

# Folded Electronic Textiles

## *Weaving, Knitting, Pleating and Coating Three-Dimensional Sensor Structures*

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**ABSTRACT**

This article reports findings from a one-month design research project in which four textile and fashion designers engaged in collaborative exploration of technical and artistic knowledge inherent in *folds and folding*. They experimented with textile technologies and construction methods to design, fabricate and analyze three-dimensional dynamic materiality in electronic textiles (e-textiles). The focus was on sensor structures achieved by knitting, weaving, pleating and coating techniques. The analysis of measurements of electrical resistance between one and 36 sensing areas per sample demonstrate the added value of folds integrated into textile sensor structures. The authors discuss types of folding and their aesthetic, textural and sensorial advantages. Detailed information on design, fabrication and experimental results is provided in supplementary materials to the article.

**THE PRACTICE OF FOLDING**

Folding has become of increasing interest in recent decades, providing blueprints for innovative 3D structures in engineering, art and design. Research has been driven by renewed popularity of the art of origami and the availability of computational tools to model and fabricate folds in paper, fabrics, ceramics, plastics, carbon and metal.

Digital technologies enable foldable structures to be constructed bottom-up, applying additive manufacturing methods and smart materials, e.g. threads in 3D woven or knitted structures, 4D printing of robotic devices [1] or lithographic nanofabrication. Modeling software allows the construction and analysis of dynamic structures focusing on optimization of mechanical and electrical properties, manufacturability [2] and new applications.

In textile practice, folding has been used for millennia for cultural and social purposes [3]. Pleating entails folding fabric in a pattern made permanent by applying heat and steam. Pleating offers versatile texture and volume creation and has been mainly explored within haute couture design. An example is Issey Miyake's seminal work on pleating technology [4], culminating in the collection *Pleats Please*, in which the designer combines aesthetic form with textile functionality, e.g. lightness, movement, ease of care and ease of fabrication.

Both weaving and knitting are textile construction techniques through which fabrics are produced by looping or intertwinning yarns. For producing folds with integrated sensing areas, this has the advantage that conductive patches are produced in parallel with folds, resulting in a precise placement. Weaving is the oldest textile technique known, and woven folds have been found in ancient Egyptian textiles using cramming and spacing techniques in the warp. Knitted folds are mentioned less often and are mostly presented as decorative pleats for women's wear, e.g. puff sleeves, skirts and ruff structures.

Today, one finds a number of experimental modifications of folded fabrics and other materials to be used for clothing, interior, furniture or product design [5,6]. The practice of folding has also been investigated in several research projects that have studied folding as arts or scientific practice [7], new materials [8] and computational tools [9]. Although the topic is evidently interesting to both design and technical researchers, folded textiles that combine electronic functionality with aesthetic qualities have been less thoroughly explored. One example is the Metatextiles project, in which antenna arrays were embedded into folded e-textiles combining unusual sensing qualities and textile craft [10].

In our work presented here, we intend to contribute to the body of work in the field of e-textiles by design. The designers broadened the current portfolio of textile sensor technology through application of folding textile construction and manipulation techniques. The work demonstrates solutions derived through experimental design practice and how these prompt engineering solutions while providing poetic outcomes.

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## The Residency

This article describes results from a four-week residency of four textile and fashion design researchers at Berlin University of the Arts. The overall aim was to develop folded textile sensor structures. The team focused on knitted, woven and pleated textiles, sensor layouts, electrical properties, material aesthetics and mechanical motion pushing capabilities of each of the techniques. The residents' focuses are briefly described below.

Emma Wood is a weaver and explored using chirimen to create lightweight, finely pleated woven structures that can incorporate numerous multidirectional sensors.

Arantza Vilas is a textile artist and designer working with print and pleating processes. She looked at bringing a sense of "the aesthetics of time" into e-textiles and how best to incorporate sensors into pleated structures.

Sophie Skach is a fashion designer and researcher interested in textile sensors embedded in clothing. In this research, she explored the many variables of machine knitting to create folds that can be used to measure body movement.

Pauline Vierende is a textile artist and researcher exploring unconventional materials for e-textile interfaces. She investigated in situ polymerization [11] for creating pressure- and stretch-sensitive textiles.

## EXPERIMENTAL STUDIES

### Sensor Topologies and Mechanisms

Our overall objective was to develop and prototype e-textile pressure and stretch sensors with variable electrical resistance ( $R$ ). While the textile techniques varied, the underlying mechanisms remained the same, as illustrated in Fig. 1. Depending on the amount of applied pressure or stretch, a continuous signal of changing  $R$  is converted into a voltage using a voltage divider circuit.

Figure 1a shows the technical principle of a folded stretch sensor consisting of a single layer of piezoresistive material. Electrodes can be attached in different locations using dressmaking pins or metallic clips.  $R$  is changed by stretching the material. Figure 1b illustrates a pressure sensor consisting of three layers. The top and bottom layers are electrodes with a layer of piezoresistive material sandwiched in be-

tween. Rather than being applied using external force, such as hands, pressure is generated directly on the fold lines by moving the structure.

The residents used an Arduino Uno Rev3 [12] microcontroller to convert  $R$  of their developed textile sensors into digital signals and printed the sensor values in real time, allowing quick determination of the textiles' performance while iterating. They subsequently recorded and plotted the values of their selected four samples as raw values (1–1023). The measurements indicate trends, as the inherently varying differences in electrical resistance of the conductive and piezoresistive areas were not compensated for in the circuit or with data processing.

### Sampling

Shifting now to the residents' design contributions, this section introduces four sensor structures. Comprehensive information on fabrication steps and sensor evaluation is provided in supplementary material.

### Emma Wood: Woven Folded Small-Scale Sensors

I explored how chirimen, a high-twist silk yarn used in kimono weaving, can be used to develop finely pleated woven sensors. After over-twisting in an "S" or "Z" direction, the chirimen is coated with sericin (a protein produced by silkworms) to lock the twist in place. Once woven, the sericin is removed in a solution of water and sodium bicarbonate, releasing the twist and causing the fabric to shrink. Various pleated effects may be obtained by applying different combinations of S and Z-twist chirimen yarns in the warp and weft.

**Process.** I combined a warp of piezoresistive yarn (Schoeller Inox/Polyester Nm 50/2), silver yarn (Karl Grimm, Copper 14/000 silver-coated 3981 7×1) and linen with chirimen and silver yarn in the weft to create a pleated, multilayered sensor matrix (Fig. 2a), woven on a 24-shaft loom using a triple-layer block threading draft. For the top layer, I employed linen with intermittent silver yarn in the warp, the middle layer was piezoresistive yarn and the bottom layer contained only linen. I used alternating twist chirimen in the weft for all layers, with intermittent silver yarn added in the bottom layer.

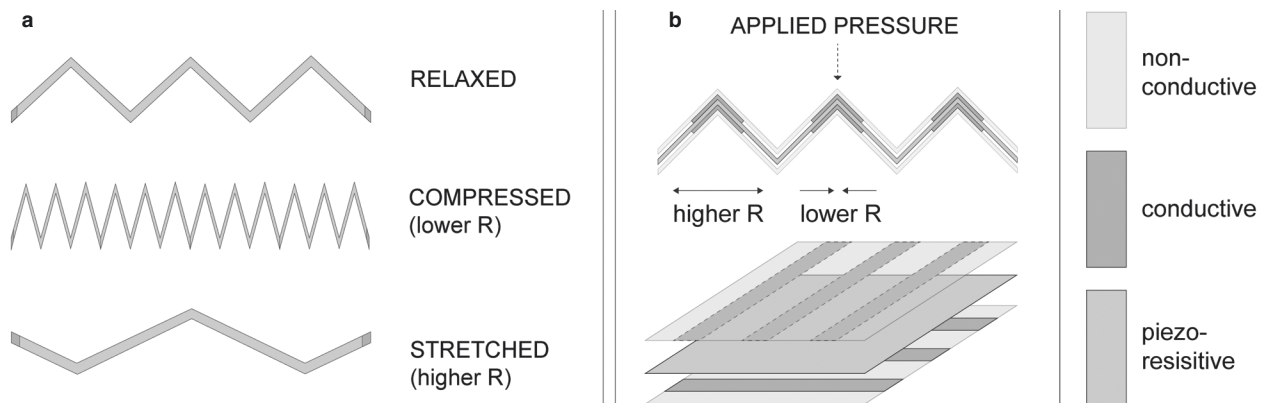
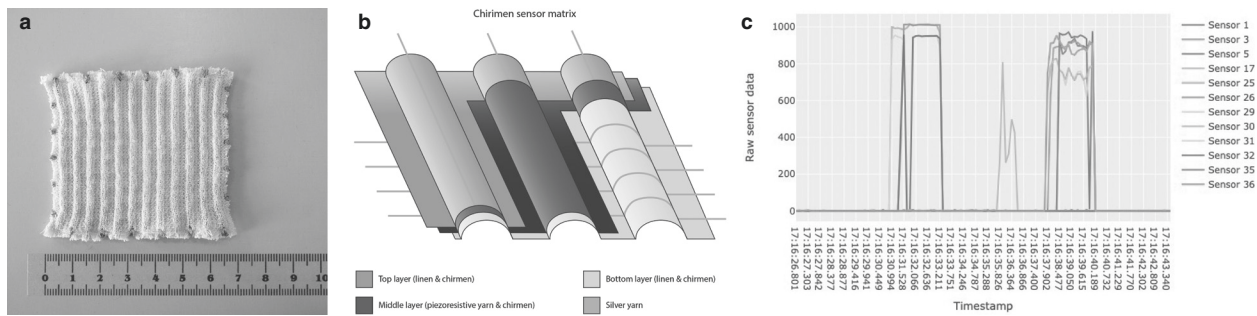


Fig. 1. Technical principles of (a) folded stretch sensor; (b) pressure sensor matrix. (© Berit Greinke)



**Fig. 2.** Woven pleated sensor matrix: (a) sample, (b) structural illustration, (c) plotted raw sensor values over time. (© Berit Greinke)

The chirimen and weave structures combine to create triple-layered micro-pleats that nest together (Fig. 2b). The intersections of silver yarn in the bottom and top layers form a grid of 120 sensors divided by the middle piezoresistive layer that make contact when direct pressure is applied. All three layers were stitched together at certain nonconductive points in the weave structure, allowing them to maintain the structural integrity of a densely woven cloth.

**Moving the Woven Sensor.** The micro-pleats present in the sensor matrix create a bounce effect that provides a resting state of separation between the three woven layers and resumes as soon as pressure is removed. Of the 120 available sensors, 36 were tested simultaneously using a matrix circuit by placing pressure at three points in a diagonal line [13]. Figure 2c shows the sensing points with the most distinct responses, demonstrating a clear separation between the three pressure areas. The proximity of the sensors to each other indicated a relational effect, resulting in a high-resolution reading.

**Arantza Vilas: Pleated Pressure Sensor Matrix**

Pleating is an ancient craft where fabric is molded in three-dimensional forms to acquire sculptural volume and movement. Molds are made from moisture-resistant parchment paper; the fabric therefore can be sandwiched between them and steamed for a length of time that varies depending on the material. Still manually produced today in specialized workshops, pleating is a laborious process requiring dexterity and an intimate interaction between crafter and materials to accomplish folds of high quality [14].

**Process.** I developed sensors with variable electrical resistance through layering and bonding techniques using

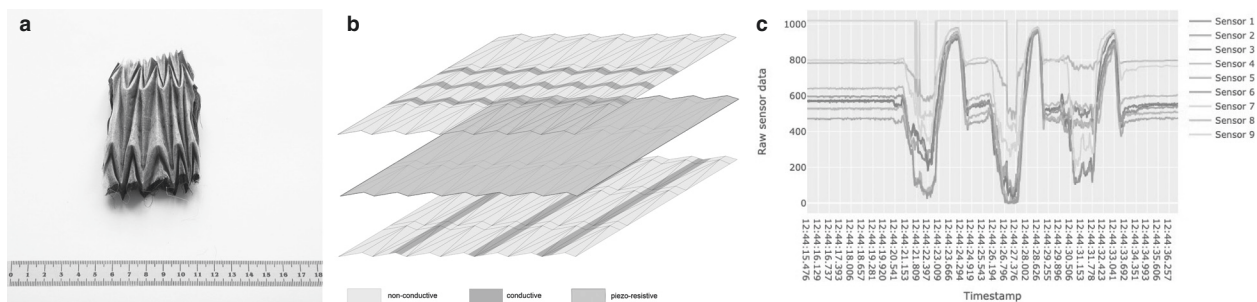
a combination of fabric substrates. The sample presented here consists of silk organza, conductive and piezoresistive materials.

I bonded a grid of strips of the conductive fabric Shieldex Techniktex P130+B on two separate layers perpendicularly. A third layer of a piezoresistive EeonTex LTT-SLPA material is placed between those two layers and pleated together as one piece. The key aspect is controlling the length of time the piezoresistive material is heated in the pleating process, resulting in a three-layered fabric with integrated pressure sensors. Most samples were steamed for 30 minutes at 125°C.

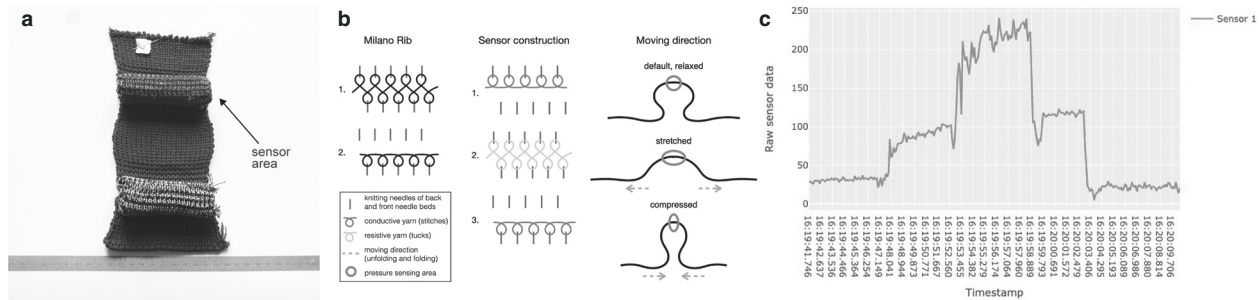
My experiment considered how to best incorporate the conductive and piezoresistive layers to achieve an outcome that was soft to the touch. This technique, furthermore, creates fabrics that are easy to disassemble to their components, making them potentially recyclable.

**Moving the Pleated Sensor.** The peacock pleat is a V-shape fold [15] in which valley and mountain folds alternate in a zigzag structure similar to the chevron (also known as *miura*) pleat. It differentiates in the proportions of the vertical folds, resulting in a pleated structure with rows of V-folds in opposite directions (Figs 3a,3b).

$R$  decreases when more pressure is applied on the mountain and valley fold lines by moving the structure. To test the functionality of the pleated sensor matrix, I connected all nine pressure points to the microcontroller using a matrix circuit, and to activate readings, the sample was pulled out and pushed back three times, focusing on the top, the middle and the bottom. Figure 3c shows measurement results, demonstrating high responsiveness and repeatability for all sensing points.



**Fig. 3.** Pleated pressure sensor matrix with Peacock pleat: (a) Sample, (b) structural illustration, (c) plotted raw sensor values over time. (© Berit Greinke)



**Fig. 4.** Knitted stretch sensor with fold. (a) Sample, (b) structural illustration, (c) plotted raw sensor value over time. (© Berit Greinke)

### Sophie Skach: Knitted Folded Sensors

Folds in knitted fabrics are often used to achieve solutions for fully fashioned garments or to create bulging shapes or textures. The direction of knit is perpendicular to the direction of folds. To make knitted folded pressure sensors, however, it is desirable for the folds to be parallel to the knitting direction, allowing for placement of conductive yarn on fold lines. To achieve this, I adapted the double-bedded Milano rib knit pattern, resulting in horizontally rolling structures with spring-like movements. The basic knit mechanism of a Milano structure is to knit additional courses (rows) on one side of the fabric, which creates more stitches on that side, eliciting a rolling behavior. This knit structure is of robust quality and only lightly elastic compared to other rib knits. The roll direction is determined by the placement of the additional courses; the fabric rolls toward the side with fewer courses, compensating for the space the additional one-sided courses require. This relationship of uneven distribution of material on the two sides of the knit fabric leads to the characteristic rolling (Fig. 4a).

**Process.** I utilized the same knitting techniques to embed a sensing element on the fold lines of this structure. I present a pressure sensor knitted with two types of conductive yarn: a Shieldex<sup>®</sup> 235/36 dtex silver coated yarn acting as electrodes and a Schoeller Inox/Polyester Nm 50/2 as piezoresistive yarn. The silver yarn is knitted as single stitches on the front side, followed by piezoresistive yarn integrated as double-sided rib stitches and completed by another course of silver yarn on the back side (Fig. 4b). This three-layer pressure sensor is knitted with the piezoresistive layer sandwiched across multiple courses between single courses of the conductive layers.

**Moving the Knitted Sensor.** The sensor measures the moments of movement when the knitted rolls are pulled apart from each other or *unfolded*, bouncing back after being stretched. This is suitable to capture movement and manip-

ulation of the textile structure, because the sensor reacts to small changes in pressure applied on the folding line—the center top of the roll, as described in Fig. 1b.

I connected the knitted sensor to the microcontroller as a single variable resistor. The sample was pulled out and pushed back in three steps as I measured a relaxed state, flat state and stretched state. The results, shown in Fig. 4c, clearly demonstrate the change in resistance over the three movement stages.

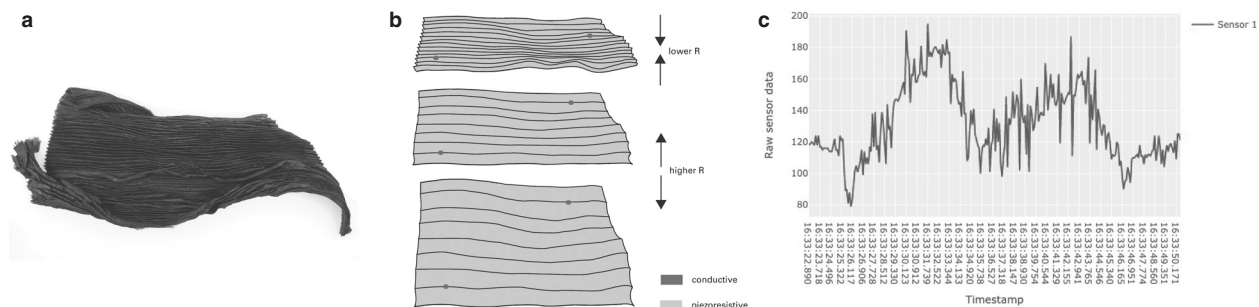
### Pauline Vierre: Polymerizing Shibori

In situ polymerization is a do-it-yourself technique with which textiles and porous materials are made piezoresistive through a chemical process. As demonstrated by Honnet et al. [16], this method of reverse-engineering a commercial piezoresistive sheet material presents new opportunities for designers to explore e-textile functionality and aesthetics at a low cost.

**Process.** For the sample, I used Arashi shibori, which is a shape-resist dyeing technique. I first submerged and processed an organza silk fabric in a polymerization bath. After drying, I created a pattern by tying a fabric around a pole and steaming it for 20 minutes at 120°C. The sample is shown in Fig. 5a.

**Moving the Polymerized Sensor.** Arashi (meaning storm in Japanese) patterns are said to resemble heavy rain or waves after a storm. Folds made with this technique can adopt many shapes; however, they are all structures that drape and move organically. The technique also produces a shape memory as structures retract easily after unfolding. This effect is sustained best on synthetic fabrics, but due to the stiffness of the silk organza, the same effect was achieved here with impermanent folds that may be ironed or washed out. The sample was first polymerized, then wound and steamed.

For measuring the changes in  $R$ , I attached two probes to the sample approximately 10 cm apart, and the sample was



**Fig. 5.** Polymerized silk organza with Arashi shibori. (a) Sample, (b) structural illustration, (c) plotted raw sensor value over time. (© Berit Greinke)

unfolded and lightly stretched twice. Figure 5b illustrates how stretch and  $R$  are linked, with Fig. 5c showing the change in  $R$  over the two stretch movements. Unfolding and then stretching increases  $R$  lightly. Although the two stretch movements can be clearly identified in the plot, the variation in the change itself is small, with a considerable amount of noise impact.

### REFLECTION OF TEXTILE TRANSLATIONS

Working side by side in the textile studios allowed us to develop a comprehensive understanding of how the principles of folded pressure and stretch sensors can be implemented in their respective textile disciplines. The designs explored here form the ground for new application areas and refined new sensors. This section briefly reflects on sampling processes that emerged as a result.

#### Technique Interpretations

Translation of the respective techniques occurred in various ways. While some woven and knitted folds were similar in final appearance, the textile characteristics, e.g. in respect to stretchability, pose opportunities for integration of such sensors in various tangible interfaces. The impact on the treatment of raw materials was highlighted through the polymerization process, transforming the functionality of conventional non-conductive fibers. This extends the possibility to design for specific aesthetics and sensory outcomes based on textile, rather than electronic, function. Combinations of the explorations presented here are also possible.

#### Passing Samples On

The residents worked closely together in textile studios, allowing for a constant exchange. In addition to discussing their results, they passed on textile samples to be used as examples or processed further with different techniques. This was specifically the case for pleating and polymerizing, as these processes could be applied after samples had been

woven or knitted. The combination of these techniques envisions customized folds and personalized designs that extend conventional sensor fabrication methods.

#### Thinking through Sampling

While most material applications relied on controlled processes in order to achieve optimal results, chance was a factor for some samples. Using a single technique did not always lead to the desired function; such results usually would be deemed failed experiments. However, passing on and processing the samples further often led to interesting new ways of making sensors through combining techniques, thus overcoming restrictions encountered through a single technique. For example, weaving can be seen as restricted to the perpendicular directionality of warp and weft, while the knitting machine produces weft-based fabric surfaces. The experiments and comparison of the different fold designs opened new directions of movement and allowed the weaver, knitter, pleater and polymerizer the possibility to plan for an added dimension.

#### CONCLUSION

The project has provided many avenues for creating novel dynamic folded sensing structures, while the principal layout of sensors remains the same. Applying different textile techniques allows for varying scales, integration and aesthetics of electronic functionality and folds. While focusing on technical insights gained during the residency, we highlight how side-by-side exploration and exchange between textile techniques can lead to new spaces for designing and understanding electronic textile functionality. The experiments created during the residency open opportunities for three-dimensional interactive textile artifacts that blend digital technology with poetic craftsmanship. We hope these results will inspire designers and engineers to experiment with folded structures as sensing devices and contribute to engineering and design knowledge in equal measure.

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