

# Supplementary Material

These pages contain detailed technical descriptions of the four samples presented in *Folded Electronic Textiles: Weaving, Knitting, Pleating and Coating Three-dimensional Sensor Structures*.

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## Woven Chirimen Sensor Matrix (Emma Wood)

### Introduction

The chirimen sensor matrix is a triple-layer pleated fabric woven on a 24-shaft handloom. Conductive yarn runs vertically and horizontally through the top and bottom layers of the matrix respectively, and they are separated by a layer of piezoresistive yarn. The pleats created by the chirimen and weave structure cause the three layers to nest together without making direct contact when the cloth is in its resting state. When pressure is applied, contact between the top and bottom layers is formed via the piezo-resistive layer.

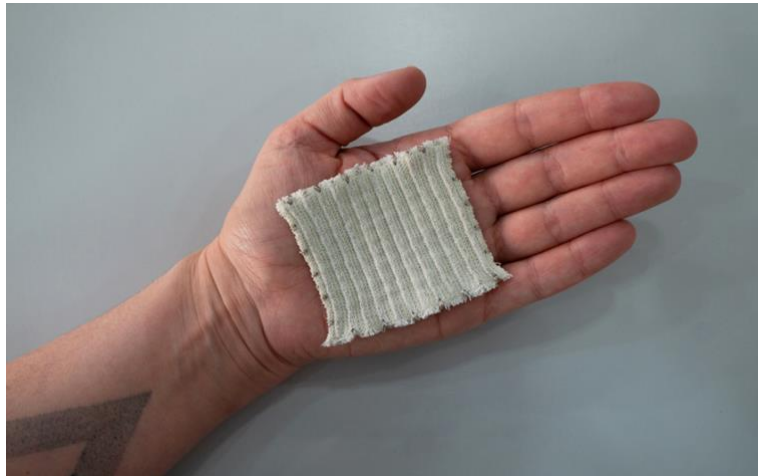


Figure 1: A completed woven chirimen sensor matrix.

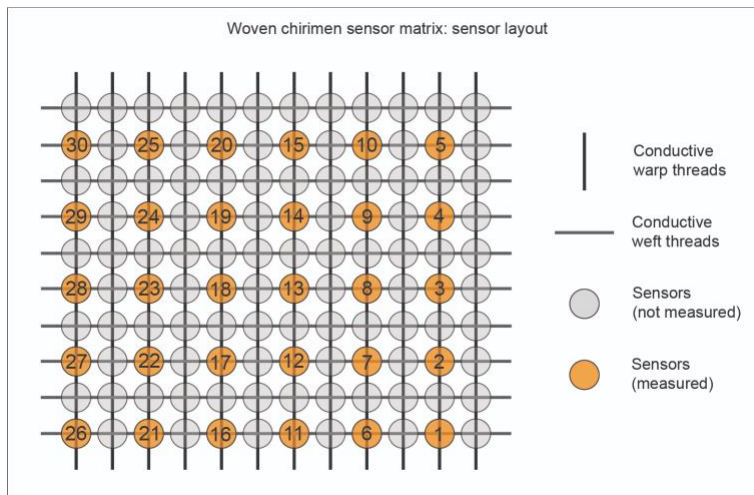


Figure 2: Visualization of the sensor layout within the chirimen sensor matrix.

## The Material

Chirimen is a high-twist silk yarn used predominantly in Japanese kimono weaving. It is coated in sericin, which is a protein created by the silkworm and which locks the high twist in place, making the yarn easy to weave with. Once the cloth has been woven, the sericin coating is removed and the twist in the chirimen is released, causing the cloth to pucker and gather, in accordance with the weave structure used.

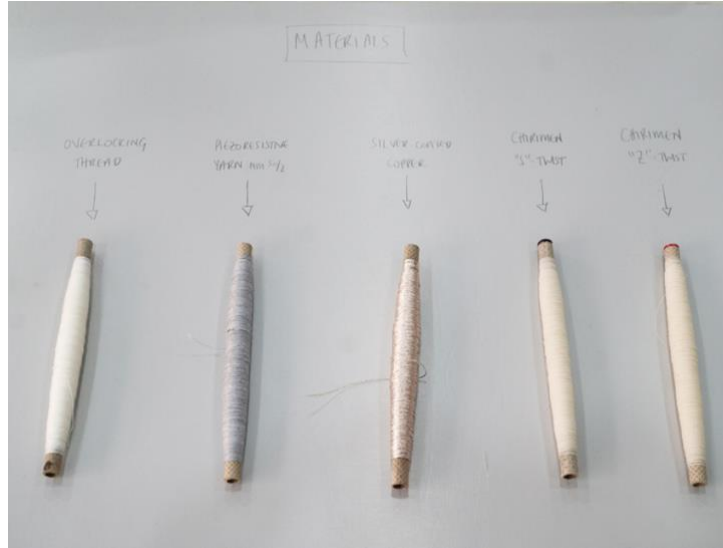


Figure 3: The materials for a chirimen sensor matrix (from left to right: overlocking thread or linen, Nm piezoresistive yarn, silver yarn, chirimen "S" twist, chirimen "Z" twist).

## The Set-Up

The warp is threaded in a two-block draft on the loom, where on shafts 1-12 the three layers are woven together as one cloth and on shafts 13-24 the warp is separated into the three layers of the sensor matrix.

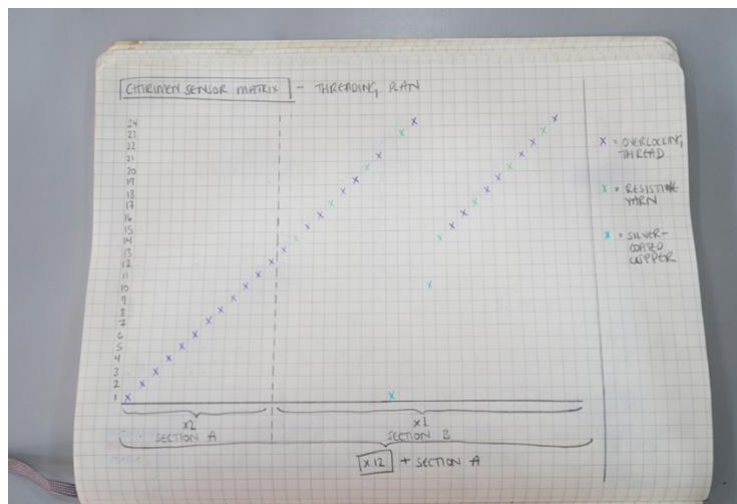


Figure 4: The threading plan for a woven chirimen sensor matrix.

## The Warp

The top layer of the warp is wound in linen or cotton, with two strands of silver yarn running vertically through the top layer of each pleat. The middle layer consists entirely of piezoresistive yarn, and the bottom layer is wound in linen or cotton.

## The Weft

The weft is woven using a combination of S- & Z-twist chirimen. Three rows are woven in S-twist (one row for each of the three layers of the matrix), followed by three rows of Z-twist. This is repeated until you reach the desired location for the sensor matrix connection, and then silver yarn is substituted in place of the chirimen for the bottom layer.

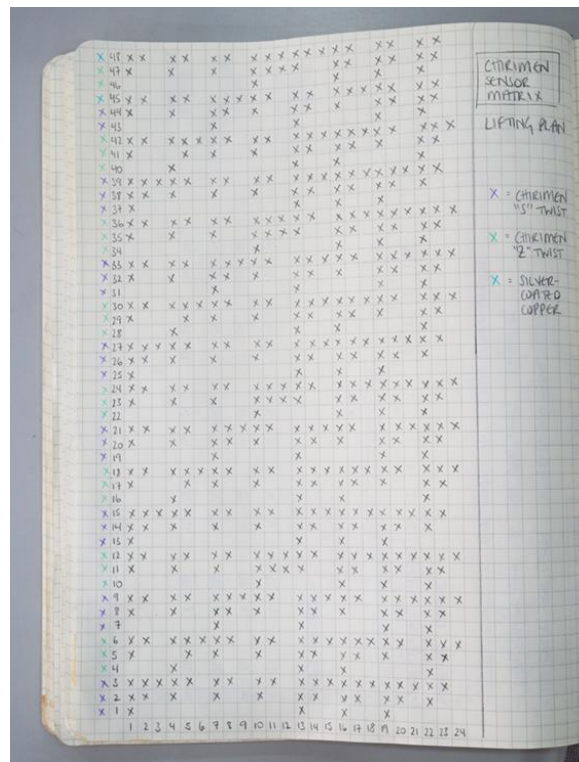


Figure 5: The lifting plan for a woven chirimen sensor matrix.

## The Structure

Shafts 1-12 use a stitched, triple-layer, 4-end satin weave, which results in a densely-packed single cloth. Shafts 13-24 use a non-stitched, triple-layer 4-end sateen weave, which results in three independent layers of cloth that form a vertical tube as the cloth is woven.

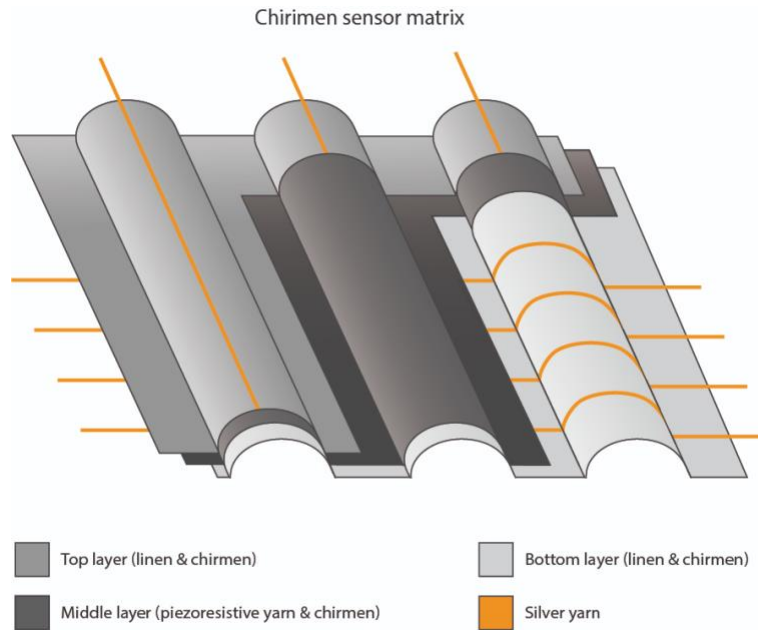


Figure 6: Visualization of the three layers of the chirimen sensor matrix.

## Finishing

When weaving on the loom, the sample will be stiff, the warp ends will be comfortably spaced apart from each other and the sample will lie flat. To finish the cloth and form the pleats, bring a large pot of tap water to 90°C and add 3 g of bicarbonate of soda for each liter of water used. Boil the woven cloth at 90°C for three hours, rinsing occasionally to remove the stiff sericin coating from the chirimen. Rinse fully, then boil in a mixture of tap water and handwash detergent for one hour. Rinse once more, then air dry.



Figure 7: Chirimen sensor matrices before being contact with the finishing bath (left part) and after (right part).



Figure 8: Chirimen sensor matrices being added to the finishing bath.

## Measurements

### Measurement setup

The chirimen sensor matrix was connected to six connection points along the top layer and six connection points along the bottom layer, allowing for a total of 36 sensors to be tested simultaneously. Each top layer connection was fed into a separate digital pin of an Arduino Uno, and each bottom layer connection was fed into a separate analog pin.

To gain an initial understanding of the general performance of the sample and to determine the collective responses of the connected 36 sensors, the sensor matrix was pressed with one finger in three points, diagonally crossing the sample (see Figure 9).

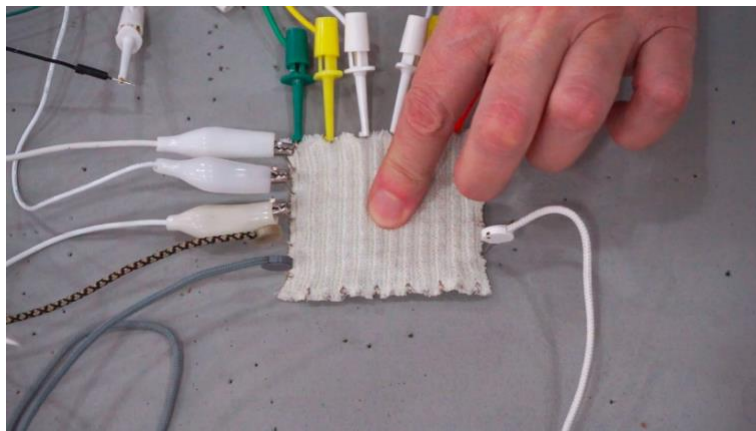


Figure 9: Testing the chirimen sensor matrix ([click here to access video](#)).

## Results and Discussion

Figure 10 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.

There are a number of sensors not reacting at all, notably close to the edges and corners of the sample. This may be attributed to the small size of the textile swatch and resulting inconsistencies in the finishing process. Other sensors did not react with sufficient difference in  $R$ . This may be resolved by changing the second (constant) resistor value in the voltage divider circuit.

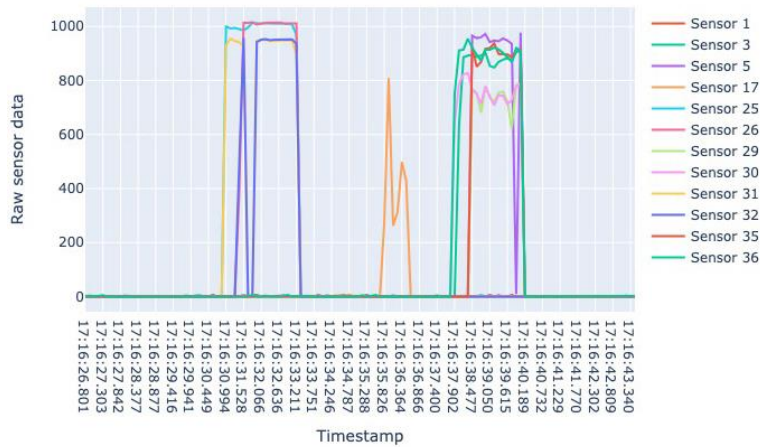


Figure 10: Electrical resistance results over time, woven sensor.

## Peacock Pleat Sensor Matrix (Arantza Vilas)

### Introduction

This sensor matrix with variable electrical resistance uses a Peacock Pleat and layering/assembly and bonding techniques to combine fabric substrates with conductive and piezoresistive materials. A matrix of conductive material is bonded on two separate layers. A third layer of piezoresistive material is sandwiched between them and the three layers are pleated as one piece. Each layer has dimensions of 90 x 150 mm.



Figure 11: Pleated peacock pressure sensor matrix, 90 x 150 mm (unfolded).

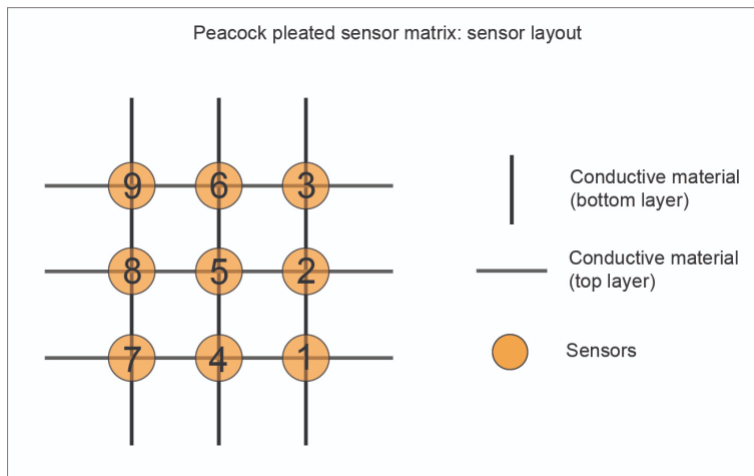


Figure 12: Visualization of the sensor layout within the pleated sensor matrix.



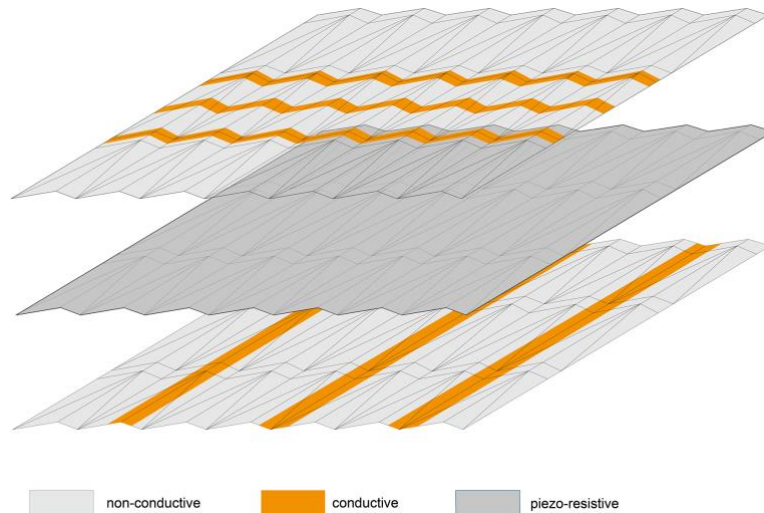


Figure 13: Visualization of the sensor layout within the pleated sensor matrix.

## The Materials

Shieldex® Techniktex P130+B was used for the electrodes on the top and bottom layer. EeonTex™ LTT-SLPA was used for the piezoresistive middle layer.

## Process



Figure 14: Steps of pleating.

Step 1: Conductive matrix positioning. Stripes of conductive material (Shieldex® Techniktex P130+B) are bonded vertically on one layer of paper silk and horizontally on another. The bonding agent (iron-on adhesive) is first applied to the conductive strips which are then placed on each of the silk layers for 30 seconds at 180°C in a heat press.

Step 2: Pleating layers. One layer of paper silk with conductive patches facing up, one layer of piezoresistive fabric (EeonTex™ LTT-SLPA) and the remaining layer of silk with the conductive patches facing inwards are introduced into the pleating mold.

Step 2.a: Peacock Pleat pattern. The Peacock pleat is a V-shape fold<sup>1</sup> in which valley and mountain folds alternate in a zigzag structure, similarly to the chevron/miura pleat but differentiating in the proportions of the vertical folds. The result is a pleated structure with rows of V-folds in opposite directions. A paper

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<sup>1</sup> Jackson, P. (2011). *Folding Techniques for Designers: From Sheet to Form*. Laurence King Publishing.

mold of the same dimensions as the layers is created with two pieces of elephant hide paper. A peacock pleating pattern is drawn on both pieces of paper and scored to then be folded.

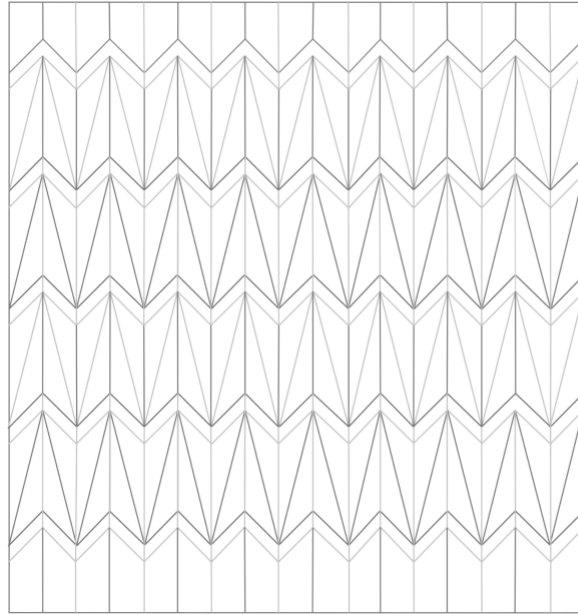


Figure 15: Diagram of Peacock pleating pattern.

Step 3: Steaming of the sample. Once the layers are introduced into the mold and secured (string can be used to hold the fabric and mold in place) the piece is wrapped in cotton cloth and steamed for 30 minutes at 125°C. Once removed from the steamer, allow the sample to cool down before taking it out of the mold. The folds should hold the three layers together, enabling the functionality of the sensor matrix.

## Measurements

### Measurement set-up

To gain an initial understanding of the functionality of the pleated sensor matrix, the nine pressure points were connected to an Arduino Uno microcontroller using a matrix circuit<sup>2</sup>. To activate pressure reading, the sample was pulled out and pushed back three times, focusing one move on the top, one in the middle, and one on the bottom. This is shown in Figure 5. Difference in pressure (and therefore electrical resistance) was recorded as raw data coming from the analog pins of the microcontroller, varying in numbers between 0 and 1023. As the aim of this measurement was to gain a first understanding, no further circuit modification or data processing was done.

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<sup>2</sup> see <https://www.kobakant.at/DIY/?p=7943>

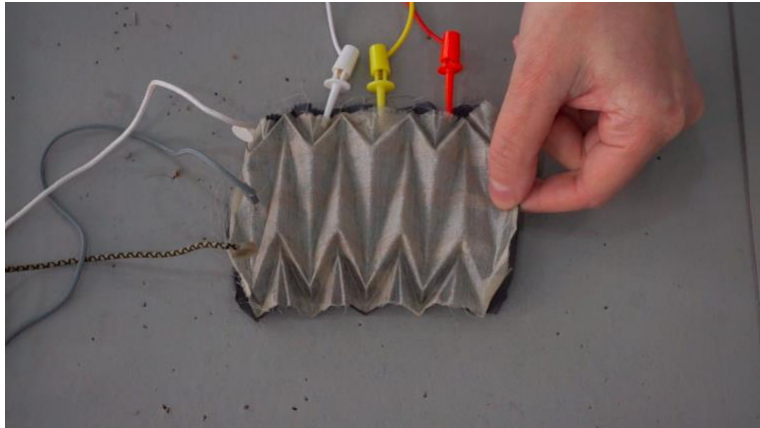


Figure 16: Testing the pleated sensor matrix ([click here to access video](#)).

## Results

Results of measurements are shown Figure 17, demonstrating high responsiveness and repeatability for all sensing points.

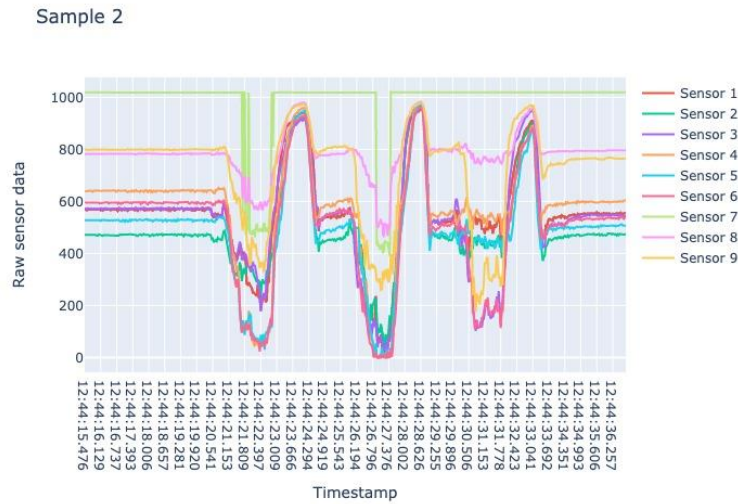


Figure 17: Electrical resistance results over time, pleated sensor.

## Spring *Milano*-Adapted Knitted Sensor (Sophie Skach)

### Introduction

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, the folds need to be parallel to the knitting direction, allowing for placement of conductive yarn on fold lines and across the flat surfaces. Therefore I adapted the double bedded 'Milano' knitting pattern, resulting in rolling structures with spring-like movements. The basic knit mechanism of a Milano structure is to knit additional rows on one side of the fabric, creating more stitches on that side, eliciting a rolling behavior. This knit structure is of robust quality and only lightly elastic compared to e.g. single jersey or rib structures. The rolling direction is determined by where the additional courses are placed; the fabric rolls toward the side with fewer courses, which optically appear longer. The side with the additional courses and therefore with more material to deal with, forms a convex curve of the roll. The more additional rows are knitted on one side, the stronger the rolling direction becomes.



Figure 18: A folded knitted stretch sensor (unit of length: cm).

### The Structure

Embedding a sensing element on the fold lines of this structure is achieved by using the same knitting techniques. I present a pressure sensor knitted with two types of conductive yarn: a highly conductive silver coated yarn acting as electrodes, and a piezoresistive yarn made with stainless steel. The silver yarn is knitted as single stitches on the front side, followed by the piezoresistive yarn integrated as double sided tuck stitches, and completed by another course of silver yarn on the back side, illustrated in Figure 19. This three-layer pressure sensor appears as one optical course with the piezoresistive layer sandwiched between the conductive layers.

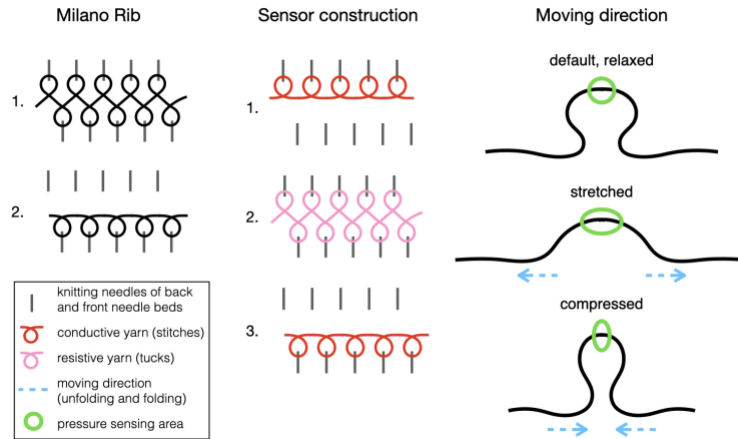


Figure 19: Visualization of the knitted sensor structure.

## Measurements

### Measurement set-up

The knitted structure was connected to one analog input of the microcontroller. The structure was measured over three stages, of which in the first the structure was relaxed, in the second it was lightly stretched to flatten it, and in the third it was stretched.

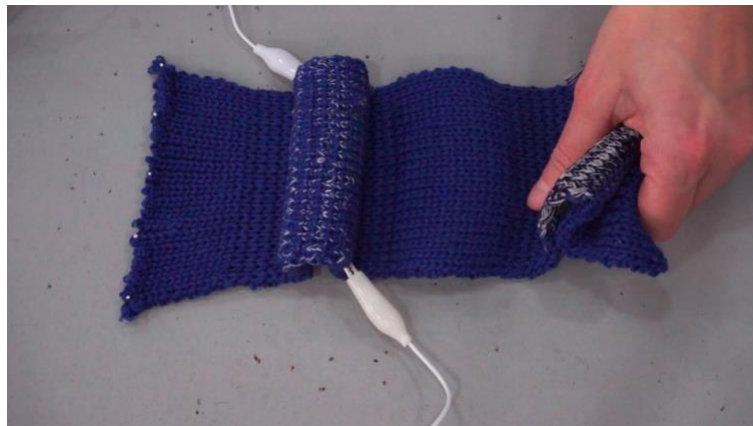


Figure 20: Testing the knitted stretch sensor ([click here to access video](#)).

## Results

The results shown in Figure 21 clearly demonstrate the change in resistance over the three movement stages. Flattening and stretching the sample decreases  $R$ . For the change from non-stretching to stretching a progressive change of resistance can also be observed, indicating that more intermediate steps of resistance are measurable. From stretched to non-stretched state however, these progressive changes do not occur. We attribute this to the mechanical properties of this knitted structure, which takes a while to retract and therefore does not pick up the expected resistance change in this experiment. To change this effect, the sample could be moved at a slower pace during measurement.

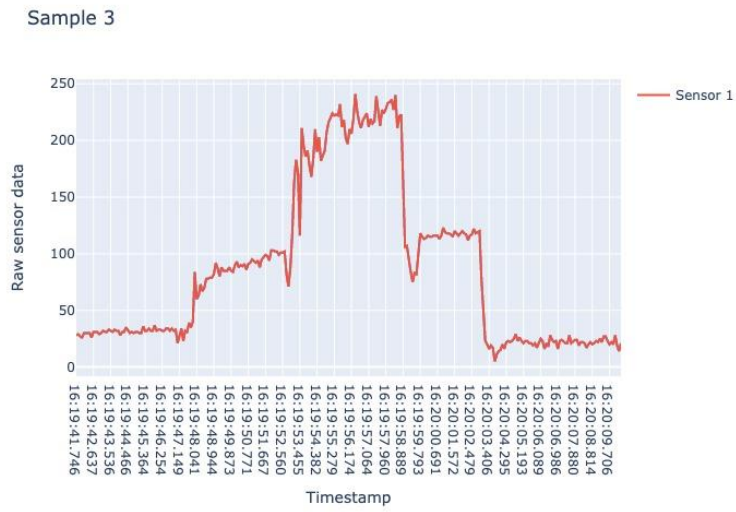


Figure 21: Electrical resistance results over time, knitted sensor.

## Shibori Polymerized Sensor (Pauline Vierende)

### Introduction

In-situ polymerization is a Do-It-Yourself technique with which textiles and porous materials are made piezoresistive through a chemical process. It was demonstrated by reverse-engineering a commercial piezoresistive sheet material and opened up new opportunities for designers to explore e-textile functionality and aesthetics at low cost<sup>3</sup>. As the technique is similar to fabric dyeing, I explored how the textile process of shibori can be used to create piezoresistive patterns as a result of folding.



Figure 22: Shibori pressure and stretch sensor sensor.

### The Material

Some shibori tying techniques can be used to create textured surfaces on silk and synthetic fabrics. Here I faced the challenge of first rendering a silk organza (with a paper-like touch) electrically conductive with in-situ polymerization. This process happened before the actual shibori folding, as water involved during the first phase (polymerization) would cancel any impermanent fold on silk.

### The Set-up

#### On the process of in-situ polymerization

Step 1: Prepare silk. The silk organza was pre-washed for 15 min using silk-specific soap in a washing machine to remove residues of grease. The washing softened the fabric and prepared it for a better uptake of the polymerization process. The silk was then subsequently submerged in water for a few minutes.

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<sup>3</sup> see <https://hackaday.io/project/168380-polysense>



Figure 23: View of beige paper-silk prepared for in-situ polymerization.

Step 2: Add Pyrrole (monomer). The silk was added to a stirrer (I used a small ice cream maker to achieve the stirring). While stirring the fabric in 1.2 l water I added 5 ml of Pyrrole using a syringe. The fabric was stirred then for about 15 minutes.

Step 3: Add Iron (III) Chloride (oxidizing agent). I measured 10 g of Iron (III) Chloride and stirred it into the mixture. The fabric was then stirred for 60 minutes.

Step 4: Finish. I removed the fabric and thoroughly rinsed it until the water was clear.

Step 5: Intermediate assessment. Using multimeter to check electrical resistance during process (see Figure 24).



Figure 24: Measuring polymerized paper-silk after first (11.5 M $\Omega$ ) and second processes (from 414 to 210 k $\Omega$ ).

After polymerizing and drying the fabric, I assessed its electrical resistance using a multimeter. Due to a high resistance in the range of M $\Omega$  after just one polymerization cycle, I decided to repeat step 1 to 4. After a second cycle of polymerization, the resistance dropped to ranges of k $\Omega$ .



## Arashi-shibori

To create the fold pattern, I used the technique of Arashi-shibori, which is a shaped-resist dyeing technique. According to the technique, I created a fold pattern by tying a fabric around a pole and steaming it for about 15 minutes at 120°C.



Figure 25: Process for Arashi-shibori. Left: placing fabric on pole. Center: tying up with cotton thread. Right: unraveling the tie.

## Measurements

### Measurement set-up

For measuring the changes in  $R$ , two probes were attached to the sample approximately 10 cm apart in a relaxed state. The sample was unfolded and lightly stretched twice, as is shown in the video.



Figure 26: Testing the polymerized sensor ([click here to access video](#)).

## Results

Figure 27 shows the change in resistance over the two stretch movements. Unfolding and then stretching increases the resistance lightly. Although the two stretch movements can be identified in the plot, the variation in the change itself is small with a considerable amount of noise impact.

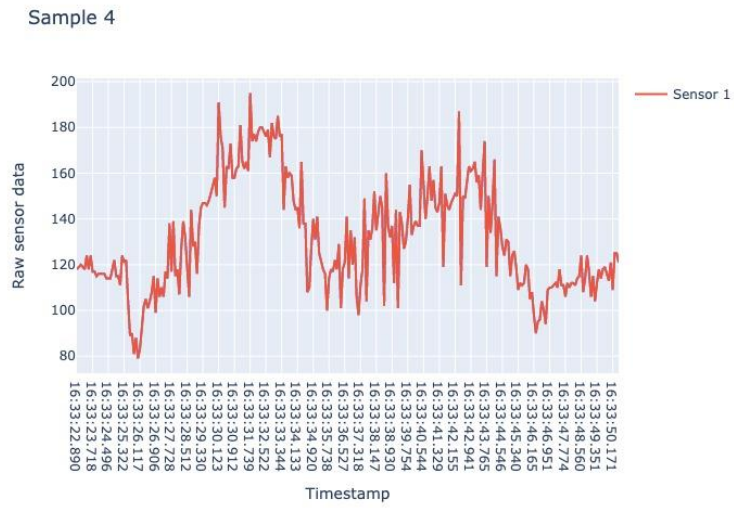


Figure 27: Electrical resistance results over time, polymerized sensor.