Kurbak 2018). Using this recorder, a participant is able to record their voice on a single thread of conductive yarn. Soundwaves of one's voice are passed to the yarn while turning a spindle. The yarn is guided through a recording head where the yarn is magnetized with the magnetic order of the voice recording (Figure 3). The yarn can then be played back by winding the yarn spindle to listen to the recording. This work uses the effect of mechanical magnetic recording as used in cassette players of previous decades. Here, the pair reveals an overlooked quality of conductive yarns: their ability to store and transmit data in their magnetic field. The two work with the finer scales of textiles (at the yarn level) and electromagnetics (at the level of electrons in a magnetic field).

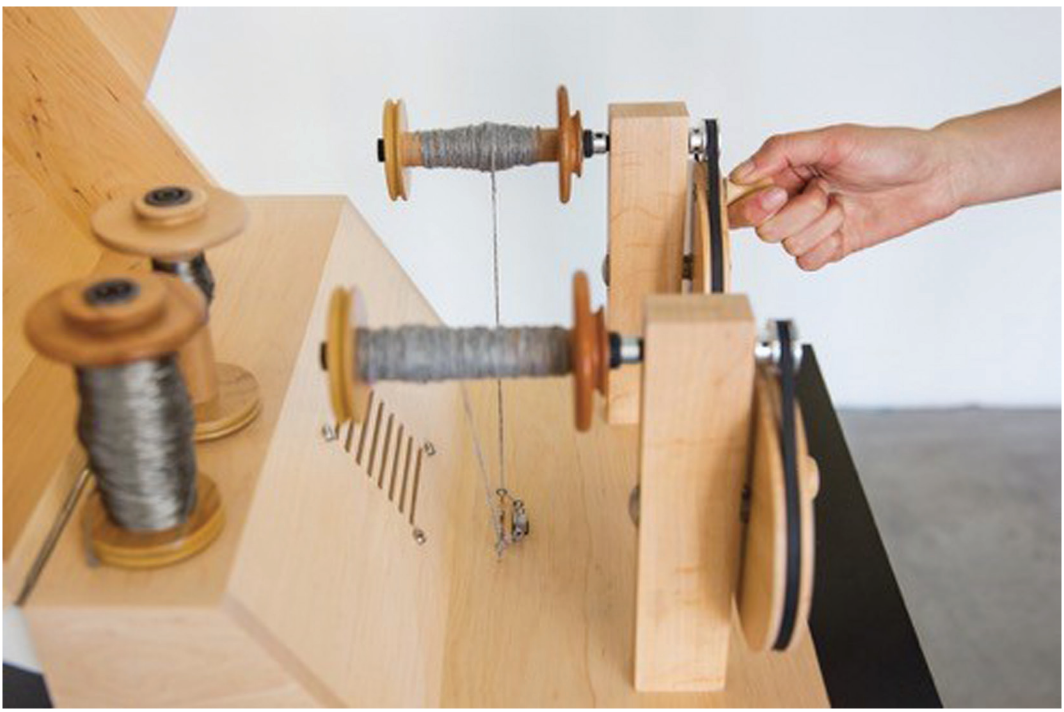

Figure 3: Ebru Kurbak and So Kanno, Yarn Recorder*, 2018. © Elodie Grethen (2018).*

Example 3: Translating radio communications into knitted textile patterns

Working with frequency-based electromagnetic expressions, Afroditi Psarra and Audrey Briot explore satellite transmission data as a material for textile design. In *Listening Space* (2019), the two used software-defined radio (SDR) to record satellite transmissions from their reception station. Psarra and Briot work with radio waves as a spatial material to be captured from free space, and later bring that data into their textile design process. The transmission data is translated as a graphical image in SDR software and turned into a Jacquard pattern for machine knitting. Radio waves are represented through changes in textile structure, material and patterning, using symbolism to balance the scales of design between yarns and electrons (Figure 4). In this work, Psarra and Briot regard the spatial qualities of radio waves at immense scales and are simultaneously concerned with the matching of frequencies, directionality and temporality of the interception (i.e. being in place at the correct time and for the duration of the satellite pass and transmission). In addition, they use 'low-cost methodologies' and 'digital crafting' combined with textile design processes (Psarra n.d.). This assists in opening textile designers to electromagnetism as material, particularly where it can be accessed through materials that textile designers are already engaged with, and are intimately familiar with.

These three examples serve to demonstrate an interest by textile designers and researchers to explore electromagnetics through textile design processes

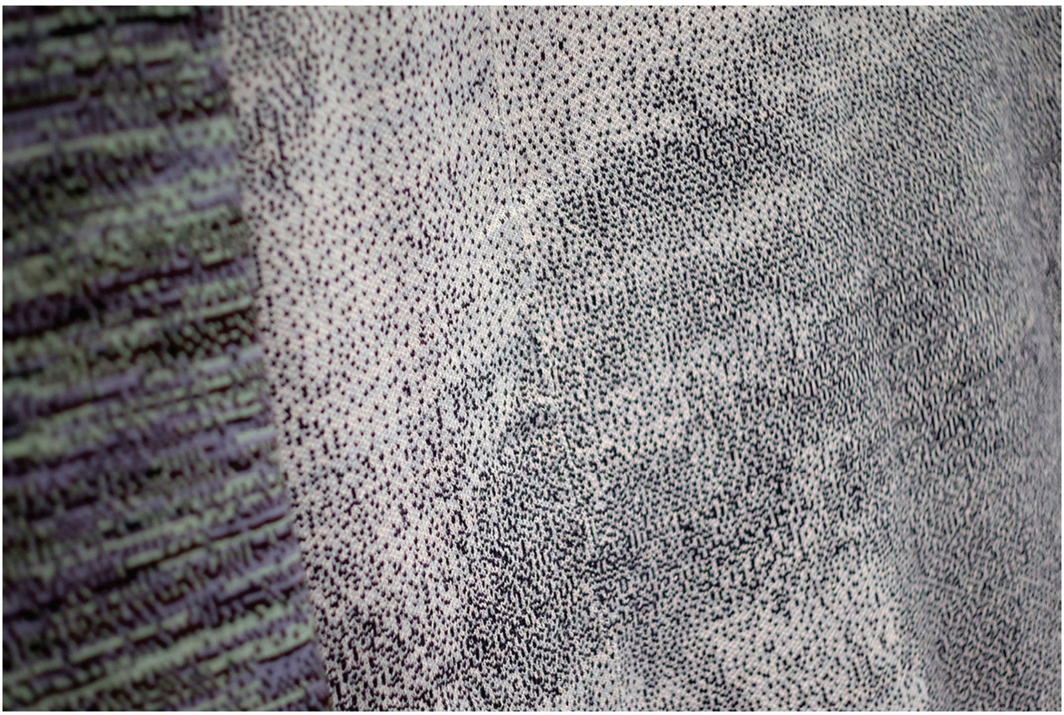

Figure 4: Afroditi Psarra and Audrey Briot, Listening Space: Knitted Archive of the NOAA 18 Transmission Intercepted on 8 May 2019*, 2019. © Afroditi Psarra (2019).*

and materials, where electromagnetic fields are generated within the yarns, or are received from an external source and set within the yarns. In doing so, the designers work fluidly from internal and external sources of electromagnetism, and between electrons, yarns and – in the case of Psarra and Briot – atmospheric scales. Thus, designers of these works present varying methods, scales and expressions of electromagnetism in textile design, and in doing so they highlight an alternative dimension to textiles and textile materials. In the section that follows, a method for sensing and visualizing a generated electromagnetic field in woven smart textile structures is described.

METHOD

Through experimental design research, a method for sensing and visualizing electromagnetic fields in woven smart textiles was designed. The method comprises a smartphone app, a physical setup, a sliding technique and a visualization approach. The method uses the magnetometer contained within a mobile phone. Magnetometers measure magnetic fields in multiple-axes and generally provide a high resolution of sensor data. Commonly, the magnetometer in a mobile phone is a triple-axis magnetometer that measures *X*, *Y* and *Z* axes for navigation purposes and determines the handheld position of the device. Mobile phone magnetometers carry several benefits of use as a measurement tool: they access computational processing power directly from the mobile phone as opposed to an external microcontroller unit; they have embedded calibration processes; they have a display screen for showing measurement data; they are small and portable; and they have internet connectivity for uploading or downloading data, in addition to other general tasks. Finally, they are incredibly accessible as they are embedded in all mobile phones. For this reason, woven textile designers are not required to purchase or otherwise acquire and assemble new tools or measurement systems as they can use what they already possess.

The basic structures of twill, waffle and honeycomb were selected to weave in this experiment for their variations in expressing electromagnetic field shapes. The samples were woven with a conductive enamelled copper yarn (0.16 mm) with an electrical resistance of 0.89 Ω/m. This yarn is thin, flexible and strong, and does not typically break under weaving tension. Cotton yarns (30/2) were used as a dielectric material in both warp and weft directions. The textile samples were woven on 24-shaft computerized ARM looms with warp density of 24 ends-per centimetre (EPC) for twill and honeycomb samples, and 12 EPC for waffle weave. Each textile was woven with the ends of the conductive yarn ends exiting the textile on left and right selvedges at intervals of 1 cm. This provided access to the conductive yarns for electrical connections.

The sensor data outputs magnitude measurements as microTeslas (μT). The textile samples were placed vertical to the Earth to avoid sensor data being affected by the Earth's own electromagnetic field. The mobile phone app 'Magnetic Field Sensor' by SMF Apps gbr was used to access the data from the magnetometer sensor in the mobile phone. The app formats the output data as a 2D graphical plot of magnetic field strength mapped over time. It stores within the mobile phone memory as a text file with positional data, magnitude and timestamps. The flexibility of this text file is that it can easily be imported into a variety of software capable of plotting and visualizing data sets.

Setup

In the physical setup, a mobile phone holder, tripods and a plastic planar surface were used (Figure 5, top left and bottom right). A sliding camera mount was modified by attaching a mobile phone holder (Figure 5, top right), allowing one to smoothly traverse the mobile phone over the surface of the textile. A textile sample was positioned vertically against a plastic board, facing the mobile phone (Figure 5, bottom left). Power and ground connections were made to the textile via conductive yarns at the selvedge, and 1 A of current was applied.

The sensing technique requires vertically sliding the mobile phone over the surface of the textile. The textile was placed vertically on the plastic board and the smartphone scanned the surface over ten to fifteen seconds moving from top to bottom, selvedge to selvedge. This duration range provided the clearest visual impression of the field. An external timer assisted in timing the movement. Subsequent readings across the textile surface need to be shifted by approximately 1 cm in order to accommodate for the sensor reading range.

Raw sensor data can be imported into software that is capable of plotting 2D data sets, for example Python, P5.js/Processing, MathWorks and Excel. The plot lines from the app can also be used in image software (e.g. Photoshop and Illustrator) to isolate the field shape line from its background, in order to produce a single line representation of the texture, as in Figure 6. Both image and raw sensor data can be imported into 3D software (e.g. Rhino, Blender and Fusion 360) to construct 3D surface visualizations. The flexibility of the visualization method is a strength, where one is able begin with either the graphical image or the raw data, to style and represent the field in whichever way is best suited to the means and the desired outcome.

EXPERIMENT

Sample 1: Striped twill

In Figure 7, the weave draft illustrates a twill structure that carries the weft yarn over one and under three warp threads (Lewis 2021). With every subsequent weft pass, the interlacement shifts one step. This gives the textile the visual effect of diagonal lines (Sinclair 2014: 272). Twills produce dense textiles as the yarns are able to sit closer together in the structure, and where conductive yarns are used, this is beneficial as it can allow for an increase in electromagnetic field strength. In this sample, the woven textile is a 1/3 weft-faced twill (6 cm × 10 cm) designed with a striped pattern which alternates between areas of dielectric cotton with conductive copper yarn. As seen in Figure 8, the conductive areas become increasingly more thin towards the bottom of the textile sample (Lewis 2021). Using the *textile surface scanning* method, a measurement set of ten sequential sensor readings were made and panelized using 3D software to create the visualization (Figure 9, Lewis 2021).

This example illustrates an incongruity that emerges between the tangible textural qualities of a textile and electromagnetic qualities that arise, where visual, tangible surface of the textile in Figure 8 is flat and smooth with minimal textural qualities yet the intangible qualities of the electromagnetic field show strong variations across the textile surface. It is noted that the field strength is strongest over the widest conductive copper stripe at the top of the textile, resulting in a strong visual peak in the electromagnetic field. Towards the bottom of the textile the peak tapers off as the conductive areas get progressively smaller while the dielectric areas increase.

Sample 2: Waffle weave

Waffle weave structure expresses a matrix of cells formed by peaks and valleys on both sides of the textile, as seen in Figure 10. As warp and weft threads

Figure 5: Full setup, sensing position (top left); detail sensing position (top right); textile suspension (bottom left); two tripods separated (bottom right). © Erin Lewis (2021).

have long floats on both surfaces, the outcome is a textile of high volume and density where the peaks and valleys give dramatic visual effect dependent on scale and material selection (Sinclair 2014: 278).

The textile is woven with a dielectric cotton warp and conductive copper yarn weft (10 cm × 25 cm) (Figure 11). Using the textile surface scanning method, ten sequential sensor readings were made and a visualization of the electromagnetic field across the surface of the textile is presented in Figure 12. The textile was scanned horizontally over the course of fifteen seconds. The visualization reveals strong variations in the electromagnetic field, where density changes in the conductive yarns are expressed as changing electromagnetic field strength across the surface of the textile. The electromagnetic field extends approximately 5–6 mm from the textile surface.

In an electromagnetic waffle weave, the strength of the electromagnetic field is increased in areas where there are long floats of copper yarns. Floats are yarns that are not tightly bound into the structure and are left to move freely between two points. This allows parallel copper yarns to sit closer together than if they were bound in a structure. In turn, the electromagnetic fields of several yarns are coupled together and the electromagnetic field strength increases in those particular areas. Therefore, the use of parallel floats with conductive yarns increases the electromagnetic field strength in areas where conductive yarns gather in the structure, and conversely the electromagnetic field strength decreases where the dielectric yarns gather in the structure. This stark contrast between conductive and dielectric areas of the textile produces a strong undulation of peaks and valleys in the electromagnetic field shape.

Sample 3: Honeycomb

The honeycomb structure is characterized by an undulating weft that circles sections of plain weave in the ground layer (Sinclair 2014: 283). Honeycomb cells are designed as alternating blocks of larger and smaller size (Figure 13), and cell shapes can be defined through contrasting yarn thicknesses between the ground and secondary wefts. The qualities of the yarns in combination with the tension

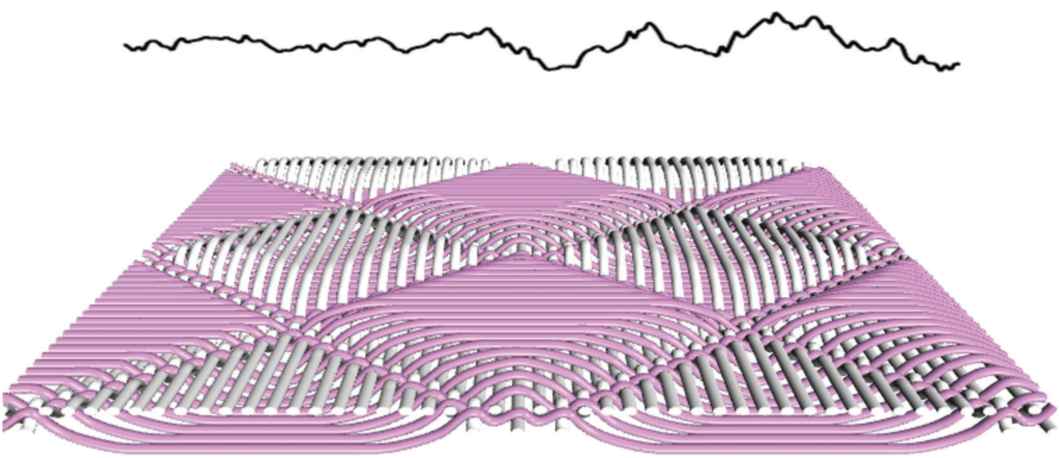

Figure 6: Single line visualization of electromagnetic field expression placed atop of waffle weave structural visualization. © Erin Lewis (2021).

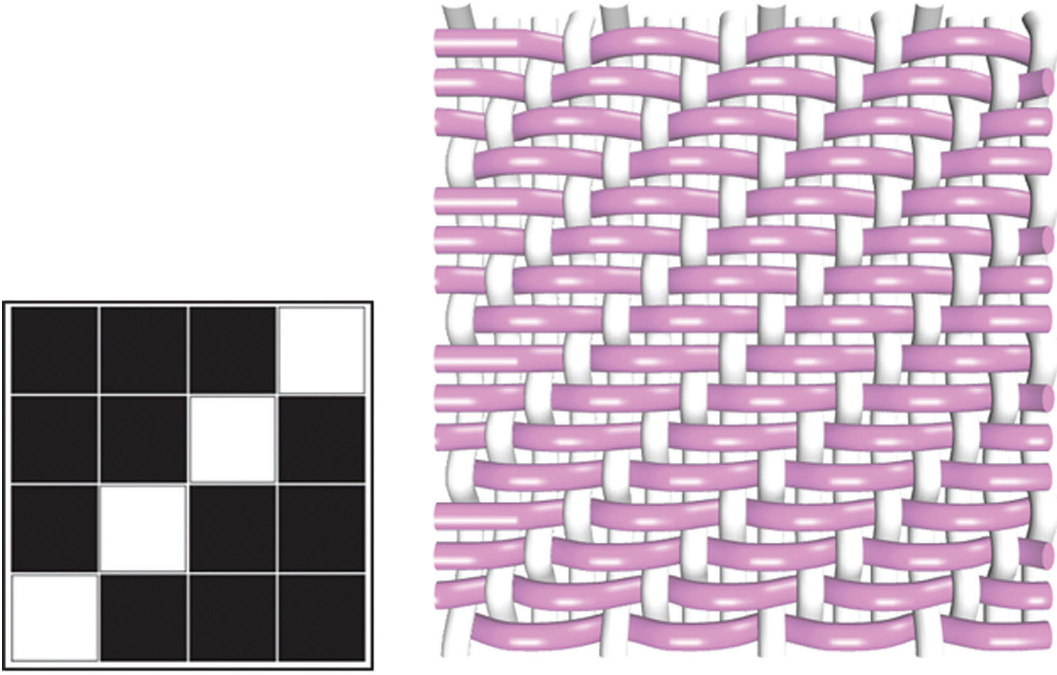

Figure 7: 1/3 weft-faced twill weave draft (left) and structural visualization (right). © Erin Lewis (2021).

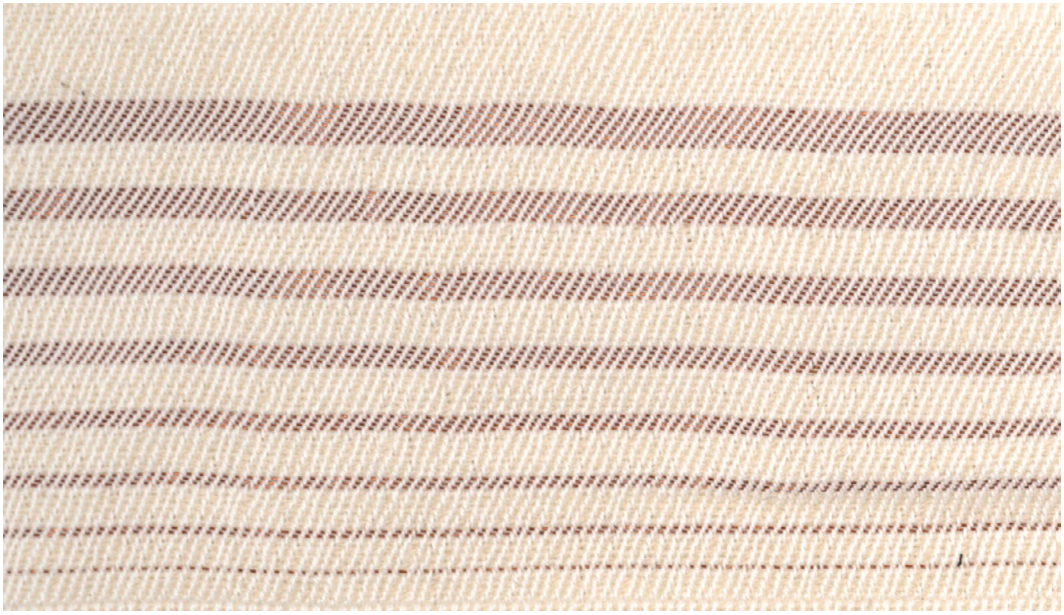

Figure 8: Striped twill woven textile. © Erin Lewis (2021).

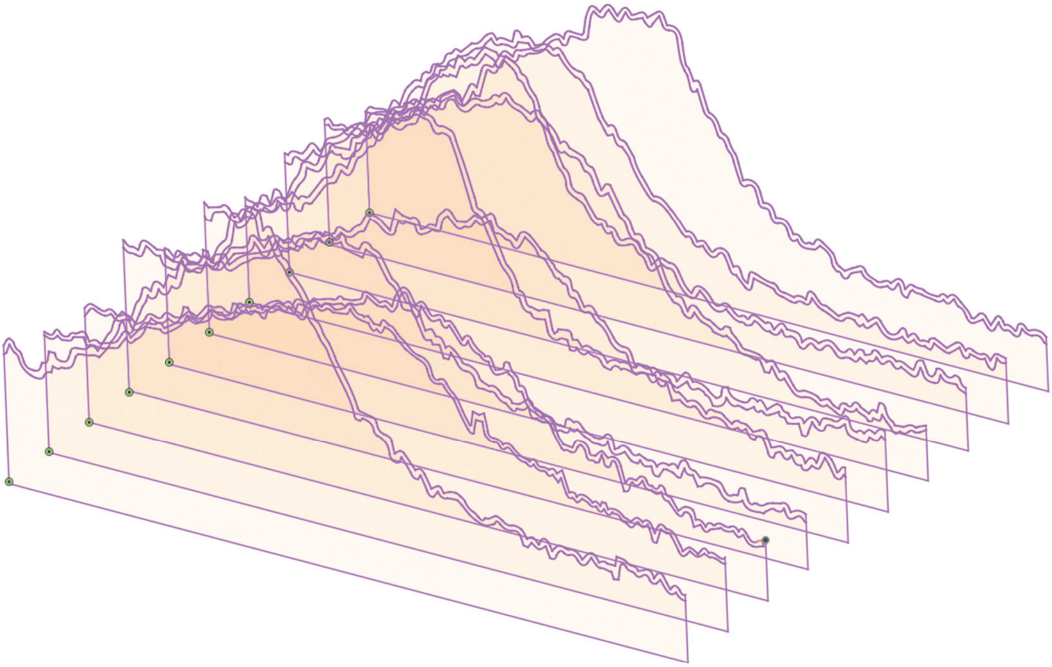

Figure 9: Electromagnetic texture of striped twill textile. © Erin Lewis (2021).

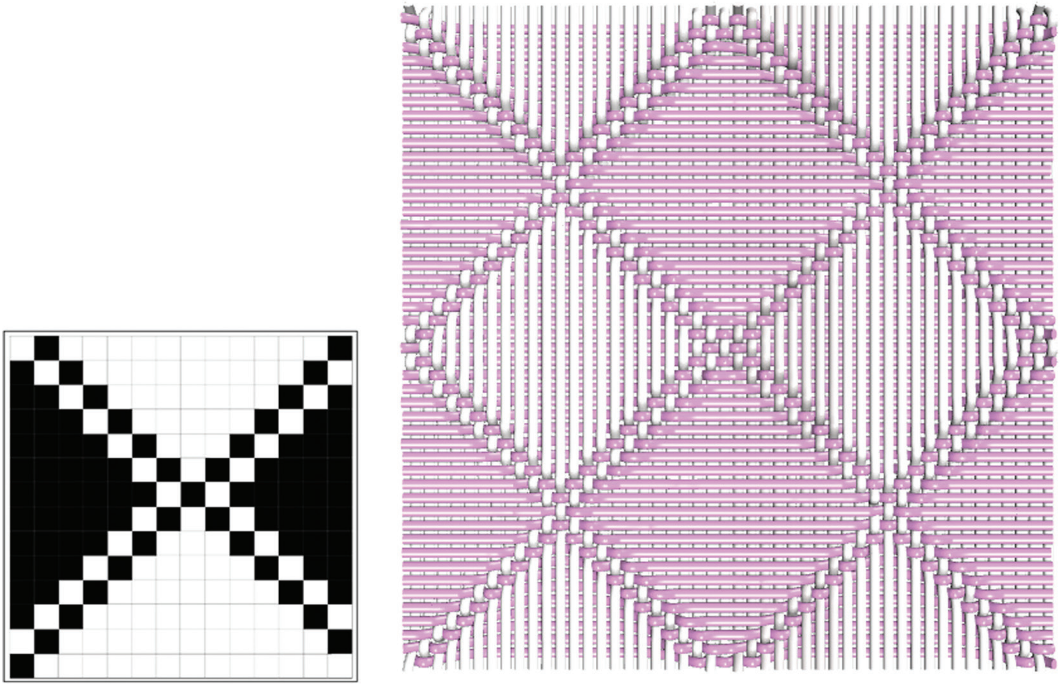

Figure 10: Waffle weave draft (left) and structural visualization (right). © Erin Lewis (2021).

of the bindings cause cells to condense and relax alternatingly throughout the structure, giving rise to the characteristic cellular matrix (Figure 14).

The textile is woven using a dielectric cotton primary ground weft, and sixteen copper yarns twisted together as a conductive, secondary weft on a dielectric cotton warp (10 cm × 25 cm). Through the method, ten sequential sensor readings were made. A visualization of the electromagnetic field across the surface of the textile is presented in Figure 15. The textile was scanned horizontally over the course of fifteen seconds. The electromagnetic field extends approximately 5–6 mm from the textile surface. In this structure, the thick copper weft yarn encircles the ground layer cells. The secondary weft generates a strong electromagnetic field that presents in the visualization as broad peaks. The broad peaks are strongest when four conductive weft yarns move close together at the top and bottom of each cell (Figure 14), and diffuses into wide valleys where the dielectric ground weft dominates. The honeycomb structure can be used to design field shapes with strong contrasts and broad peaks and valleys rather than steep inclines. Additionally, the use of multiple conductive wefts in a single pass assists in increasing contrasts in the field shape by increasing field strength in those areas.

Results

The result of this experiment is the formation of a design language that can be used to set up new woven smart textile designs. The result was formed by

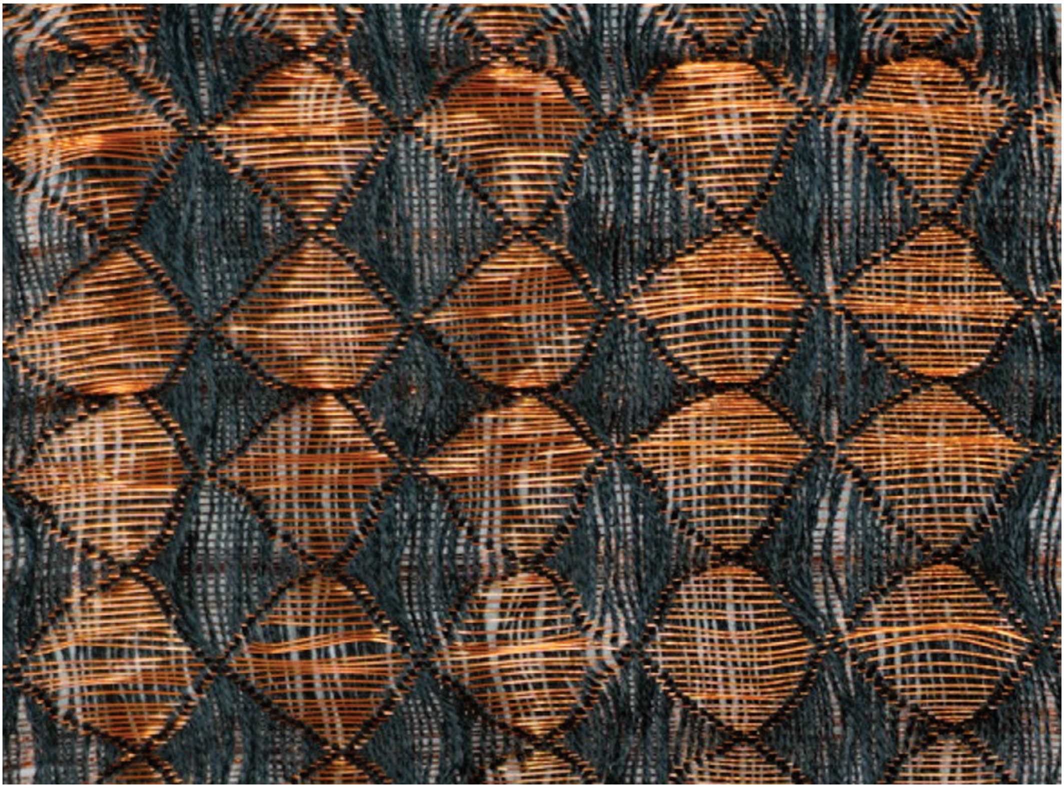

Figure 11: Waffle weave textile. © Erin Lewis (2021).

reflecting on the passage of conductive yarns within the textile structure and how they corresponded to peaks and valleys in the graphical plots. To do this requires knowledge of both woven textile structures and a basic understanding of non-frequency electromagnetics, and the ability to consider what is occurring at the scale of the electron with what is occurring across the textile surface. Through these corresponding elements – the textile structure and the graphical plots – certain behavioural patterns appeared. Wherever conductors laid densely together either through adjacent weft passes or through layering and floats, the magnetic field strength increases, and where dielectric yarns separated the conductive yarns either through adjacent weft passes or through layering and floats, the magnetic field strength would conversely decrease. These density changes in the textile structure, regardless of its surface texture or visual appearance, would be

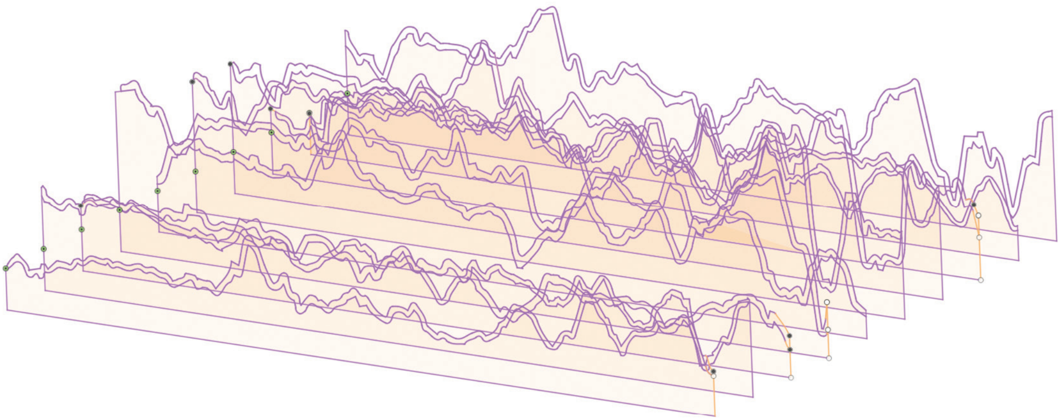

Figure 12: Electromagnetic texture of waffle weave structure. © Erin Lewis (2021).

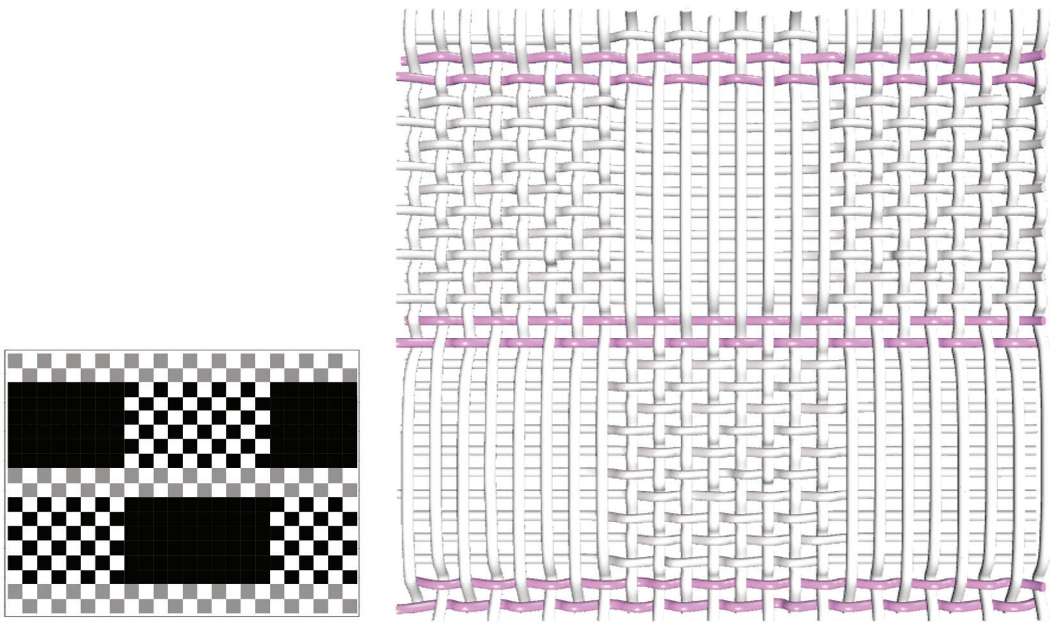

Figure 13: Honeycomb draft (left) and structural visualization (right). © Erin Lewis (2021).

reflected in the electromagnetic field produced by the textile. These qualities of increasing and decreasing the electromagnetic field through the woven textile structure, as well as the resulting surface expression, lack terminologies in this context and so three new notions for woven electromagnetic smart textiles are suggested: *electromagnetic texture*, *field strength* and *diffusion*.

The suggestion of an *electromagnetic texture* offers a new notion for the design of textural qualities that expands the textile convention of visual and tactile sense. Much like the conventional quality of texture in woven textiles, *electromagnetic texture* is dependent on the structural and material selections of the textile, yet it is both designed and expressed in different ways. *Electromagnetic texture* is an overall surface expression of the electromagnetic field across a textile (Figure 16). It is designed through variations in the

Figure 14: Honeycomb textile. © Erin Lewis (2021).

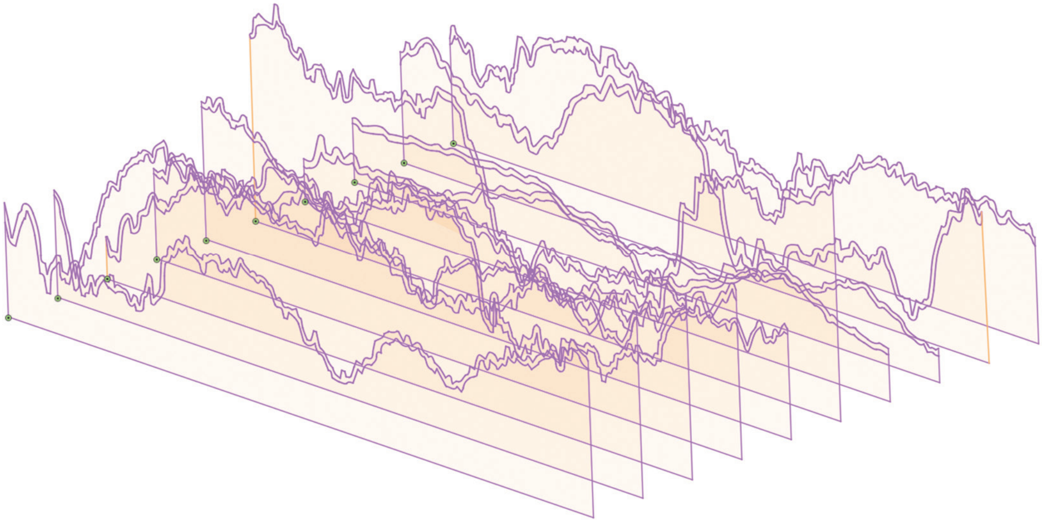

Figure 15: Electromagnetic texture of honeycomb structure. © Erin Lewis (2021).

placement and density of conductive yarns through variables of *field strength* and *diffusion*. The amount of variation in the field shape, as opposed to the magnitude of the field, is what determines its degree of texture. A lesser degree of electromagnetic texture may present as very small differences in the field expression, i.e. the electromagnetic field across the surface of the textile is more flat rather than expressing pronounced peaks and valleys, whereas a higher degree of electromagnetic texture across the surface expresses as peaks and valleys. Therefore, to increase the electromagnetic texture of a woven smart textile, a textile designer might look to incorporating strong contrasts between conductive and dielectric yarns (Figure 16A), for example in stripes, waffles, herringbone and other patterns distinguished by changing yarns.

Field strength is the rising intensity of the electromagnetic field (Figure 16B). It presents in areas of the textile structure where conductors lay closely together to produce a conjoined field, as in the tightly wound coils of conventional electromagnets. In the electromagnetic field shape this is represented by peaks, or mountains. Designers can work with this quality by strategically placing conductive yarns in the structure, understanding that where conductive yarns lay closer together, the field strength is increased. Further, where conductive yarns sit closer to the surface, are more densely set in the structure, or are free to float, allows them to move closer together than when they are bound in a structure.

Diffusion is the decreasing intensity of the electromagnetic field as it becomes obscured by dielectric materials, or where conductive yarns are spaced apart in the textile structure (Figure 16C). It is marked by valleys in the electromagnetic field. Diffusion occurs when dielectric yarns pass over or between conductive yarns, diminishing the field strength before it reaches the outer surface of the textile (where it is sensed by the magnetometer), or spacing conductive yarns apart in the structure so that the electromagnetic fields cannot couple, resulting in lesser field strength.

Designers attempting to design intentionally in the electromagnetic field may apply these notions to shape the field through managing field strength

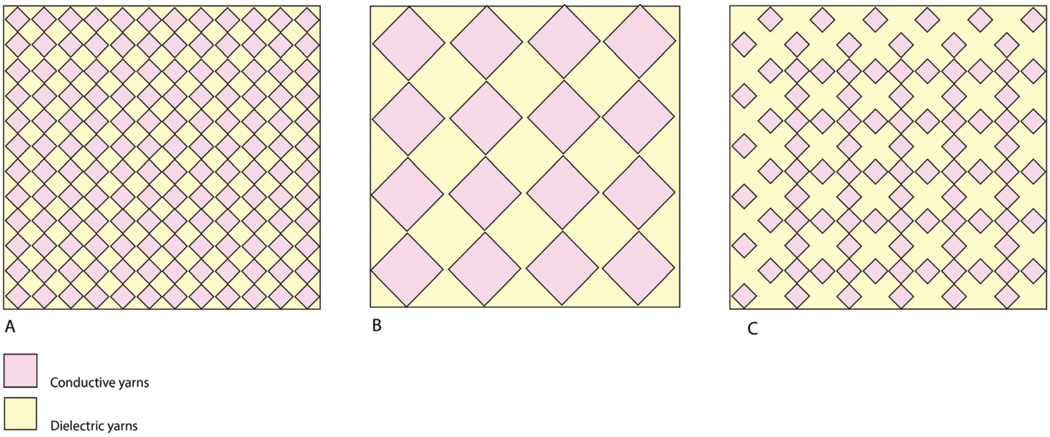

Figure 16: (A) Stark contrast of conductive and dielectric yarns produce a strong electromagnetic textural quality across the surface of the textile. (B) Increasing the density and number of conductive yarns in contact with one another allows for increased field strength in those areas. (C) Decreasing the amount of conductive yarns while increasing dielectrics will diffuse the electromagnetic field and simultaneously result in decreased electromagnetic texture.

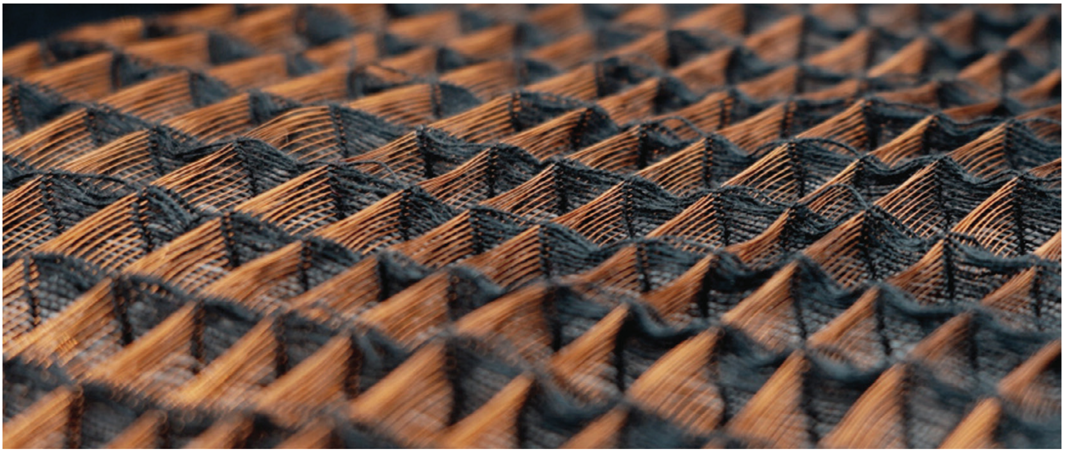

Figure 17: Copper and cotton yarn floats in a waffle weave, resulting in dense areas of conductive yarn. This expresses a high degree of electromagnetic texture across the surface of the textile. © Erin Lewis (2021).

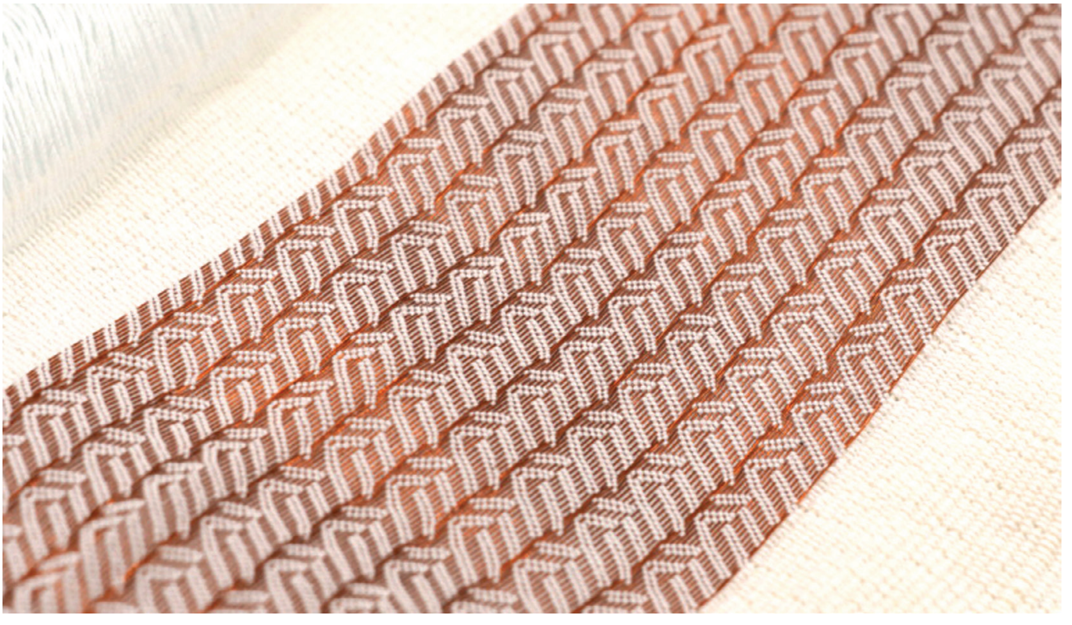

Figure 18: Diffusion of the electromagnetic field by increasing the amount of dielectric yarns that sit on the surface of the textile. © Erin Lewis (2021).

and diffusion within the design, resulting in an overall quality of electromagnetic texture. Then, the designer may also use the textile surface scanning method as a way to perceive the hidden dimension of the textile. In this way, smart textile designers can embed hidden elements of their designs that, only through scanning the textile, can be revealed. This opens to new expressional possibilities for woven smart textile design.

Discussion

This research has been conducted in the context of doctoral studies in smart textile design. The broader research aims to develop methods and tools for exploring this alternate physical domain of conductive smart textiles, and discusses these in the context of textile design thinking. It also seeks out new means for producing artistic expressions of electromagnetics through textile design methods, and argues that electromagnetism is a non-visual design material to be worked with in this context. The method of *textile surface scanning* introduces new textile design notions of *electromagnetic texture*, *field strength* and *diffusion* that serve as a contribution to the smart textiles design field. These notions build vocabulary towards describing qualities of the textile that extend into the non-visual, intangible surrounding space. In doing so, this article responds to an ongoing call for new methods, techniques and terminologies for working with smart textiles and materials that are intangible, invisible, temporal and spatial (Berzowska 2004, 2005; Berzowska and Coelho 2005; Hallnäs 2008; Worbin 2010; Kettley 2016). These designers have recognized that engaging with electronic and computational materials within textiles opens to new qualities and properties of the textiles that effect or are effected by the textile's basic structural elements. Working towards identifying, characterizing and naming these qualities and properties has been addressed by the smart textiles design community to some extent, though rarely towards electromagnetic phenomena (cf. Beuchley 2008; Worbin 2010; Korooshnia 2017; Bredies 2017; Greinke 2017; Townsend and Mikkonen 2017; Friske et al. 2019; Scholz and Greinke 2021). Even still, as the smart textiles design community looks further into basic properties of light, colour, sound, spatial and temporal behaviours, for example, new design possibilities emerge through the discovery of unearthed qualities properties and the advancements of design research, practice and knowledge. This gives momentum for researchers to explore intangible, invisible design materials and their expressions through the lens of textile design. This further suggests that to explore possible expressions of textiles, one might adopt a multisensorial approach that looks beyond our dominant senses and, by engaging with new methods and tools, hidden properties of textiles may come to light.

Basic knowledge of electromagnetics that present in this work can be incorporated into the textile thinking that woven textile designers engage in when ideating, sampling and designing woven textiles such as these. Using these notions and terminologies, woven textile designers can anticipate certain electromagnetic expressions that result from decisions made using tangible textile materials. Furthermore, these new notions and terminologies can be seen as interdisciplinary communication tools where electromagnetic and electronic engineers (for example) who may pair with smart textile designers on a collaborative work may share this hybrid understanding and new notions of the tangible and intangible qualities of a conductive textile.

Using the *textile surface scanning* method and the aforementioned terminologies, smart textile designers may be able to take this work further to design new electromagnetic expressions in textiles. This could, for example, involve kinetic expressions that result due to the generation of an electromagnetic field (as with conventional electromagnets), the embedding of data within textile materials (e.g. the weaving of 'secret messages' that only appear in the electromagnetic field and need to be scanned to be interpreted) or representative approaches such as producing 3D-printed topographical objects that tangibly illustrate the electromagnetic field shape alongside its textile source. These approaches suggest ways smart textile designers to move deeper into the properties of conductive and electronic textiles.

Notably, *electromagnetic texture* may contradict the conventional textural quality of a textile. A textile with a visually smooth surface and little tactile texture may express a highly textural and nuanced electromagnetic field as the result of the placement of conductive and dielectric yarns in the structure. This is evident in sample 1: twill stripes, where a conventionally flat and smooth textile reveals a high peak and long slope as the field strength decreases over the dense dielectric area. Similarly, in sample 2 the uniformity of waffle weave peaks in the tangible textile is expressed electromagnetically as being highly irregular. This discrepancy between expressional domains is what makes *electromagnetic texture* an intriguing textile design notion – it follows its own expressional way of being, and that may be inverse to our perception of the tangible textural expression of the textile.

Improvements to the method can be made by standardizing the timing of the scanning motion through motorized, timed movement. This would remove any unwanted variations related to the pace and steadiness of scanning movements. Further exploration into working with the raw data in various software to produce alternative expressions of the visualizations could be undertaken to explore alternative expressions of the magnetometer data. The *textile surface scanning* method could be trialled with a variety of other woven textile structures, and has yet to be applied to other techniques such as knitting or embroidery. These are viable future directions for developing the method further.

CONCLUSION

This article has presented a method for sensing, visualizing and discussing expressions of electromagnetism in woven smart textiles. Through a method of textile surface scanning, woven textile designers can easily produce a visualization of its electromagnetic field of the textile without specialized knowledge or lab equipment. The contribution of the method both supports and expands upon textile designers' inherent practices of textile design thinking and the constant toggling between scales of design, where the textile surface, yarns and electromagnetic behaviours and properties must be held in perspective and negotiated between. The presentation of new notions and terminologies of *electromagnetic texture*, *field strength* and *diffusion* provides textile designers with a way to describe the properties of the textile in novel ways. The application of this method can stimulate new expressions of woven textiles that move beyond surface and selvedge, into the electromagnetic domain and the space that surrounds the textile.

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