

# Exploring qualities of woven sensors

The development of Senzhi: a functional fully woven electronic interface

Maya Hu

Master Thesis Integrated Product Design  
TU Delft Faculty of Industrial Design Engineering  
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### **Exploring Qualities of Woven Sensors**

The development of Senzhi: a functional fully woven electrical interface

#### **Author**

Maya Hu – 4660412

#### **Supervisory team**

Kaspar Jansen – Chair

Holly McQuillan – Mentor

#### **Degree**

Msc Integrated Product Design

Faculty of Industrial Design Engineering

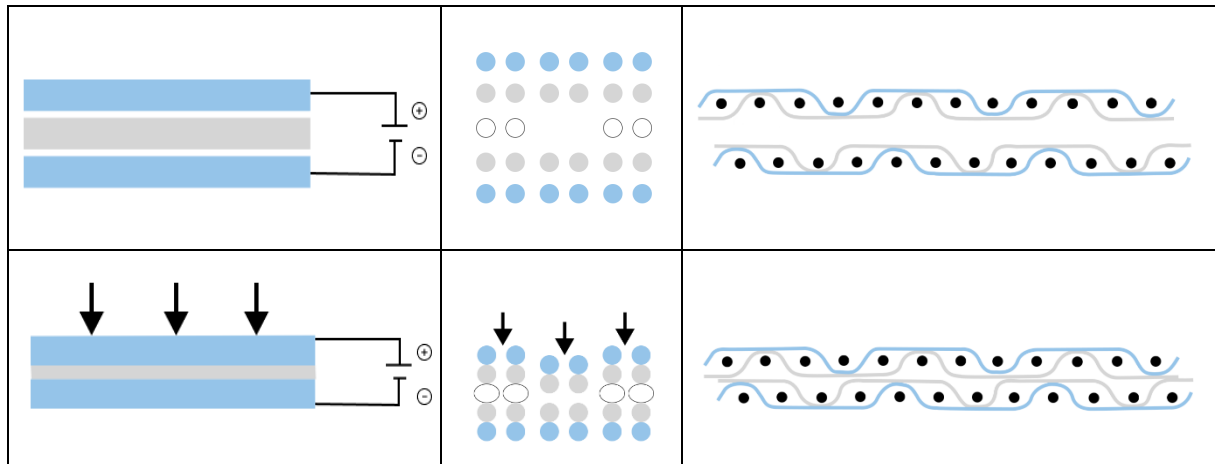
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# Abstract

Animated textiles and textile technology provide new research areas for implementation in many use cases, such as human computer interaction and the development of smart materials. Of these technologies, woven pressure sensors is an area that has been under researched as opposed to other textile technologies. Through cycles of experimental design research resistive based pressure sensing technology, will provide the knowledge to develop and test different versions of a woven sensor.



The ultimate goal of this research is to develop a woven pressure sensor, that gives clear output signals when used. These woven sensors will then be utilized in a textile electronic interface to demonstrate the potential of this technology.

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# 1. Introduction

## 1.1. Animated textiles

### 1.1.1 Definition

Animated textiles is an umbrella term used to describe textile systems that are active, adaptive or autonomous during use through physical, digital or biological means (Buso, 2025). The term expands on the concept of Smart textiles, by not only considering the smartness of computational and/or biological components, but also the intrinsic textile qualities as equally important for its function.

Research in animated textiles builds on established principles from smart materials, embedded computation, and user centred interaction. It involves integrating responsive materials, sensors, and actuators into flexible textile systems and developing them through prototyping. In the past, designers have often treated textiles as a separate entity and medium for computational or smart materials. It is argued that these projects lack a deeper understanding of how the inherent qualities of textiles can be utilized in a functional artefact (Buso, 2025).

Animated textiles shifts this understanding by treating the textile itself as a primary mechanism of interaction. Instead of simply embedding technology into or onto fabric, designers increasingly explore how textile architecture can become a programmable, responsive system. This interdisciplinary approach combines textile knowledge with material science and computation. It redefines fabric as a dynamic interface rather than a static surface. Because methodologies and standards are still developing, the field remains experimental, highlighting its strong potential for innovation.

### 1.1.2 Functionality of textiles

Function is defined by an objects ability to serve a purpose. Animated textiles are compelling artefacts as they can serve many different purposes. Some examples of functions performed by animated textiles are endowing textiles with living organisms, allowing bioluminescent microalgae to grow in a garment and purify the air around the wearer. Other examples use different materials to animate textiles such as shape memory alloys, that are activated by temperature and fold the fabric to its desired shape. Another example is incorporating computational materials in textiles to sense, to actuate, and to program the fabric to behave in desired ways. Incorporating sensors to detect and programming them to actuate through for example LED's (Buso, 2025).

This thesis focuses specifically on textiles that are animated through computational materials. Though generally known as electronic textiles, or e-textiles, these textile systems use digital components and a processing unit to execute its functions.

After electronic components are removed, smart textiles are washable, without damaging the electronic system, because the textiles are made with conductive fibres. A material that is both sturdy and adaptable for textile applications. Textile technology offers high flexibility and durability, as textiles have more freedom of movement as opposed to traditional electronics (Zang et al., 2015). This would makes them potentially suitable for wearable applications, where body movement does not damage the sensor or disrupt the electrical network.

## 1.2. Goal of this thesis

This project aims to explore how different weaving patterns and combinations of yarn materials influence the sensitivity and accuracy of pressure sensors made from woven fabric. Due to limited existing research on the relationship between weave structure, yarn materials, and sensor performance, the study investigates how changes in structure and materials affect sensor functionality. The main hypothesis is that modifying the woven structure can improve sensor performance under repeated pressure. This hypothesis is tested by adapting a Research through design (Stappers & Giaccardi, 2014) approach for this thesis, through iterative cycles of design, prototyping, and testing, all situated primarily in the lab setting (Koskinen et al., 2012), the project seeks to better understand woven sensor behaviour, ultimately producing a series of functional prototypes and a comprehensive report of the findings.

## 2. Background

### 2.1 Pressure sensors

This chapter provides an overview of previous research conducted in the fields of animated textiles, pressure sensors, and woven materials. The insights gained from this existing body of knowledge serve as a reference for the development and evaluation of new samples within the scope of this research project.

#### 2.1.1 Application in projects

There is potential for many different applications of pressure sensors combined with the flexibility in use of animated textiles. The technique of creating textile sensors warrants many research opportunities.

##### *Medical applications*

In medical fields textile sensors are used for applications such as monitoring in prosthetic sockets (Tabor et al., 2021). Many amputees experience discomfort and pain when wearing their prosthetic devices. To develop new prosthetic technologies, they need better systems to monitor pressure in the inner socket environment. Textile pressure sensors were a suitable solution for this due to their flexibility and breathability. The designed system consisted of a patch of fabric containing an array of embroidered sensors. The system performed well during testing, showing a clear input when amputee participants were walking on their prosthetic.

##### *Human computer interaction*

In human computer Interactions (HCI) textile pressure sensors can be used in wearables, for example to sense and identify human social behaviour (Skach et al., 2021). Skach et al. designed a pair of trousers with matrixes of pressure sensors integrated into the upper front legs. The test set-up let the subjects wear these trousers during a conversational task. The collected data from the trousers pertained to posture and movement, which was then cross-referenced with an annotated timeline of the task. The goal of this design was to create a wearable sensing system that can identify social behaviour, which leads to more insight into non-verbal communication.

Sensor systems can also be used in wearable sports trainers, for example to recognize activities performed by the user in sports (Holleczek et al., 2010). In snowboarding, pressure insoles with force-sensitive resistors are commonly used to analyse weight distribution during snowboarding, however, because these insoles are often uncomfortable to wear, researchers have designed textile based sensor systems in the form of socks. Textile pressure sensors were stitched to the sole of the sock at certain points. The system was tested during a snowboard practice, where the sensors were able to accurately detect whenever the user made a turn.

Another notable example is Levi's Commuter Trucker Jacket with Jacquard Google, a collaborative research project on the development of touch sensitive textiles. Project Jacquard produced an interactive textile that could be used as a control surface for connected devices (Ivan Poupyrev et al., 2016). This technology was later integrated into a Levi's denim jacket to create the Levi's Commuter Trucker Jacket.

With the exception of the Levi's Commuter Trucker Jacket with Jacquard Google (*Levi's Jacquard*, z.d.), there are few examples of smart textile products that are available on the consumer market. This is because it is not viable yet to produce and sell smart textile garments. Creating such a garment is labour intensive due to the integration of electronics and wiring. The complexity of the

textile technology and its time consuming creation process, though readily producible in small numbers of product, make it harder to scale production up (Jansen, 2019).

### 2.1.2 Working principles

Current pressure monitoring technologies are based on five different working principles: pneumatic, fluid-filled, piezoelectric, resistive or capacitive. In a pneumatic sensor, the compression force is transferred to air pressure, which converts to an electric signal. A fluid-filled sensor uses the same principle, but replaces air with a fluid, such as water or oil (Farooq et al., 2020). In a piezoelectric sensor, piezoelectricity is used as a transduction method. Piezoelectricity occurs when electrical charges are generated in certain solid materials, for example, crystals or ceramics, in response to applied forces (Zang et al., 2015). Resistive pressure sensors work when a change in the contact area between the active resistive layer and the electrodes occurs due to applied pressure, which changes the effective resistance of the sensor (Fig. 2 and Fig. 3). Capacitive sensors use the distance between capacitor electrodes as a transduction method for applied pressure.

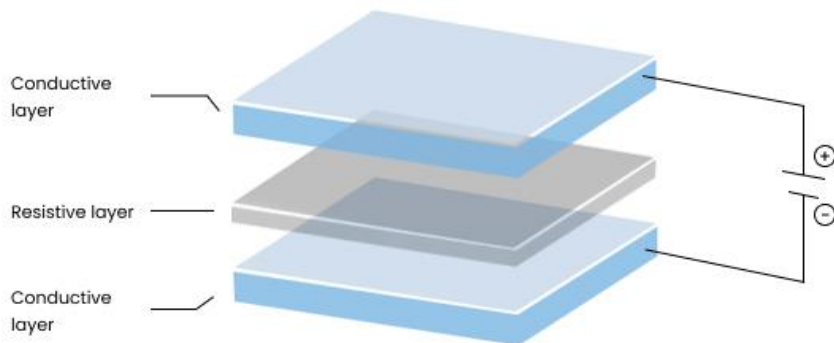


FIGURE 1: WORKING PRINCIPLE OF A RESISTIVE PRESSURE SENSOR

Of these working principles, the one typically used for textile based sensors is resistive pressure sensing technology. Since the other work principles require specific solid materials or a compression element such as air or water. The resistive pressure working principle typically acts using three layers of material: a conductive layer, a resistive layer and another conductive layer (Fig. 1). Through integrating metal fibres in yarns, the fabric created from the yarn exhibits these conductive and resistive qualities. (Pizarro et al., 2018) shows a textile pressure sensor using this principle, in a simplified form.

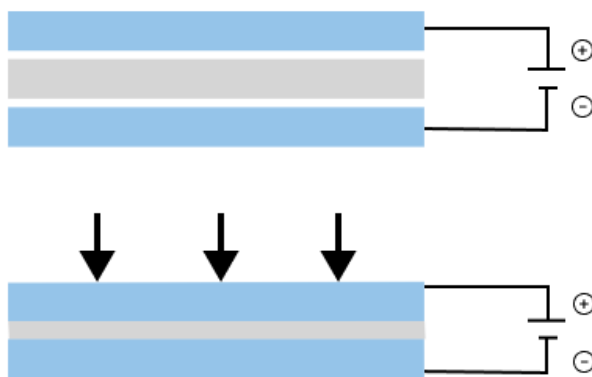


FIGURE 3: 2D VIEW OF A PRESSURE SENSOR NON-ACTIVATED (ABOVE) AND ACTIVATED (BELOW)

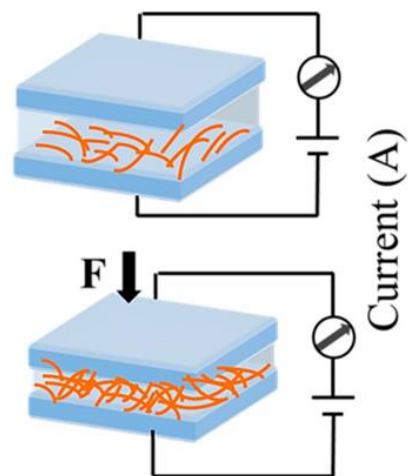


FIGURE 2: 3D VIEW OF A PRESSURE SENSOR NON-ACTIVATED (ABOVE) AND ACTIVATED (BELOW)  
SOURCE : (LAI ET AL., 2023)

## Advantages of smart textiles

The advantages of using textile based sensors as opposed to traditional sensors are as follows:

### *Flexibility / freedom of use*

Textile based sensors are versatile in their use since it is a flexible material, where the changes in its shape do not inhibit the sensors ability (Zang et al., 2015). This makes it a durable sensor applicable in many situations.

### *Wearability*

Due to its flexibility, textile based sensors are especially useful in wearable application. Since different movements of the human body will not interfere with the sensor or damage the network in any way. It's seamless integration in fabric makes it less noticeable in garments as opposed to traditional pressure sensors. Resulting in a light garment that still maintains the comfort qualities of regular clothing (Meyer et al., 2010).

### *Washability*

Sensors made from conductive fibres can be washed without damaging the electrical wiring, which helps with the durability of the sensors, when used in wearables that make contact with human skin. (Meyer et al., 2010) It is without given, that the computational parts connected to the fabric need to be removed before washing the garment and reattached after washing.

### *Adaptable functions by altering the materials*

There are many opportunities to adapt the sensor by altering materials for different intended purposes. For example, swapping out yarns for thicker materials to create a more rigid sensor, that requires more force to activate, swapping out yarns with different fibres to enhance conductivity, or using a looser structure to create a more flexible and light sensor.

### *More hygienic compared to non-textile pressure sensors*

Traditional pressure sensors when used in contact with a person, especially in medical circumstances, will contaminate, making them unfit for reuse. Otherwise the process of keeping the sensors clean will take a rigorous amount of time, to follow protocol standards. Even still the process of cleaning the sensors may affect the performance of said sensor by scratching the material or damaging the electric circuit with fluid.

## 2.1.3 Examples of textiles as sensors

Researchers have used different approaches to creating textile pressure sensors. Each approach has its own advantages and disadvantages for their use case. The following are some examples of research projects developing textile pressure sensors.

### *Sewn*

The first example is a textile based pressure sensor designed to measure data from the a person sitting in a chair to classify sitting postures (Meyer et al., 2010). For this purpose, Meyer created a sensor system that consists of a three-layer structure, two layers of conductive textile, with a spacer made of foam in

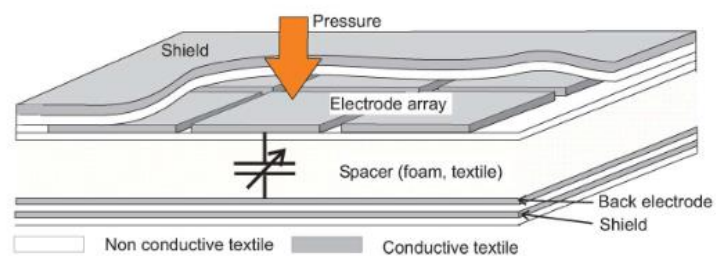


FIGURE 4: CROSS SECTION OF A TEXTILE BASED PRESSURE SENSOR (MEYER ET AL., 2010)

between (Fig. 4). The conductive textile is made by embroidering patches of conductive yarn on a non conductive fabric.

Another example is a textile sensor that also uses a three-layer structure (Fig. 6), consisting of a top sheet of conductive fabric, an LDPE sheet as spacer and a bottom sheet of conductive fabric (Fig. 5). The sensor was tested by increasing applied pressure to the surface and release with a short time, after which the recovery time was measured. Though the sensor was effective in measuring the increase in pressure, the recovery time of the sensor under these conditions were less desirable (Pizarro et al., 2018).

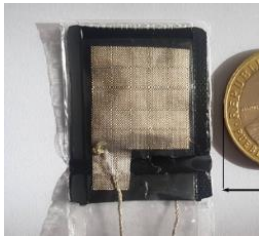


FIGURE 5: PICTURE OF TEXTILE SENSOR (PIZARRO ET AL., 2018)

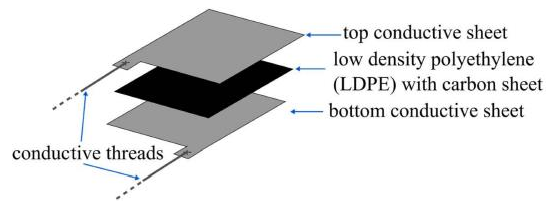


FIGURE 6 : SCHEMATIC OF A THREE-LAYERED TEXTILE SENSOR (PIZARRO ET AL., 2018)

The final sewn example is a pressure sensor that uses a novel approach compared to the former examples (Aigner et al., 2020). The upper layer consists of an resistive sheet of fabric that is embroidered with conductive thread, under which is a base layer fabric stitched with another conductive thread (Fig. 7). When applied pressure to the current from the upper conductive thread flows through the resistive sheet to the under conductive thread. The paper experimented with different patterns in which the conductive threads are embroidered. Different patterns dictate how the current is able to flow through the resistive fabric and how the resistive value changes.



FIGURE 7: PICTURE OF EMBROIDERED SENSOR (AIGNER ET AL., 2020)

Advantages of sewing pressure sensors is that the process is relatively quick and simple. By using ready made conductive fabric or stitching conductive thread on a already finished piece of cloth, the process of creating a multi-layer pressure sensor is significantly simplified. Disadvantages of this technique however are the scalability of textile, since larger pieces of fabric require more areas of sensor. Embroidering patches of conductive thread and cutting patches of conductive fabric to stitch together, calls for much time and labour, because it requires precision work. Sewing also limits the flexibility of use, since fabrics that are used for the sensors are premade, making it harder to modify the sensor.

### Knitted

Of knitted textile sensors, there have been many documented cases. One case (Fig. 8) presents a pressure sensor composed of three layers, an upper knitted surface with a pattern of knitted conductive threads, in the middle a spacer structure, and on the bottom another knitted fabric with incorporated conductive threads, of which the pattern runs parallel to the top layer (Hughes-Riley et al., 2019). Hughes-Riley et al.

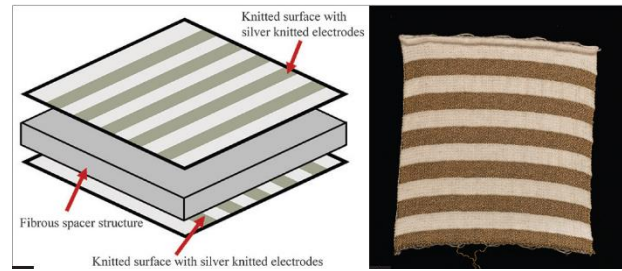


FIGURE 8: SCHEMATIC AND PICTURE OF A KNITTED TEXTILE SENSOR (HUGHES-RILEY ET AL., 2019)

characterized the pressure sensor on the response of the sensor, area of applied force response and hysteresis of the sensor. Results showed that the thinner sensors operated more sensitive in resistive values.

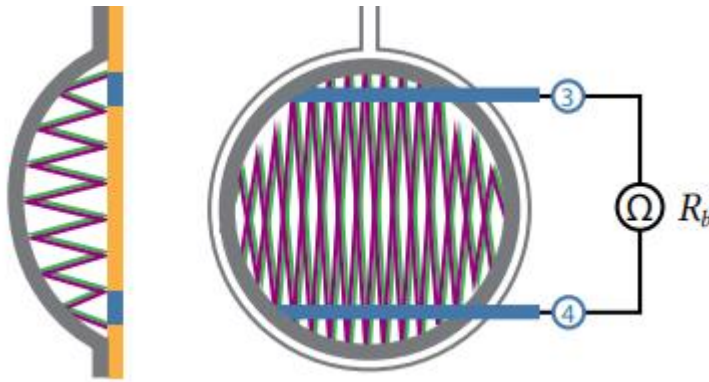


FIGURE 9: A TACTILE FORCE KNITTED SENSOR (AIGNER ET AL., 2020)

Another example shows a highly responsive tactile force sensors (Aigner et al., 2020). The knitted sensor uses nylon filament as a spacer between two knitted layers. The current flows from one point in the sensor through the spacer filament into another conductive contact point (Fig. 9). The material within the sensor becomes more densely compressed when pressure is applied, which causes the electrical resistive values to drop (Aigner et al., 2022). Performance of this pressure sensor was tested with variables in spacing, density and stitch size. Of which the narrow spacing had a more positive effect on the resistive value range in the sensor.

Another notable example is a study performed to analyse the electrical and compression features of a sensor system made using a knitted structure (Ullah et al., 2022). Though the compressibility measured in these sensors performed well, the resistance value showed little variation between inactive and under pressure. Moreover the graph also shows an inconsistent pattern indicating unpredictable or unreliable performance when repeating the test with different weights.

Advantages of knitted pressure sensors is that the process of knitting is relatively quick. Yarns can be easily interchanged during the production of a fabric, allowing more freedom in the design of sensor areas. Disadvantages are that a knitted sensor uses a continuous thread to create the fabric. This means that if one thread comes loose the whole fabric unravels, increasing the risk of losing its durability. A knitted structure is also more malleable than a traditional woven structure. In some use cases, this could be advantageous for its natural ability to withstand repeated pressure and its wearability comfort. However, there are also disadvantages to this property, such as the irregularity of movement when force is applied to the fabric, creating an inconsistent pattern when registering pressure.

## Woven

Of woven pressure sensors there are less studies available, one found was the design of a single-layer resistive technology pressure sensor. The design and fabrication of a pressure sensor that uses conductive wool yarn to create a current in a single layer fabric. For this project a textile pressure sensor is woven, where the conductive yarn threads lay criss-cross over two spaced electrode conductive yarns (Fig. 10). By applying pressure to the sensor, a change occurs in the electrical resistance value by decreasing the distance between the conductive wool threads and the electrode yarn. The sensor performs well under low amounts of pressure with a small hysteresis (Kim et al., 2020).

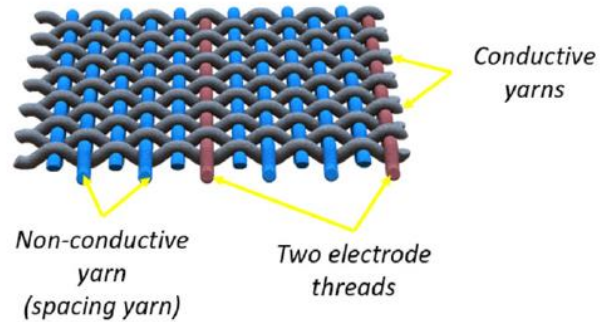


FIGURE 10: SINGLE LAYER WOVEN SENSOR (KIM ET AL., 2020)

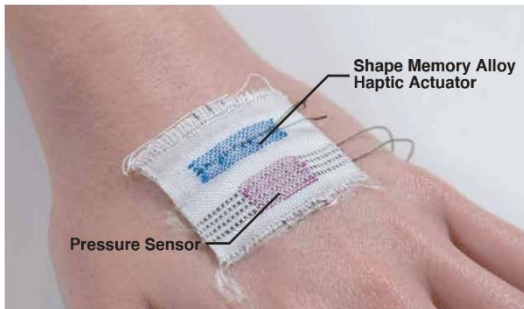


FIGURE 11: PICTURE OF WOVEN SKIN ON INTERFACE (SUN ET AL., 2020)

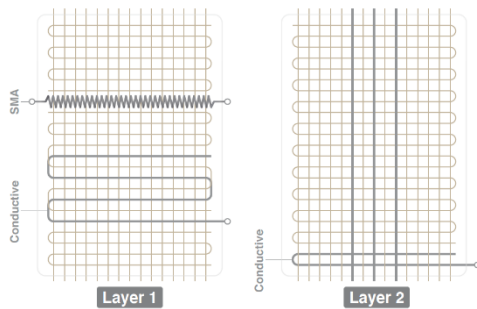


FIGURE 12: SCHEMATIC DESIGN OF WOVEN SKIN ON INTERFACE (SUN ET AL., 2020)

Another example explores opportunities for weaving skin on interfaces. Specifically the exploration of weaving techniques for interfaces, designed to adhere to the human skin. It presents a multifunctional interface, with a pressure sensor and a shape memory alloy actuator (Fig. 11).

The pressure sensor is based on the piezoresistive principle, causing the resistance of the sensor to change linear with the applied pressure. The sensor itself is woven with two layers, of which the top layer has conductive threads travelling criss-cross opposed to the conductive threads in the bottom layer (Fig. 12) (Sun et al., 2020).

Advantages of weaving are that the technique creates sturdy fabric, that can withstand stretching and pressing rigorously over a long period of time. This makes it suitable for applications that require rigorous use or where longevity is prioritized. Disadvantages are the complexity of the technique, due to the many different parameters involved in weaving a fabric.

## 2.2 Woven sensors

This chapter relays the process of creating woven sensors and what materials are needed to create them. It also highlights the potential of using weaving as a technique for pressure sensors and the different opportunities for research.

### 2.2.1 Advantages

Woven sensors offer numerous advantages over other forms of textile-based sensing technologies, along with additional opportunities that have not yet been fully explored through weaving as a fabrication technique. One of the key benefits is their strong potential for industrialization at a large scale. Weaving is already an established and highly automated manufacturing process, which makes it well suited for efficient, high-volume production. This automation enables consistent quality, reduced production costs, and easier integration into existing textile manufacturing systems.

Another important advantage is that woven sensors can be easily replicated within a fabric structure. Because weaving allows precise control over yarn placement and patterning, sensing elements can be systematically repeated across large areas of textile. This creates opportunities to develop fabrics with extensive sensing surfaces, such as large-area pressure sensor arrays capable of capturing greater amounts of spatial information.

Washability is also a significant strength of woven sensors. Due to the structural integration of conductive or functional yarns directly into the woven fabric, the sensors can withstand repeated washing cycles without significant deterioration in performance. This durability is essential for wearable and everyday textile applications, where regular laundering is expected.

In addition, woven sensors demonstrate notable sturdiness and structural stability. Woven constructions provide a robust framework that maintains sensor integrity under mechanical stress. The interlacing of warp and weft yarns contributes to secure dimensional structures and long-term reliability (Pouta et al., 2024).

A further advantage lies in the mechanical behaviour of woven fabrics, particularly their bias stretch characteristics. Woven textiles primarily stretch along the diagonal (bias) direction. When tension is applied along the horizontal or vertical axes, the fabric does not significantly deform. This controlled and predictable deformation contrasts with knitted fabrics, which stretch in multiple directions. The limited stretch of woven fabrics can be beneficial for sensor accuracy and consistency, as it reduces unintended deformation and noise during use.

### 2.2.2 Materials and function

Overall, woven sensors are made solely from yarns, which composition can derive from different materials. Distributors offer a range of different yarns consisting of polymer fibres, natural, or metal fibres. Each yarn has different properties and function of which the following can be identified as necessary for a resistive pressure type sensor.

- Electrodes– electrical conductive yarns made from stainless steel, often blended with textile fibres such as polyester  
Other examples, use a silver plated yarn, which can consist of pure silver spun filaments or twist these filaments with textile fibres.
- High Resistance layer – an in-between layer of high resistance yarns ensure that the electrode layers do not directly touch and create a current. This way there is a clearly discernible difference in resistive value between a sensor in an activated state and a non-activated state.

- Non-conductive yarns – these yarns or materials offer support to the structure without interfering with the interface by accidentally conducting electrical current. This is ensured by the electrode layers not touching and there is no material that would conduct the current when not activated.

Further information on the specific materials used for this project can be found in Chapter 3.3.

## 2.3 Motivation and opportunities

As previously mentioned, the use of textiles provides many opportunities and advantages for the development of pressure sensors. Textiles are flexible, lightweight, and inherently suited for close contact with the human body. Despite these benefits, weaving as a specific fabrication technique has not been explored as extensively as other textile methods, such as knitting. Several aspects of woven pressure sensors remain underdeveloped.

Large-scale implementation, for example, has not yet been fully realized. Although weaving is inherently suitable for industrial-scale production, there has been limited research and application focused on scaling up woven sensor systems. Expanding the number of integrated sensors could enable more complex and precise pressure-mapping capabilities across larger textile surfaces.

Another important advantage for further development is wearer safety and durability. Because the sensors are embedded within the woven structure of the garment, this embedding not only shields the sensing components from damage, but also protects the wearer from direct contact with electronic elements, enhancing comfort and safety. These properties create more freedom for experimentation without compromising on the sensors functionality and adaptability for use.

Additionally, there is currently no widely accepted standardization for woven sensor structures. The absence of standardized construction methods, material selections, and performance benchmarks limits comparability between studies and slows broader adoption. Establishing clear structural and functional standards would support scalability, reproducibility, and industrial implementation.

### 2.3.1 Opportunities

Woven pressure sensors present several promising opportunities for future development. One significant opportunity lies in integrating sensors directly into wearable garments at the surface level. Such integration could allow garments to respond to touch, pressure, posture, or movement, potentially creating new forms of human-computer interaction.

Full integration into wearable systems is another area that remains largely unexplored. While individual textile sensors have been demonstrated, seamlessly incorporating woven pressure sensors into complete wearable garments, where sensing, signal processing, and power supply function as a cohesive unit, has not yet become standard practice. This leads to a related opportunity: positioning woven sensors as components within larger digital ecosystems. Rather than functioning as isolated sensing elements, woven pressure sensors could become integral parts of electronic textile systems.

Finally, weaving offers opportunities for the development of novel textile structures that integrate electronic circuits. As noted by Pouta et al., the controlled interlacing of warp and weft yarns makes it possible to design complex systems where conductive yarns, resistive yarns, and structural elements coexist within a single fabric construction. Rethinking how electronic functionality can be embedded directly into textile structures, moving beyond add-on components toward fully integrated smart fabrics.

## 3. Experimental

### 3.1 Objective

The research aim of this project is to perform explorative research to discover how different weaving patterns and utilizing the combination of different yarns will affect the sensitivity and accuracy of a pressure sensor created from woven fabric. The problem that would need solving is that currently there are not enough research examples to substantially determine the relation between the weave structure, yarn materials and the sensors properties.

The research question stated is: *How do changes to a weaving structure and the chosen materials in yarn affect the performance of a sensor?*

The primary hypothesis is that by primarily adjusting the woven structure of the sensor, the performance of the sensor undergoing repeated pressure can be enhanced. The hypothesis will be tested through multiple cycles of experimental design research.

The purpose of an iterative process of design, prototyping and testing, is to gain an overall better understanding of woven sensors behaviour so this knowledge can be used to further develop sensors for common use. The goal will be to deliver a series of working prototypes at the end of this project and a report that entails the findings from all attempts of creating a working sensor.

### 3.2 Methodology

#### 3.2.1 Research approach

This thesis project will adapt the Research through design method by Stappers and Giaccardi. An approach that uses design as a tool to undergo iterative material development (Stappers & Giaccardi, 2014). Research through design defines the different components within a research. With a focus on design, the object that is created during a design process is referred to as Artifact. Examples of an artifact are blueprints, proposals, briefs or specifications. A Prototype is when the Artifact is used in research to realize the action that is to be studied. Examples of this are proof of concept, exploration, realization and construction.

This project will focus on the creation of woven sensors as prototype, the weave diagram would act as an artifact. With the goal to obtain knowledge on how to design a working sensor, and then use it as artifact in a larger prototype, as a product demonstrator.

Research through design is an umbrella term for many methods that encapsulate design as a tool to do research. The specific method that would be used in the creation of artifacts is named Experimental design research (Brandt & Binder, 2007). Within this method, experiments is defined as the result of a design activity and simultaneously a deliberate attempt to question what we expect, from such a design. Brandt and Binder have established Question, Program and Experiments, as parameters in experimental design research (Figure 13).

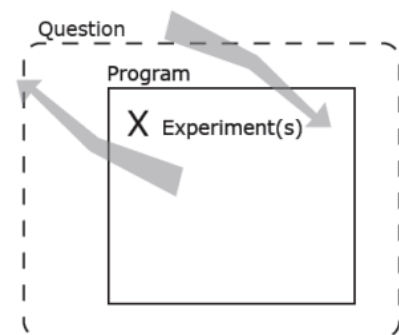


FIGURE 13 : EXPERIMENTAL DESIGN RESEARCH PROCESS (BRANDT & BINDER, 2007)

Where research question drives the research in a particular direction. The program is the framework in which a particular context is described. It is in this program that the experiments are conducted.

To obtain answers to the research question, one has to define the program and conduct experiments to gain knowledge on those particular aspects. However, it is argued in this paper that the method could also work the opposite way. Meaning that the experiments could yield results that propose new programs and eventually shape or sharpen the research question.

The latter part of this method is especially relevant for this thesis project. Though we start with a question and an established design for the pressure sensor. It is with development of these sensors and testing that we find out more about the properties of the sensor, and what areas could be improved upon. Through systematic variation of weaving structures and yarn types, new programs are created. These will lead to more insight into the behaviour of woven sensors by evaluating the performance in iterations. These evaluations are necessary to verify the primary hypothesis, which is to find credible relations between the changes to the sensor and improved or worsened results.

### 3.2.2 Iterative steps

#### *Hypothesis*

The process of the experiment starts by establishing an hypothesis first, determining how to change the weave design and what its effect will be on the sensors' performance. An hypothesis can entail changing a material or yarn in the existing design to create a more even structure or to change certain strands in the weaving pattern to create a structure that prevents the yarns from shifting out of place during use. The purpose of the change in design, is to isolate components of the sensor and from there analyse and identify how it affects the structure as a whole and the performance.

#### *Weaving*

Based on the weaving pattern and chosen yarns, a sensor is woven in fabric on the TC2 loom. The sensor is photographed to analyse the structure of the yarns and whether the sensor is fabricated as the intended design. It is possible for example that the structure is faulty due to yarns shifting or yarns being too thick, causing an uneven texture. If this is the case, then there could still be changes applied to the weave before testing. Further explanation on weaving is provided in 3.3.1.

The goal of this phase is to create a sensor that is structurally secure and corresponds visually with the intended design. Microscopic pictures are taken of the sensor so the structure can be analysed closely.

#### *Test*

To test the woven sensor, a test set-up (Fig. 14) is made using a Rheometer to simulate pressure perpendicular to the woven fabric.

The Rheometer works by letting the foot come down slowly with a constant pressure. The experiment that is set-up with the program lets the foot press down for 10 seconds with a force of 10 N, then release in 2 seconds and pause for 10 seconds, to allow the sensor to return to its original state. This process is then repeated 3 more times, to account for the repeatability of the sensor. This procedure is discussed in more detail in Ch. 3.4.

To measure the performance of the sensor, two ends of the electrode thread, one corresponding to the upper layer, the other to the bottom layer, are attached to a Data acquisition centre. This Data acquisition centre continuously measures the Resistance value of the sensor over time. This raw data is saved on an USB drive.



FIGURE 14: WOVEN SENSOR IN TEST SET-UP

### *Evaluate*

The raw data collected during testing is analysed by creating a line graph that plots Resistance over time. The shape of the graph and the values of the peaks determine the sensor's performance. Analysing the sensor's performance during the test, will reveal how well it works and how the structure and materials have affected the performance.

For example, an accurate sensor that is able to depict when pressure is applied has flat peaks with straight vertical lines showing at what exact time the pressure was applied and that the value of the force is constant. This will be discussed further in Ch. 3.5

Any deviations from the graphs desirable result shows a flaw in the sensor's design and creates an opportunity for improvement. Further analysis and speculation, helps identify what could impact the error in performance and how to change the design.

### *Conclusion / New hypothesis*

The analysis of the sensor's performance will give more insights which properties of the sensor could be improved, leading to a redesign of the sensor. Based on these findings either a change the weave pattern, a change in material, or both would be viable for a new sensor and thus new hypothesis. And with the new hypothesis the cycle of iterative steps starts again for the next round of experiments.

## 3.3 Materials

### 3.3.1 Yarns

To weave a pressure sensor, a number of yarns with different qualities are needed to create the structure. Each yarn in the sensor has a different purpose, of which the following have been identified:

**Electrodes** – Electrode yarns conduct the electricity, these are crucial for the creation of a sensor

For electrode yarns the following qualities are especially important:

*Material* – The type of material a conductive yarn is made of determines its structure, texture and conductive ability. Conductive yarns are often made from stainless steel, often blended with textile fibres such as cotton or polyester. Other examples, use a silver plated yarn, which can consist of pure silver spun filaments or twisted with different fibres

*Electrical resistivity* – This quantifies the value of the electrical resistance per meter

*Dtex* – The Dtex measures the yarns linear density (mass over 10.000 meters), the thickness or fineness can be derived from this, though this also depends on the materials in the yarn

**High Resistance** – High resistance yarns share the same properties as electrodes: material, electrical resistivity and Dtex. However it is crucial for its function that the high resistance yarn has a higher resistivity than the electrode. This ensures a larger difference in the sensor's overall resistive value when the electrodes make contact through the high resistance layer.

**Non-conductive** – these yarns or materials offer support to the structure without interfering with the interface by accidentally conducting electrical current.

**Elastics** – since the sensor experiences repeated pressure, elastic material is needed to let the sensor return to its original non-activated state. Without it the sensor could flatten over time, increasing the risk of lower sensitivity or short circuits.

**Warp yarns** – these are cotton fibres in the loom that follow the vertical plane of the sensors fabric. The warp yarns are crucial for the weaving pattern, as will be further explained in 3.3.1.

After identifying the different purposes each yarn suffices, a selection was made of yarns that are suitable for weaving (Table 1).

TABLE 1 MATERIAL LIST AND PROPERTIES

<b>Function</b>	<b>Material</b>	<b>Name/notation</b>	<b>Diameter (mm)</b>	<b>Resistivity (Ohm/m)</b>
Electrode	Polyamide/Nylon 6.6, coated with 99.9% Pure silver	Statex Shieldex 235/36 dtex 2 ply HC +B	0,38	600 (Statex Produktions- und Vertriebs GmbH, 2025)
High resistance	Polyester/Steel 60%/40%	Bekaert Bekinox 50/2 KS 400 dtex PES 60/40		1000 (Bekaert, 2017)
High resistance	Polyester/Steel 80/20	Bekaert Bekinox 50/2 KS 400 dtex PES 80/20		2000 (Bekaert, 2017)
Elastic	Elastane	Prym elastic thread	0,15	-
Elastic	Elastane/PA 50/50	Prym elastic yarn	0,40	-
Elastic	Elastane / PA 40/60	Zimmermann	1,08	-
Surrounding fabric	Cotton	-	1,05	-
Surrounding fabric	Mercerized cotton	-	0,86	-
Surrounding fabric	Acrylic	Acrylic yarn HB	1,05	-
Weft Interlacement yarn	Polyester	-		-

In previous studies have proven that Statex Shieldex and Bekaert Bekinox, suitable materials are for creating textile sensors. Statex Shieldex is commonly used in products in the textile industry due to its antistatic and anti-odour properties. It is also often used in sensors, because it is a high strength conductive yarn.

Bekaert Bekinox is chosen because the diameter of the yarn is approximately the same size as the Shieldex. This is important for the symmetry in the sensor, when all yarns used for weaving the sensor are around the same diameter, it prevents yarns from shifting out of position. This ensures that the performance of the sensor stays constant. Aside from that it is cost effective, has a long lifetime, is antistatic and easy to maintain. These qualities make it a suitable material for woven wearable electronics.

Another notable conductive yarn commercially available is Silver-Tech HY7LK, however the decision was made to not include this material in research as it has shown unwanted qualities. Hoogstraten's research has shown that Silver-Tech yarn performed worse than Bekaert Bekinox yarn, as the sensors woven with Silver-Tech had less repeatable results.

### 3.3.2 Weave

#### Fundamentals of weaving

The Thread Controller 2 (TC2) is a digital jacquard loom (Fig. 15), which follows a bitmap to control the heddles during weaving. A jacquard loom is characterized by its mechanism that moves individual heddles (Stankard, 2015). This makes it especially useful for weave structures with intricate patterns, as opposed to a traditional shaft loom, because the loom allows for precise warp yarn movement (Fig. 16).

Warp yarns are aligned next to each other in the vertical direction, the ends are setup beforehand on the loom and are not easily interchanged after setup. The density at which the TC2 is set up stands at 36 ends per cm and 72 cm wide, resulting in a total of 2640 ends. For this project, the TC2 loom comes prepared with FILMAR Ne 44/2 (tex 13.4 x 2) Mercerized Cotton yarns on a single warp beam.



FIGURE 15: THREAD CONTROLLER 2

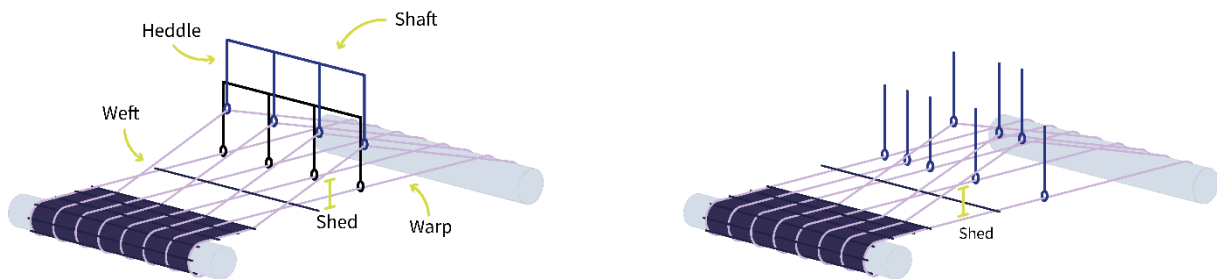


FIGURE 16: SCHEMATIC OF A SHAFT LOOM AND JACQUARD LOOM (PRUMMEL, 2026)

During weaving the warp yarns are lifted up by heddles so the shuttle can insert the weft yarn (Fig. 17). The weft yarn is beaten with the reed to even out the yarn and make it snug to the cloth. When the warp yarns are then lifted up in a different configuration, the weft yarn cannot move in the vertical direction anymore. This is called creating an interlacement. Weft yarns are inserted in the loom in the horizontal direction with a shuttle. Due to being inserted manually, weft yarns are easily interchangeable during weaving.

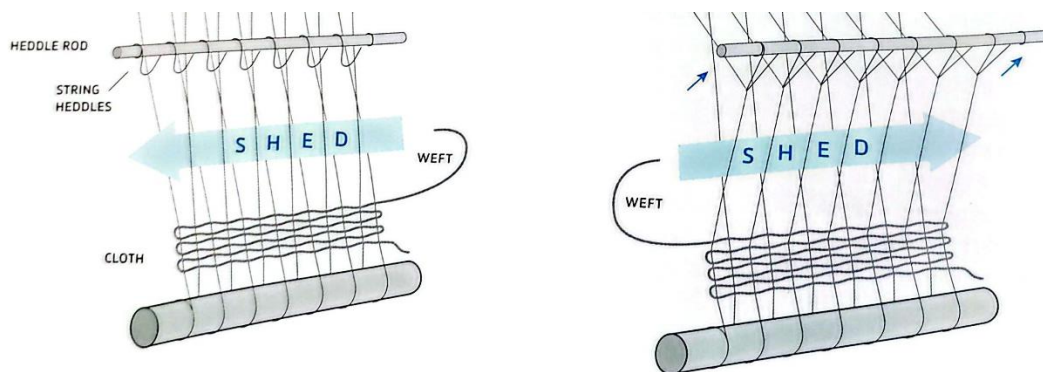


FIGURE 17: SCHEMATIC OF WEAVING (SALOLAINEN, 2015)

The shuttle does not necessarily need to be inserted all the way through the warp. The weft yarn can be insert and exit at any point to interlace with the warp threads. For this practice, the term “partial weft” is used (Fig. 18).

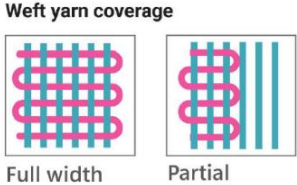


FIGURE 18: WEFT YARN COVERAGE (VOORWINDEN ET AL., 2025)

A weave diagram indicates how the warp and weft yarns interlace through a pattern on a grid. Each square represents a strand of yarn, where black indicates a weft yarn going under the warp yarn, and white a weft yarn going over the warp yarn (Fig. 19).

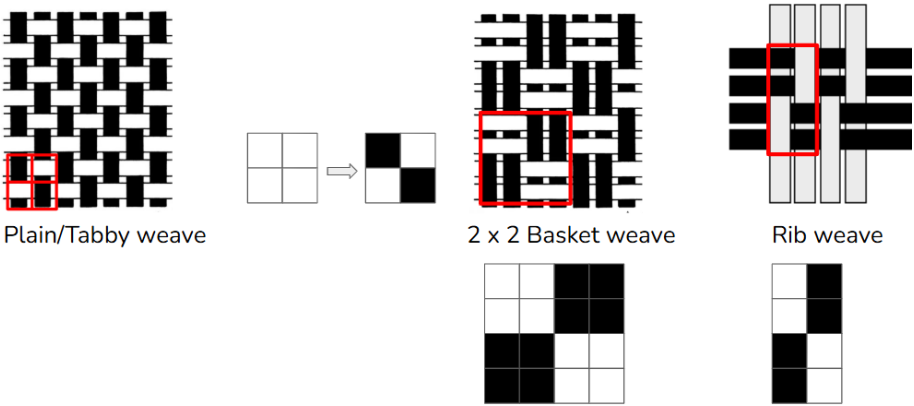
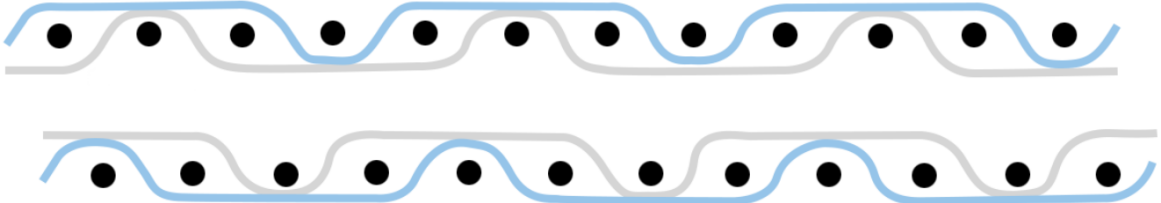


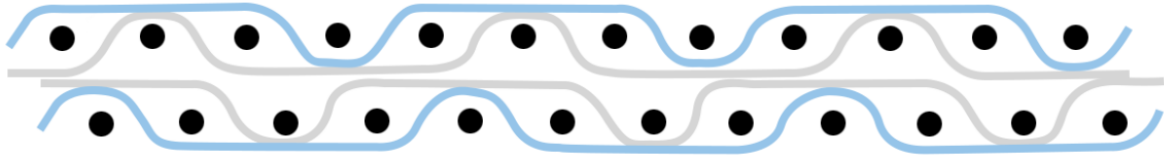
FIGURE 19: WEAVE DIAGRAM

Said weaving diagrams are compiled in AdaCAD, an open source program which can automatically generate diagrams with commands. This is essential for this project, because a multilayer structure is needed to create a woven sensor. A multilayer structure can be made by using a technique called compound weaving, which combines two diagrams to generate one diagram that weaves a double faced fabric.

**Multilayer weaving**

Compound weaving is a technique in which two or more sets of warps and one or more sets of weft yarns are interconnected to create a multi-layered cloth. There are many variations of compound weaving (Fig. 20) to create different structures, which each have its own properties (Salolainen, 2022).





*FIGURE 20: CROSS-SECTION OF MULTILAYER WEAVING – NON-COMPRESSED (ABOVE) AND COMPRESSED (BOTTOM)*

For a woven sensor multilayer weaving is used to a structure with two separate layers that are able to make contact when compressed (Fig. 20). During compression, the distance between the two electrode yarn layers will decrease allowing the current to flow from top to bottom.

## 3.4 Procedures

### 3.4.1 Measuring instruments

For this project a rheometer was used to simulate pressure, because the machine and its software made it possible to program an experiment that used the exact same parameters. This made sure that when the experiment was repeated it would repeatedly put the same amount of pressure on the sensor.

The specific model of the rheometer used is a TA Instruments AR-G2 Rheometer (Fig. 21). The instrument consists of a base plate with a surface of 78,5 cm<sup>2</sup>. And hanging over that a pressure foot connected to a shaft that lowers perpendicular to the base plate. The program shows direct momentary feedback on the amount of pressure (N) that is performed on the base plate and the position of the foot. The speed and force (N/m) at which the foot comes down on the base plate can be programmed within the software. This gives a lot of control in placing the position of the foot in a preprogrammed sequence. Since the experiment needed to be repeated for each sensor the rheometer was the best option to create an exact repeatable sequence.



FIGURE 21: PHOTOGRAPH OF AR-G2 RHEOMETER



FIGURE 22: EXPERIMENT SET-UP



FIGURE 23: WOVEN SENSOR UNDER PRESSURE FOOT OF THE RHEOMETER

#### *Programming the experiment*

As mentioned in 3.2.2 Iterative steps, the foot of the Rheometer presses down for 10 seconds to measure whether the sensor will maintain a constant value during compression (Fig. 23). This also simulates a realistic scenario, where the pressure sensor is used for undetermined prolonged periods of time. Then the foot goes up again and stays there for 10 seconds, to let the sensor return to its non-activated state.

During the experiment the resistive value of the pressure sensor is measured through the data acquisition centre (Fig. 22). The electrical current flows through two points in the sensor, one thread of yarn going in the upper layer and one yarn going out the bottom layer. The collected data can then be plotted in a graph using Excel, see Ch. 3.5.

### 3.4.2 Simulating pressure

The foot of the Rheometer comes down with a constant force, to translate that force to pressure, a piece of rubber is stuck to the surface of the foot (Fig. 24). Said piece of rubber is cut into a square with a surface of 1 cm<sup>2</sup>. To calculate the pressure exerted by the foot, 10 N is divided over 1 cm<sup>2</sup>. This leads to the following calculation:

$$1 \text{ cm}^2 = 0,0001 \text{ m}^2$$

$$\text{Force/surface} = 10/0,0001 = 100.000 \text{ N/m}^2 = 100.000 \text{ Pa} = 100 \text{ kPa}$$

This value is the benchmark, because according to Zang et al., this is the amount of force typically exerted by a finger press (Zang et al., 2015).

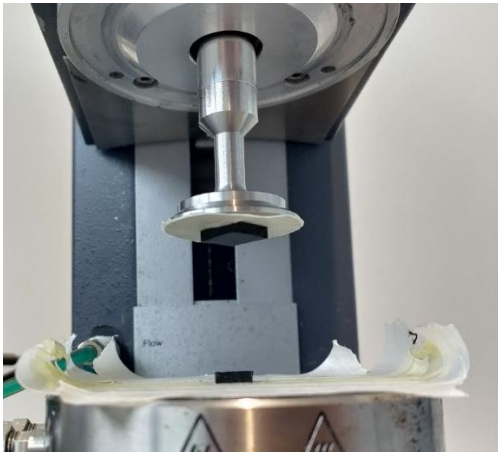


FIGURE 24: RUBBER ON THE PRESSURE FOOT AND THE PEDESTAL

From this it can also be concluded that 1 N/cm<sup>2</sup> is 10 kPa. In the future, for example when testing a prototype for a specific scenario, the amount of force can be reinstated for the experiment to simulate different conditions.

Some examples of these conditions and the corresponding pressure needed would be as follows:

- Hand press = 14,5 N (Figueroa-Jacinto et al., 2018) = 145 kPa
- Heel press = 22,2 to 32,9 N/cm<sup>2</sup> = 222 to 329 kPa

### 3.5 Evaluation method

Evaluation of the woven sensors is done by collecting the data on the resistive values during testing. These data points are plotted in a line graph that measures Resistance over time.

It is expected that the graph will show a square U-shape for each time the sensor is activated in compression (Fig. 25). R<sub>0</sub> signifies the normal value of an uncompressed sensor, R<sub>1</sub> during compression, and R<sub>2</sub> the return value after compression, which will become R<sub>0</sub> for the new cycle of compression.

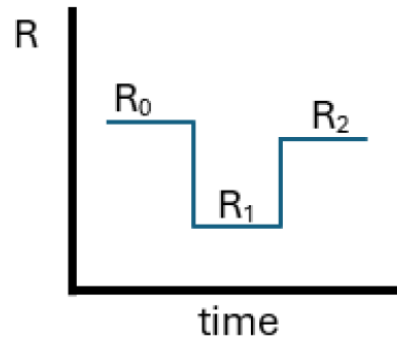


FIGURE 25: EXPECTED GRAPH OF RESULTS

The cyclic compression repeats a number of 4 times during the test. After each compression, the sensor remain uncompressed for 10 seconds to allow the sensor to return to its normal value and measure R2.

Preferably, the graph would show flat peaks and valleys, indicating a constant resistive value in non-activated and activated state. The flatter a section the more constant the output of the sensor is, which indicates more reliable and conclusive data.

### 3.5.1 Performance metrics

When analysing the graph the following performance metrics are used to quantify the results.

#### *Resistance ratio*

The drop in resistance value is calculated by measuring the normal resistive value, when not compressed, R0, and subtracting the resistive value when compressed, R1. This value difference is then calculated as a percentage of R0 to determine the resistance ratio.

$$\text{Resistance ratio: } RR = \frac{R_1 - R_0}{R_0}$$

The resistance ratio is required to quantify how effective a sensor is. The minimum required resistance ratio is between 20% to 30%, any value beneath that is too low for programming to be able to distinguish between activated and non-activated state. This is important when mapping the sensors output to a digital metric.

#### *Recovery*

Recovery ratio is the difference between R2 and R0 calculated as a percentage of R0.

$$\text{Recovery ratio} = \frac{R_2 - R_0}{R_0}$$

When reading the height difference between R0 and R2, when there is little difference that is an indication of good recovery. Ideally then, the lower the recovery ratio, the better recovery is.

#### *Repeatability*

This entails the sensors ability to repeatedly, maintain the same resistive value under compression. Combined with a consistent recovery rate, this would also entail repeating the same Resistance ratio.

#### *Sensitivity*

Sensitivity refers to the height of the resistance ratio in relation to force of compression, a higher Resistance ratio when under lower force of compression indicates a more sensitive sensor. If a sensors Resistance ratio is lower than minimum required there is no possibility to test sensitivity since the resistance range would be too small.

#### *Hysteresis*

Hysteresis in pressure sensors refers to the difference in output sensitivity between the activated and non-activated phases. It occurs because the sensor does not instantly return to its original state once the applied pressure is removed. Hysteresis is a problematic phenomenon, because it creates inconsistencies in measurements, which results in reduced accuracy and unreliable data.

## 3.6 Pilot round: Testing with premade sensors

### 3.6.1 Hypothesis

For the pilot study, the original woven sensors of Christiaan Hoogstraten are used in the test set up to create a reference of what a woven sensor is capable of.

This pilot consists of two sensors, one made at the beginning of Hoogstraten's project, one made towards the end of the project. The hypothesis is that the latter will show considerable better results as there have been many iterations of sensors in between. Resulting in improving design choices for the latter sensor. The results of this set up are also compared to the results featured in Hoogstraten's report. A key difference however is that Hoogstraten only tested each sensor for one press, while the test setup for this research repeats the pressing to account for reproducible results.

### 3.6.2 Samples

#### Exploration 2 : Sensor 1

This sensor is made from the following yarns:

- Shieldex conductive yarn
- Elastic yarn
- Bekinox resistive yarn - Bekaert Bekinox 50/2 KS 400 dtex PES 60/40
- Cotton

It is structured to have only one electrode yarn on the upper layer and one on the bottom layer. These are separated by two thick elastic yarns in between (Fig. 26).

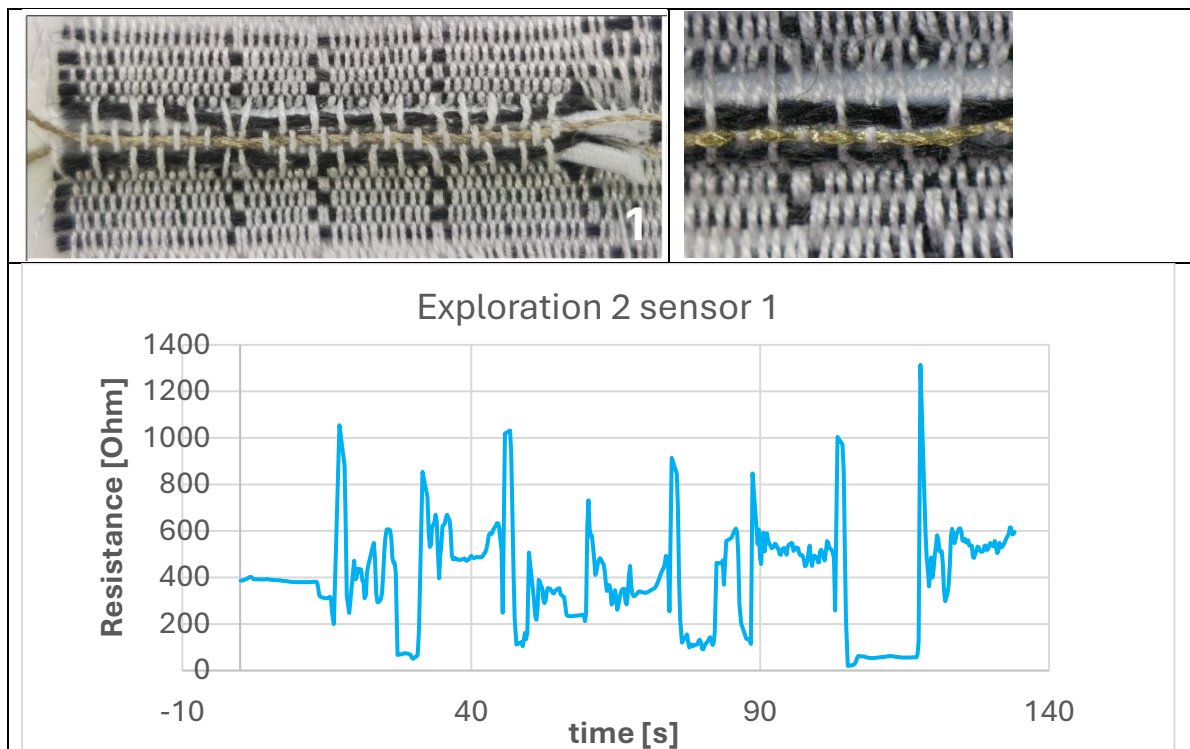


FIGURE 26: UPPER LEFT: PICTURE OF SENSOR EXPLORATION 2 SENSOR 1 (HOOGSTRATEN, 2025), UPPER RIGHT: A MICROSCOPIC PICTURE OF EXPLORATION 2 SENSOR 1 AND TEST RESULT

Test results (figure 26) show that Exploration 2 Sensor 1 has considerably high peaks in resistive value, but the sensor is inconsistent due the peaks and valleys not being flat. A large difference in the highest and lowest value does indicate that the sensor has a high Resistance ratio. Except for in

between 85 and 120 seconds, which shows a discernible peak around 500 Ohm and a valley consistent at 50 Ohm.

Something that stands out is that the peaks seem to be inversed, showing that during compression the resistive value increases instead of decreasing. This corresponds with the test from Hoogstraten’s thesis report as the graph also shows one reverse U shape (Fig. 27).

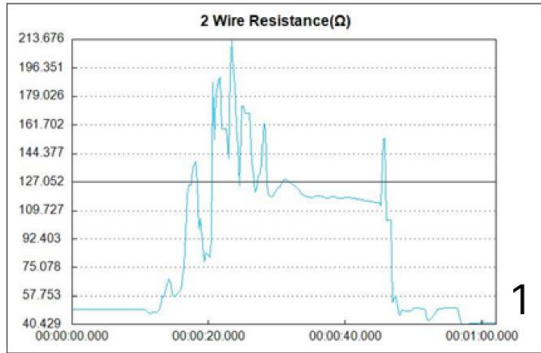


FIGURE 27: GRAPH OF TEST WITH EXPLORATION 2 SENSOR 1 (HOOGSTRATEN, 2025)

### Exploration 10

This sensor is made up from the following materials:

- Shieldex conductive yarn
- Bekinox resistive yarn
- Polyester weft interlacement yarn
- Elastic yarn

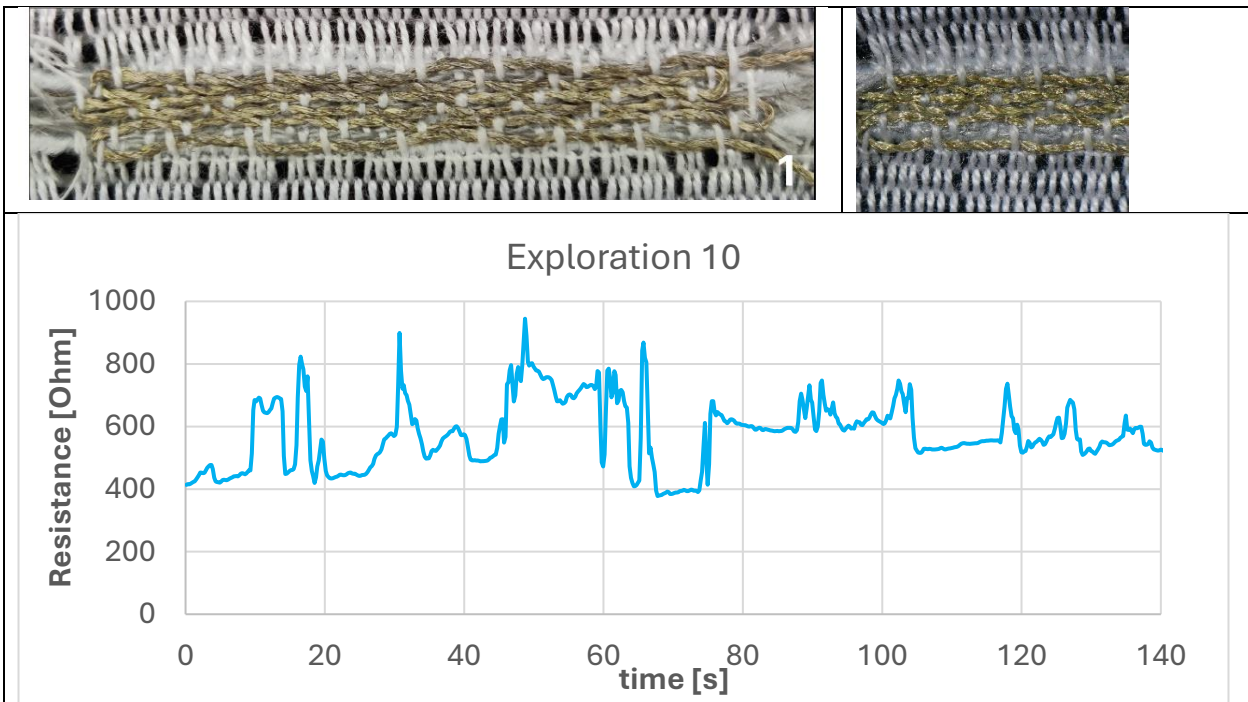


FIGURE 27: UPPER LEFT: PICTURE OF EXPLORATION 10 (HOOGSTRATEN, 2025), UPPER RIGHT: MICROSCOPIC PICTURE OF EXPLORATION 10 AND TEST RESULTS

Exploration 10 though showing more consistency in resistive value does not have clear discernible flat peaks and valleys (Fig. 27). There is one example between 65 and 90 seconds, and one flat valley in between 100 and 120 seconds. Compared to Exploration 2 this sensor also displays overall lower peaks and higher valleys, indicating a lower Resistance ratio.

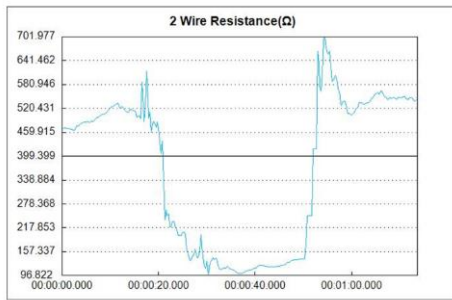


FIGURE 28: GRAPH OF TEST WITH EXPLORATION 10 (HOOGSTRATEN, 2025)

Compared to the results from Hoogstraten’s research (Fig. 28) the sensor shows less desirable results. It can not be said with certainty, why the graph from the original report shows an U shape, while the results seem irreproducible in the current test. Though the appearance of one U-shape at 65 and 90 seconds seems to suggest that it is possible to gain U-shaped graphs, though not repeatable.

### 3.6.3 Conclusion

The test has shown what level the current sensor design stands at. Overall the sensor requires changes to allow for flat peaks and valleys, to differentiate more clearly between an inactivated state and activated state. Flat peaks and valleys require the sensor to be both sensitive, registering high values inactivated and low values activated, and structurally strong to keep the materials in place.

Following these tests an interesting direction to research is changing materials. Exploration 2 Sensor 1 has results that show an inverted U-shape, one possible explanation for this is the thickness of the elastic yarn inhibit the electrode layers to connect. An elastic yarn that is too big would flatten under compression and create a larger surface that acts as a barrier. Of these two sensors, Exploration 10 shows more potential for experimentation, since the sensor is build up of more materials and has shown in the previous research to deliver favourable results.

## 4. Results

### 4.1 Round 1 : Weaving with variations of elastic

#### 4.1.1 Hypothesis

The first woven sensors are based on Hoogstraten's Exploration 10, by using the same weave diagram and materials (Appendix B). Differentiating by using different thicknesses of elastic yarn to see how this affects sensor performance. The expectations is that the yarn will perform better under thinner elastic yarns as opposed to thick yarns. As during compression the thicker yarns will push together and create a barrier for the upper and bottom layer of electrodes making contact.

- The upper conductive layer and bottom conductive layer must not touch each other when the sensor is inactivated. Otherwise it will cause short circuiting and inhibit the change in resistive value. However the material in between must still allow for compression. The sensor must be flexible enough to flatten under pressure so the distance between the upper and lower conductive layers can decrease.
- The sensor must be able to repeatedly return to its original inactivated stance, to maintain consistency in resistive value.

#### 4.1.2 Samples

##### R1V1

The first sample shown is R1V1. This version has the elastic, an original design swapped out for polyester yarn. The overall pattern is based on a twill structure. Visually the sensors yarn structure looks secure, the electrode yarns are packed tightly together.

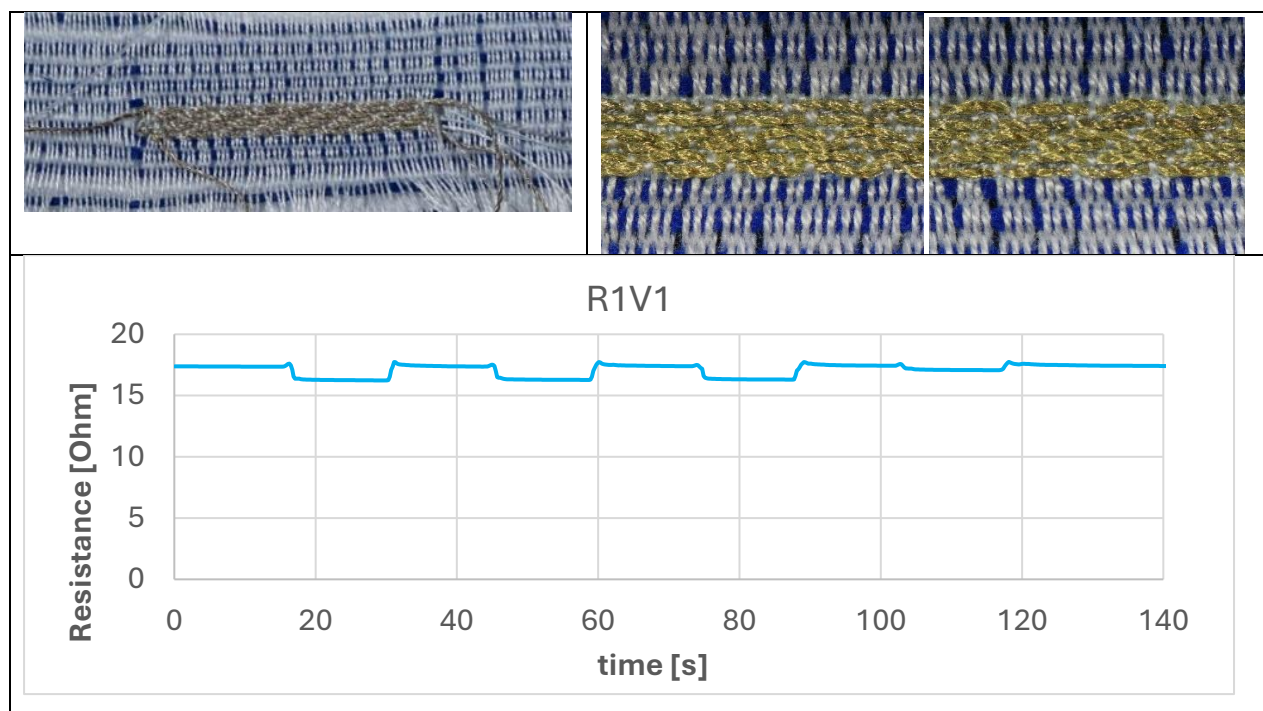


FIGURE 29: R1V1 - PICTURE OF R1V1, MICROSCOPIC PICTURE R1V1 FRONT (LEFT) AND BACK (RIGHT) AND TEST RESULTS

However, the results show a graph that though has symmetrical U-shapes (Fig. 29), the values are a very low Resistance ratio. For the first three cycles, the sensor does have good repeatability as the resistive value when activated is consistent. The sensor also shows good recovery, since the return values are consistent throughout the test.

### R1V2

This version of the same diagram is made using Prymm elastic yarn as the elastic in the sensor. For details of the materials refer to Ch. 3.3.1. R1V2 shows another structure with an even upper electrode layer. For the bottom layer there is a small gap visible, where the elastic is poking out (Fig. 30).

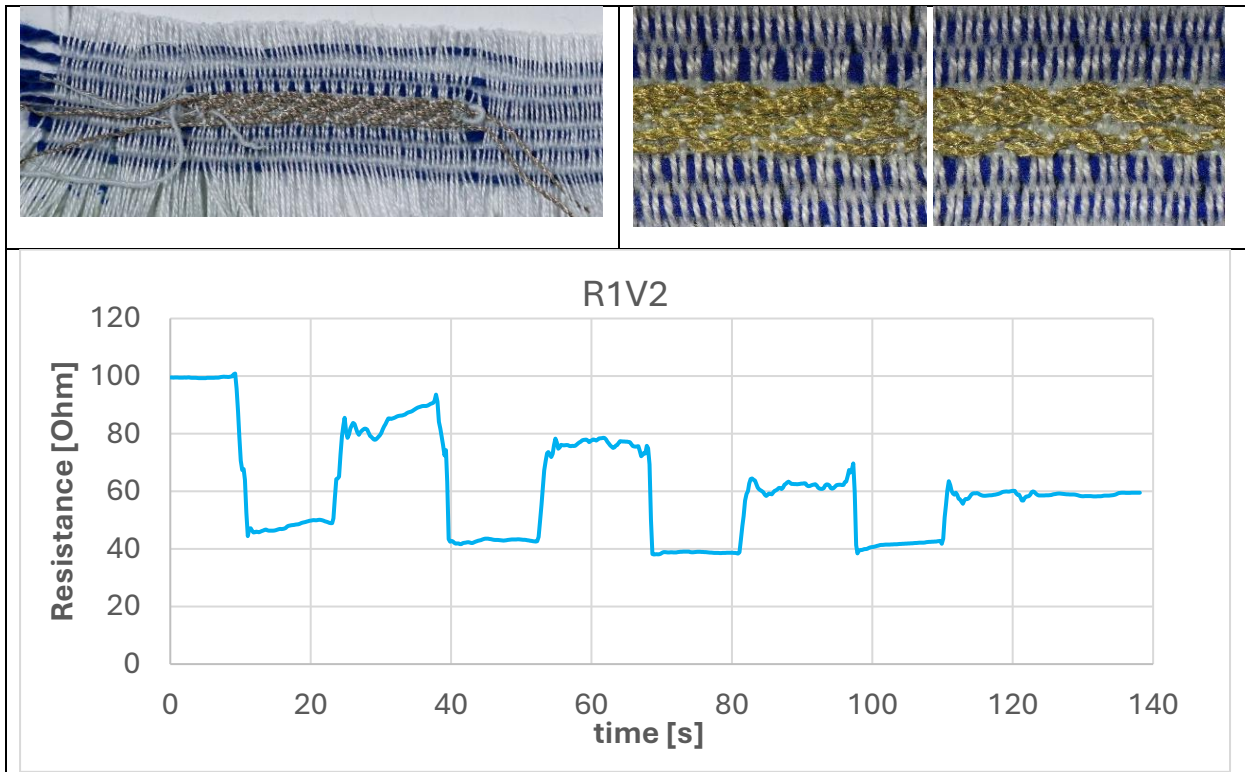
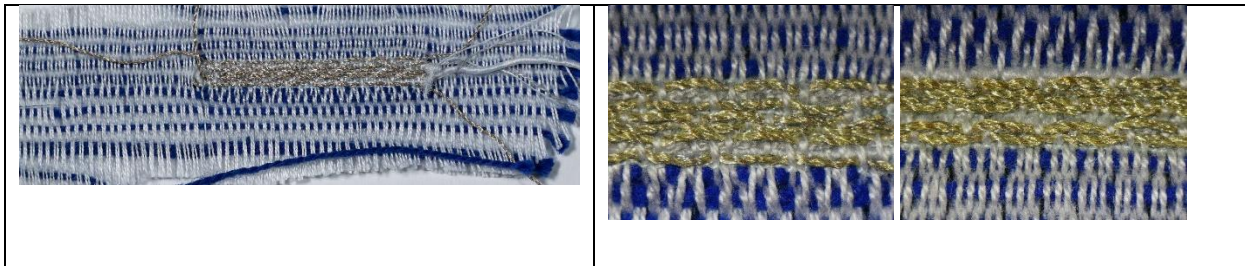


FIGURE 30: R1V2

The results of R1V2 (Fig. 30), show a greater Resistance ratio compared to R1V1, the value goes from 100 Ohm to 45 Ohm, which is a RR of 55%. Repeatability is also well since the activated sensor drops consistently to around 40 to 45 Ohm. However, the sensor shows a bad recovery as the return value of the sensor keeps diminishing with every cycle.

### R1V3

This version is made using the thickest elastic, Zimmermann elastic yarn, which is the thickest elastic. The structure of sensor does not look well (Fig. 31), as there is separation of the electrode yarns both on the front side as well as the back side. On the front side, the elastic yarn can be seen poking out between the electrode yarns.



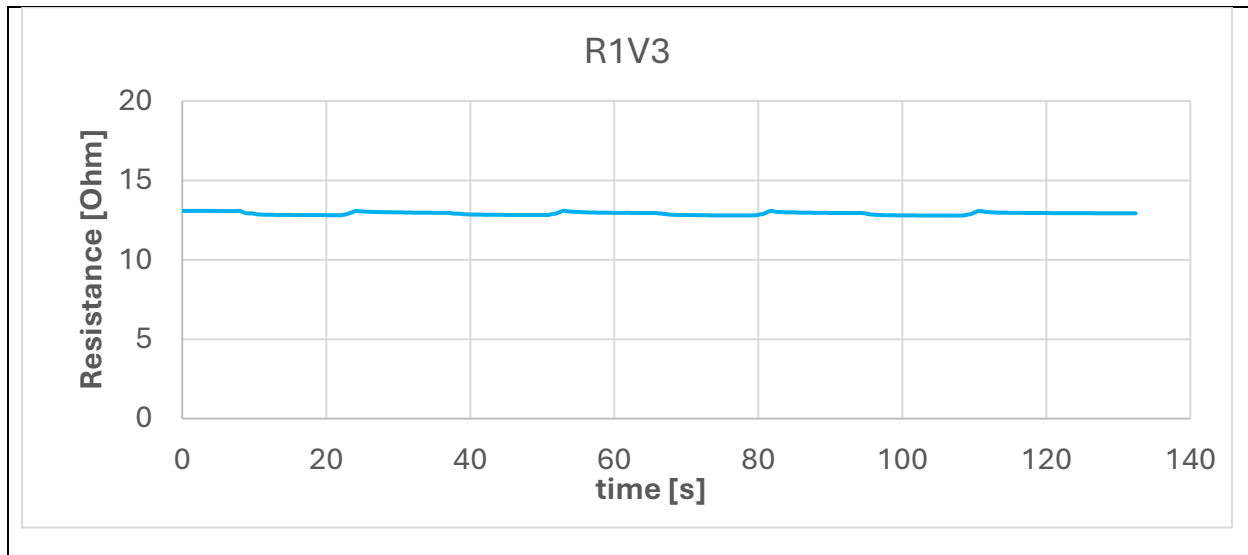


FIGURE 31: R1V3

The results from testing the sensor are inconclusive, as the graph shows very little difference in values. This could be caused by a very low, Resistance ratio.

#### 4.1.3 Conclusion

The current pattern creates a consistent performing sensor, however the Resistance ratio differs greatly per sensor. Sensor R1V1 showing little difference in resistive value and R1V3 showing almost no difference.

Thus far R1V2 is the sensor that shows good repeatability as well as the highest Resistance ratio. However it also shows diminishing recovery.

- Discovered that the way the sensor is woven on the loom causes some warping due to the warp yarns around the sensor laying slack while weaving the sensor itself. Next round do a check to ensure the warp yarn tension is higher.
- For next iteration try to adjust the pattern to have some yarns go all the way across the weft and let the Shieldex yarn go on continuously throughout the sensor.

## 4.2 Round 2 : Exploring impact of structural changes on the sides of the sensor

### 4.2.1 Hypothesis

One major change made to the sensor in this round is changing the surrounding structure. During Round 1, the only part across the warp woven was where the sensor was positioned. This created a difference in tension across the warp threads (Fig. 32), which could result in damages to the warp yarn and affect sensor performance by creating unplanned tension.



FIGURE 32: CROSS SECTION OF THE SENSOR'S OLD DESIGN (LEFT), CROSS SECTION OF THE SENSOR'S NEW DESIGN (RIGHT)

This was changed to creating a structure that elongates components of the sensor, by adding woven fabric without electrode yarns on both sides of the sensor (Fig. 32). Consisting of the same materials as the sensor but being ineffective due to the removal of electrode yarns, which can be derived from the weaving diagram (Appendix B).

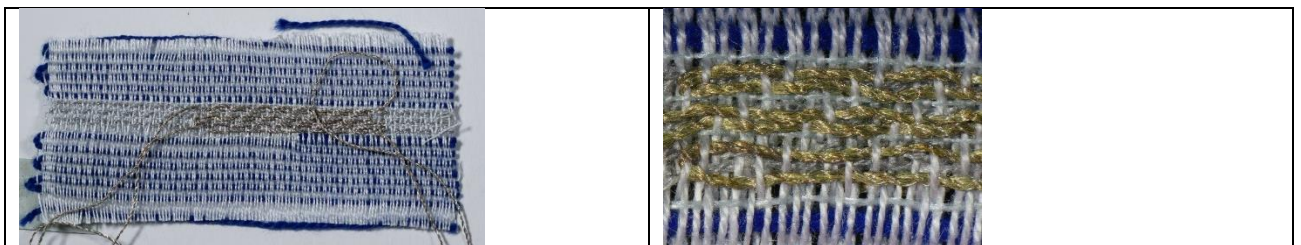
Additional change to the pattern were to decrease the amount of (black spots) in the weft interlacement yarns. It is suspected that the frequency at which the weft interlacement yarns occur can cause the sensor to be slightly compressed at all times and inhibit the sensors ability to create distance between the upper electrode layer and bottom layer. Removing certain places where the weft yarns interlace, could increase the change in resistive value during compression.

### 4.2.2 Samples

#### R2V1

This sample is made without elastic yarn, it is instead replaced with a polyester yarn. It acts as our control group, since a polyester yarn does not have any elastic properties.

the pictures show the structure. Of the electoral layer is. Not secure. As there is little contact with in between electrode. This is an indication that the new pattern needs some adjustments, and research for what would make it possible to create a more even surface (Fig. 33).



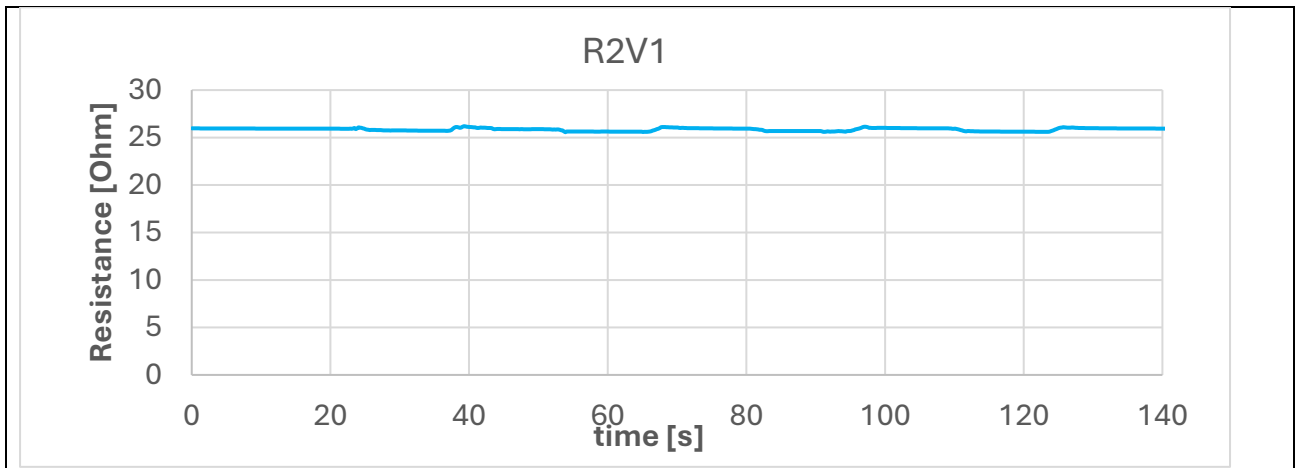


FIGURE 33: R2V1

As for the test results, these are inconclusive, as the graph shows no U-shapes, but instead, an almost flat line.

### R2V2

This version is made with the Prymm elastic yarn, which from the selected elastic yarns is the medium thickness (see Ch. 3.3.1). The decision was made to use only the medium thickness elastic yarn for this version, since this corresponds best with the diameter of the conductive and resistive yarns. And showed the most promising results in the last Round. Visually, the sensor's new design has not improved the structure of the electrode layers and there are still gaps visible (figure 34).

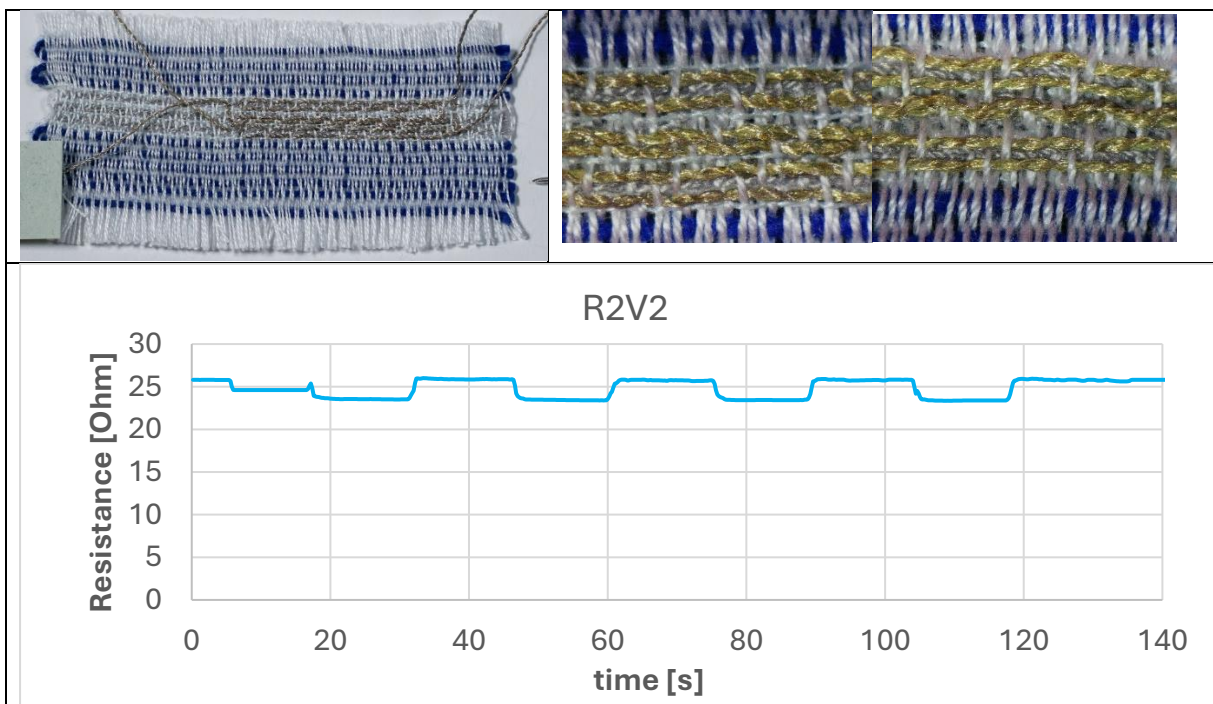


FIGURE 34: R2V2

As for the results from the testing, R2V2 (Fig. 34) does show some improvement over R2V1 (Fig. 33). This is because there are visible U-shaped graphs. Distinct U-shapes are an indication of better Resistance ratio. And since the graphs are symmetrical and it consistently returns to same value in activated and non-activated state. It is an indication of good recovery and good repeatability.

### 4.2.3 Conclusion

Changes applied to the diagram have thus far given little improvement in the results. More changes to the sensors design is needed to enhance the sensor's Resistance ratio, which requires a larger difference in value for the peaks and valleys. However, notable qualities of this sensor are its recovery and repeatability, as it appears to be both consistent in higher and lower resistive values and the graphs appear symmetrical.

## 4.3 Round 3 : Removing weft interlacement yarns to improve layer structure

### 4.3.1 Hypothesis

For this round the decision was made to remove the weft interlacement yarn altogether, as it is not essential because the warp yarns also interlace throughout the structure. The current theory is that the weft interlacement yarn was the main cause for the gaps in between electrode yarns (Fig. 35) and thus affects the sensor's inability to increase RR.

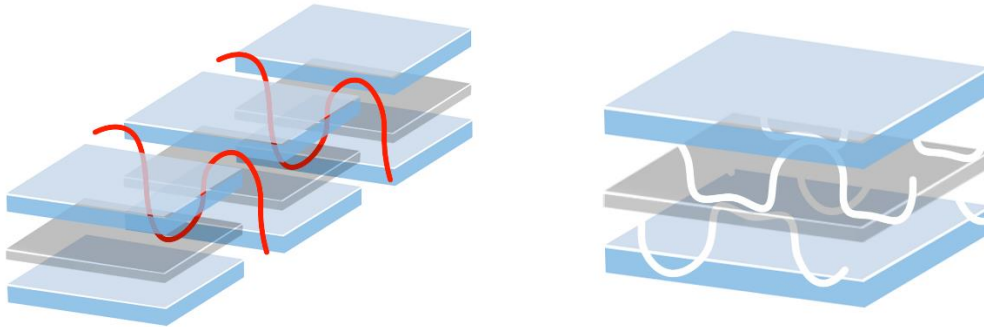


FIGURE 35: PLACEMENT AND USE OF WEFT INTERLACING YARN – OLD DESIGN (LEFT) AND NEW DESIGN (RIGHT)

By removing the weft interlacement and using the elastic yarns instead to interlace the layers, it will keep the electrode layers intact (Fig. 35). The new weave diagram (Appendix B) will consist of only three materials: electrode yarn, resistive yarn and elastic.

### 4.3.2 Samples

#### R3V1

The first sensor R3V1 is made by using a Polyester yarn to interlace, instead of an elastic yarn. Again this is because it acts as the control group. The structure of the sensor looks well, compared to the last round. The electrode yarns are packed more tightly. There are little visible gaps in between, but overall, the structure looks even and secure (Fig. 36).



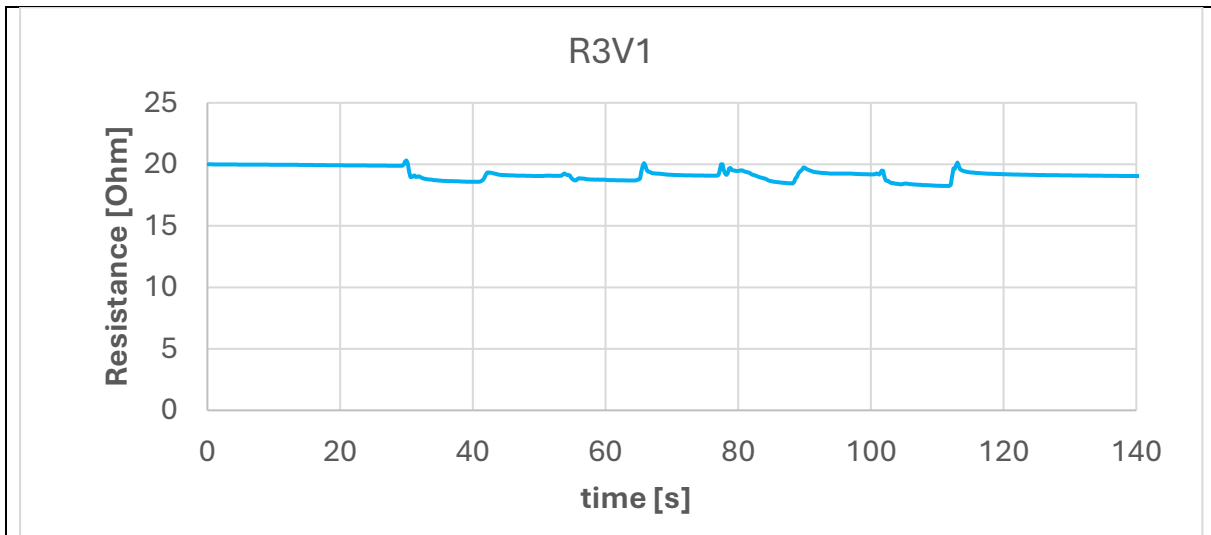


FIGURE 36: R3V1

As for the results from testing. There are two barely distinguishable, U-shaped graphs. However, there is a lot of noise making the shapes unrecognizable and where there is a U-shape the Resistance ratio is very low. The graph itself does not distinguish four instances of compression, which indicates a bad repeatability and bad recovery.

### R3V2

This sensor is woven with a medium elastic, Prymm elastic yarn, and consists of four consecutive strands for both the top and bottom layer. Visually the sensor looks well, as the size of the gaps in between the electrode yarns has decreased.

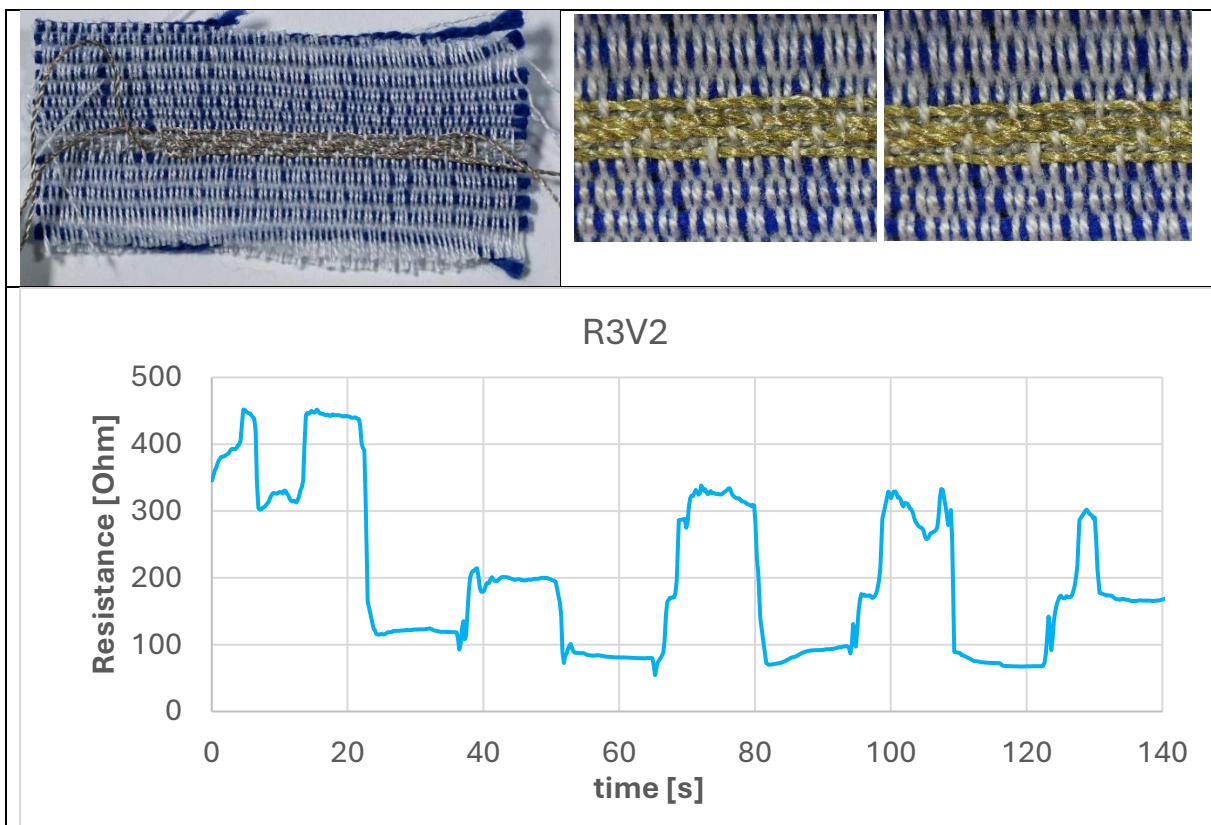


FIGURE 37: R3V2

And as for the results from testing (Fig. 37), the Resistance ratio has improved significantly compared to R3V1, and there are discernible U-shaped graphs. The first cycle drops the resistive value from 450 to 120, which calculates to a RR of 73%. The third cycle shows a drop from 320 to 100, which is an RR of 67%. However, the return value differs greatly per cycle, which indicates a bad recovery. During compression the resistance values stands on average around 100, since it is fairly consistent it is assessed as a medium good repeatability.

### R3V3

This sensor is woven with a thick elastic, Zimmermann elastic yarn. The sensor structure visually looks not much improved. The front side shows the electrode yarns clearly tightly packed (Fig. 38). However, the backside shows that some of the warp floats, around the sensor, and gaps in between the electrode yarns.

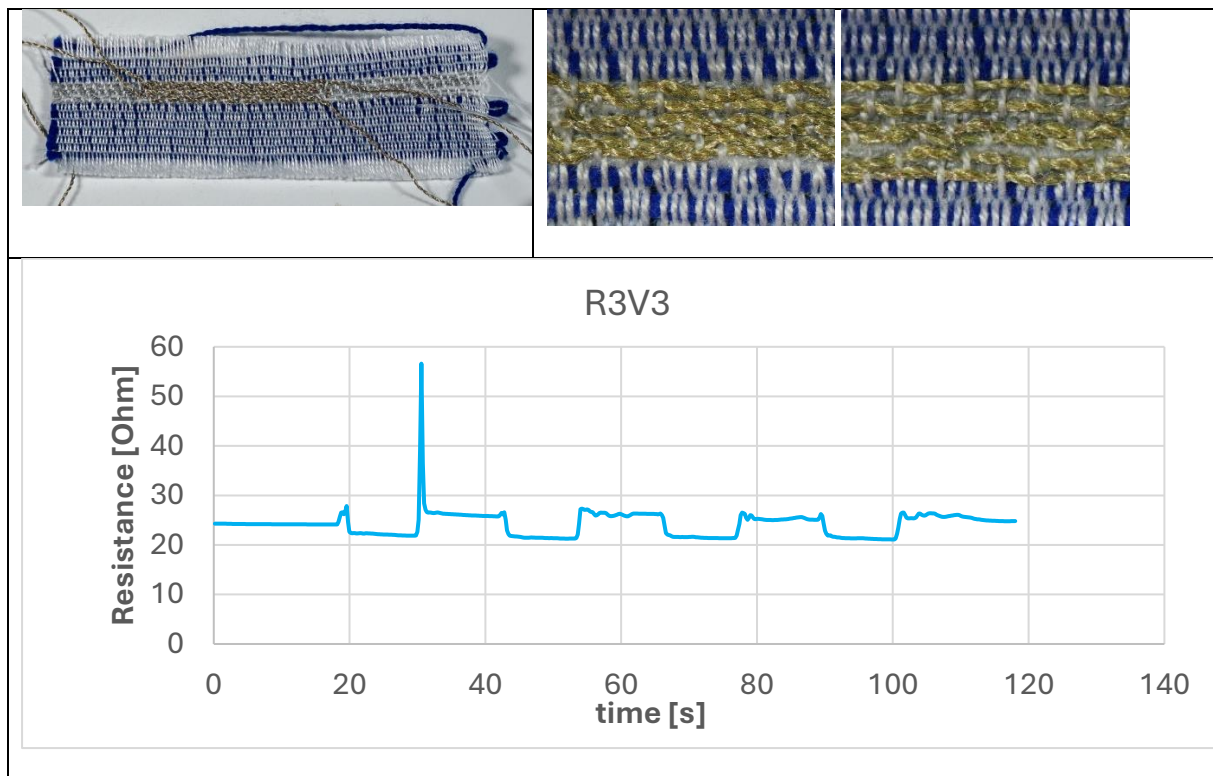


FIGURE 38: R3V3

The test results of R3V3 (Fig. 38) show a with four discernible U-shapes. However, the Resistance ratio is again very low, dropping consistently from 26 to 21 Ohm, resulting in a RR of 19%. Since the dropped values are consistent and the shapes of the graphs are symmetrical, this sensor is assessed with good repeatability. And aside from the peak in the first cycle, this sensor also shows good recovery.

### 4.3.3 Conclusion

The Resistance ratio of the sensor has improved compared to Round 2. Measured resistive values of the tops are overall higher, which can be considered an improvement on Round 1.

However, the sensors now shows less recovery and repeatability during testing. This is especially apparent in R3V2, because the peaks as well as the valleys of the graph do not occur at the same value. This indicates that the yarns shift around in the sensor, causing the distance between the upper and lower electrode layers to be irregular. Since there is no discernible consistent value for the R0 it is not possible to state a conclusive Resistance ratio.

## 4.4 Round 4 : Change the composition of yarns to increase sensor sensitivity

### 4.4.1 Hypothesis

For this round the focus lies on creating a woven structure that secures the yarns in each layer to ensure they do not shift during use. This will create a sensor that behaves consistent and shows reproducible results during testing.

The design for the sensor is as follows:

- Changing the pattern to weave bottom to top to ensure the yarns slides over more easily and creates a neater structure
- Instead of using one elastic yarn in the repeated pattern use two per pattern (Fig. 39) to create a more symmetrical design. Because the composition of elastic yarn has changed, there will be three samples made with different thicknesses of yarn.



FIGURE 39: CROSS SECTION OF WEFT YARNS, OLD COMPOSITION (LEFT) AND NEW COMPOSITION (RIGHT)

The new pattern will increase chances of a more even surface of conductive yarns, which will increase the sensors accuracy and performance. The Map of Bindings and weave diagram for this sensor can be found in Appendix B.

### 4.4.2 Samples

#### R4V1

This version uses Prymm elastic thread as the elastic yarn, which has the thinnest diameter. Visually, the sensor appears well-constructed on both the front and back sides. The yarns are tightly packed, and there is no visible elastic protruding through the yarns.

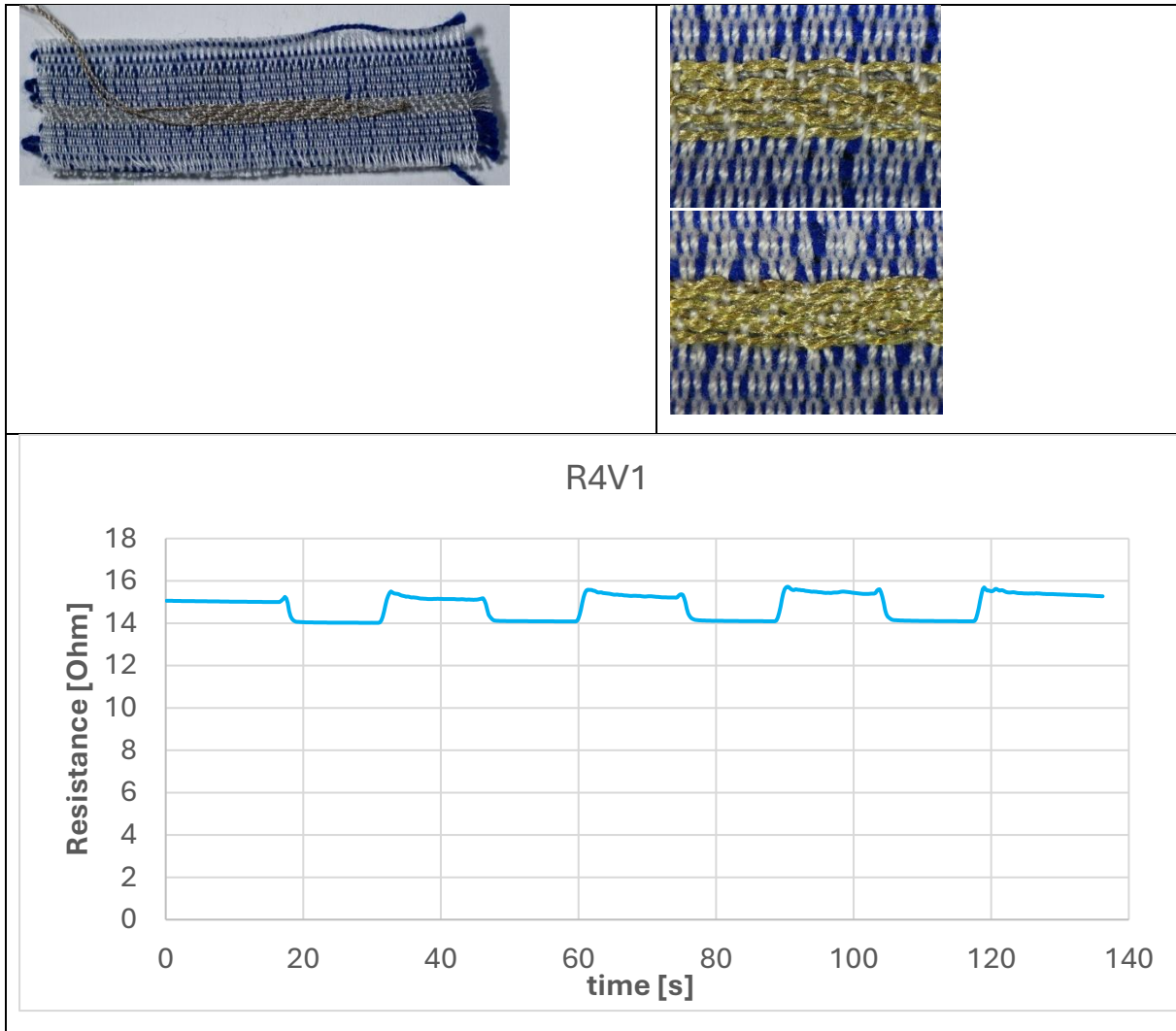
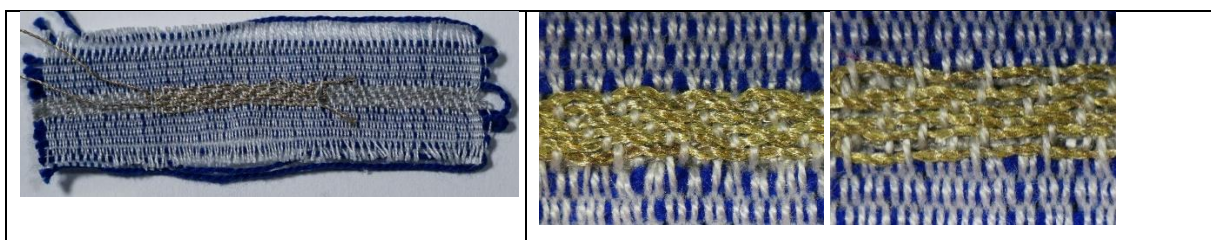


FIGURE 40: R4V1

However, the test results show a low Resistance ratio. The graph is symmetrical, meaning the return and activated values are at the same level, which indicates good repeatability and recovery.

#### R4V2

This version uses Prymm elastic yarn, which is the medium size diameter elastic yarn. The sensor appears visually well-constructed. However, on the backside there are some warp floats that pull the structure apart. There are also small amounts of other material protruding through the electrode yarns.



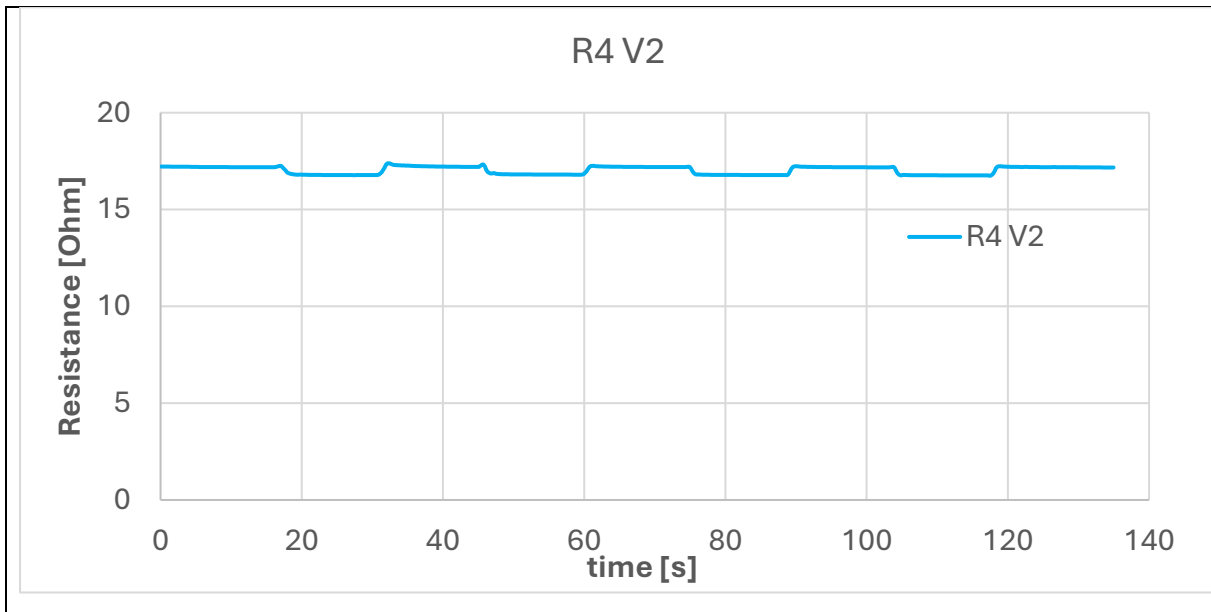


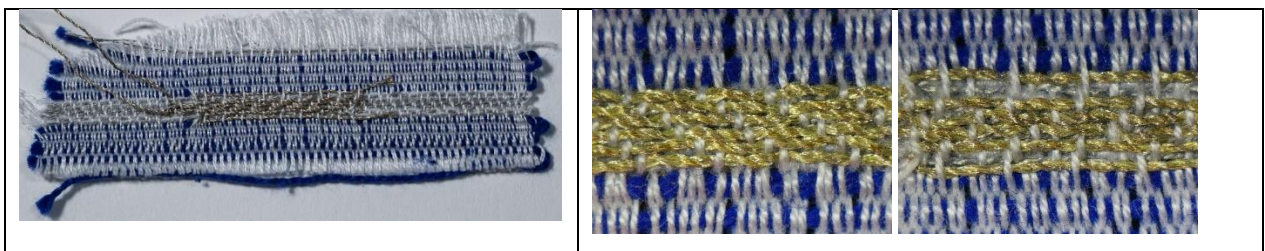
FIGURE 41: R4V2

Regarding the test results, this sensor does not show improved performance. The resistance ratio remains very low, with almost no discernible U-shaped peaks.

However, compared to other tests, the U-shapes that do appear occur at consistent time intervals, similar to the previous version. This still indicates good repeatability and recovery.

### R4V3

This version uses Zimmermann elastic yarn, which has the largest diameter of all elastic yarn. Visually, the front side of the sensor appears well-constructed. However, the backside clearly shows warp floats that pull apart both the upper and lower electrode yarns.



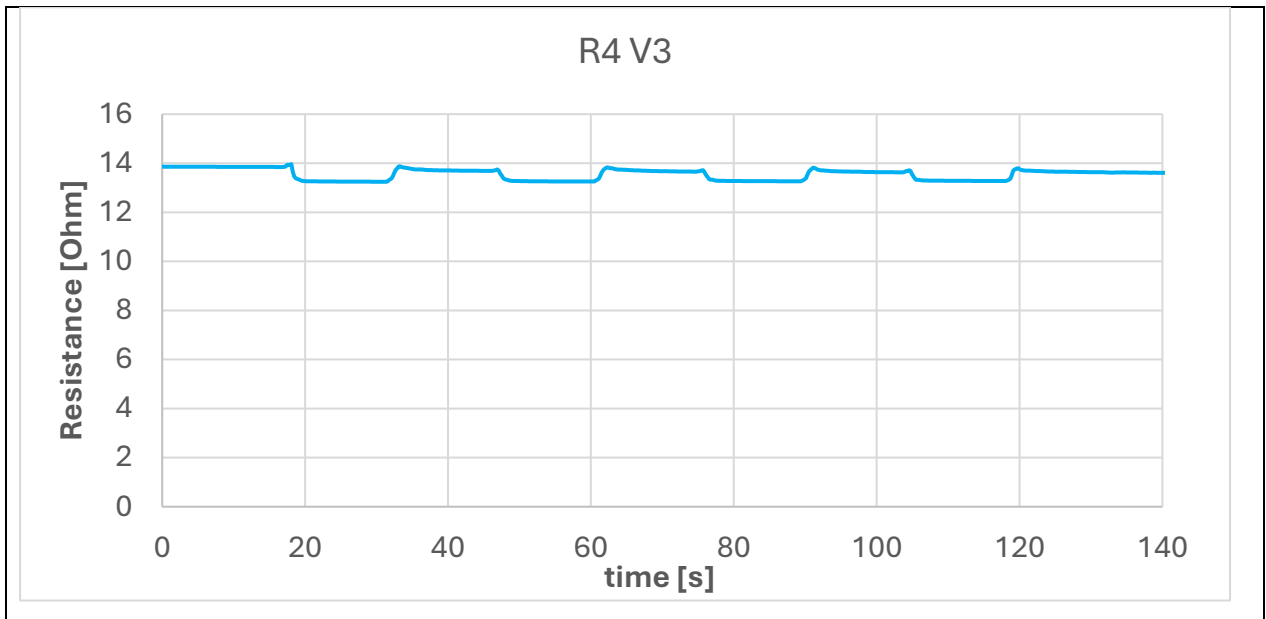


FIGURE 42: R4V3

Test results again show a very low resistance ratio. The graph displays only very small, barely discernible U-shapes. However, similar to other sensors in this round, the U-shapes occur at consistent time intervals, indicating good repeatability and recovery.

#### 4.4.3 Conclusion

Though the results show some improvement in the sensors repeatability and recovery, it occurs again that the resistive values show little difference between the peaks and valleys. There is also no discernible difference between the three variations of yarn thickness, related to each sensors resistance ratio, recovery and repeatability, as all three graphs appear the same.

## 4.5 Round 5 : Weave a satin structure to improve conductivity

### 4.5.1 Hypothesis

For this round the focus is back on increasing the sensitivity of the sensor. There are noticeable gaps, often occurring in between the electrode yarns of the bottom layer. These gaps in the structure could inhibit the conductive capabilities of the bottom electrode layer. A more even surface of the electrode layer could allow the current to flow better through this layer and increase the initial resistive value.

To create that even surface, the electrode yarns need to increase the surface area where individual threads touch each other. The new weave diagram will be based on a satin structure. Satin is a structure where yarns interlace less often in the warp, leading to longer horizontal floats thus more contact surface in between individual yarns. The Map of Bindings and weave diagram for this sensor can be found in Appendix B.

- Another possible solution to creating an overall higher initial resistive value is by using a resistive yarn that has a higher resistive value than the current one. (see Ch. 3.3)
- Both these solutions are implemented in this round, in separate sensor samples.

### 4.5.2 Samples

#### R5V1

This sensor is made using a satin structure, and polyester yarn is used instead of elastic yarn. The front side appears well-constructed with no visible anomalies. However, the backside shows many gaps between the electrode yarns, which is a structural issue that requires further investigation.

Test results show an almost flat line, with only one small U-shape in the first cycle. This indicates a very low resistance ratio, as well as poor repeatability and recovery.

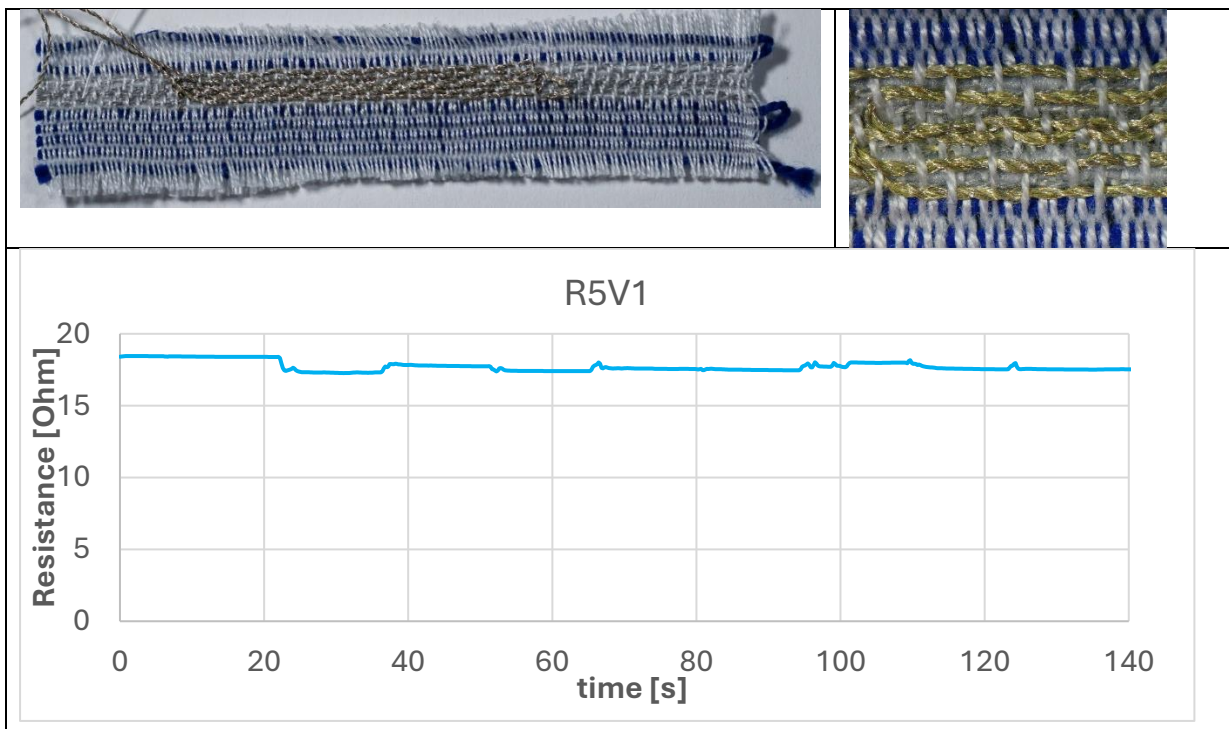


FIGURE 43: R5V1

### R5V2

= satin structure w/ regular yarn comb flipped

This version also uses a satin structure with polyester yarn, but the pattern is flipped. The weaving direction was changed from top-to-bottom to bottom-to-top.

Visually, the structure appears well-formed, and the yarns are tightly packed, which was the goal of changing the weaving direction.

However, test results show poor performance. The resistance value increases at the start of the test instead of decreasing and remains around 25 ohms throughout. There are no discernible U-shapes, making the results inconclusive.

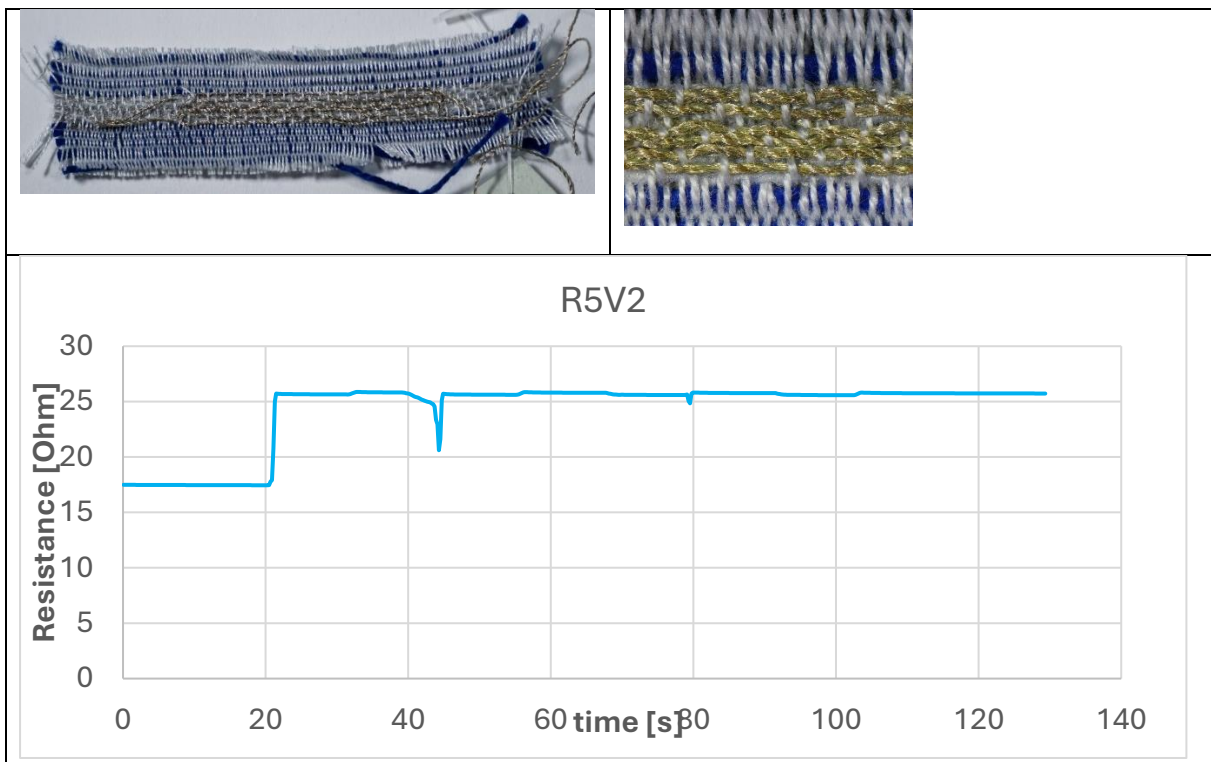


FIGURE 44: R5V2

### R5V3

= satin structure w/ new bekinox resistive yarn

This sensor uses a satin structure with a new Bekinox yarn that has a higher resistive value.

Visually, the sensor shows gaps, especially near the borders, where warp floats pull on the structure.

The test results show an almost flat line with barely discernible U-shapes at around 40, 70, and 100 seconds. This indicates a very low resistance ratio.

However, there are slight signs of repeatability and recovery.

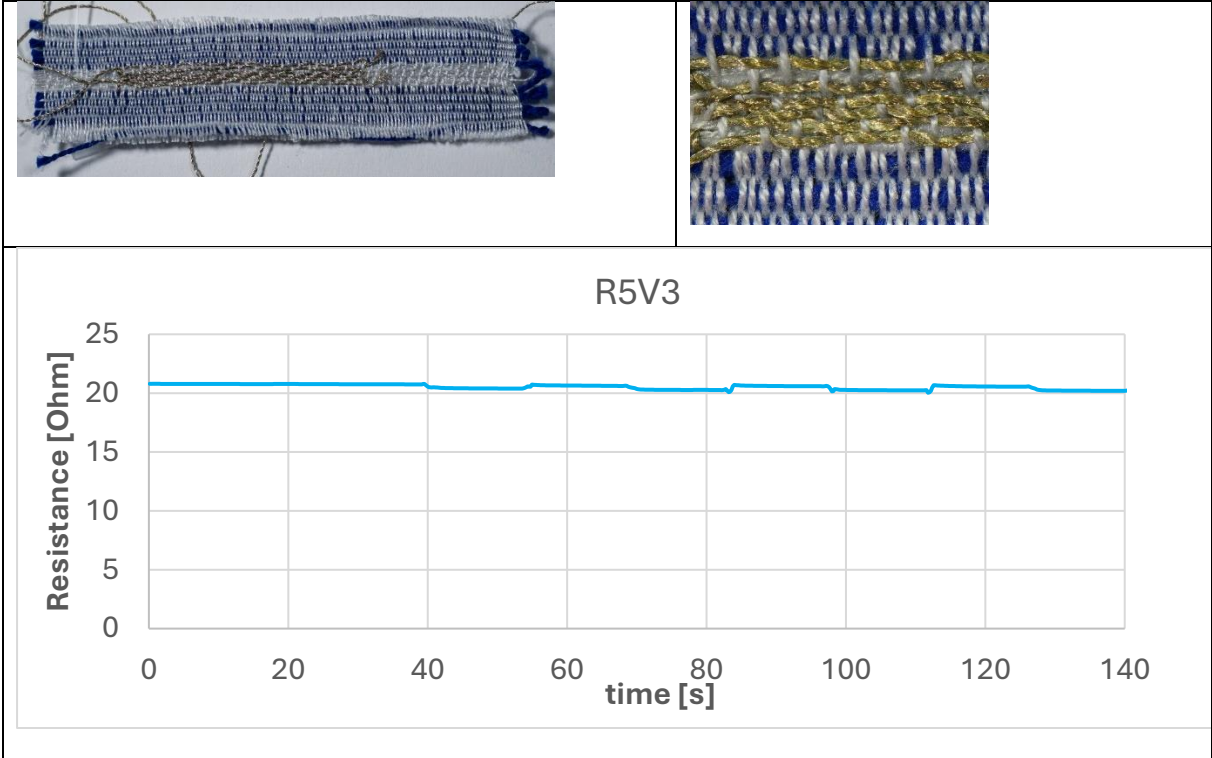


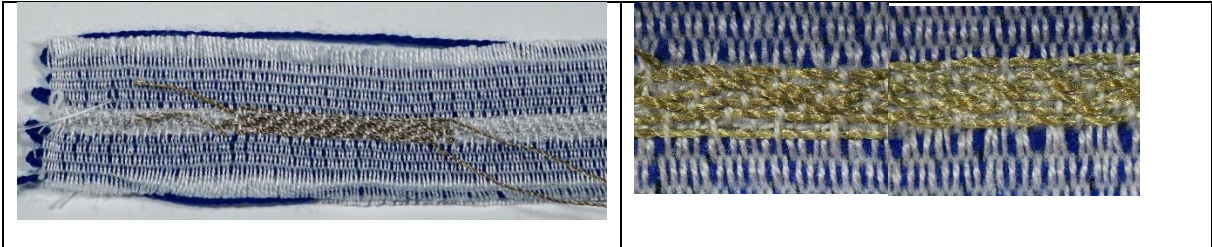
FIGURE 45: R5V3

**R5V4**

= twill structure w/ new bekinox resistive yarn

This version uses a twill structure (similar to R4) combined with the Bekinox resistive yarn.

Visually, the front side shows some gaps between electrode yarns, while the backside appears more secure.



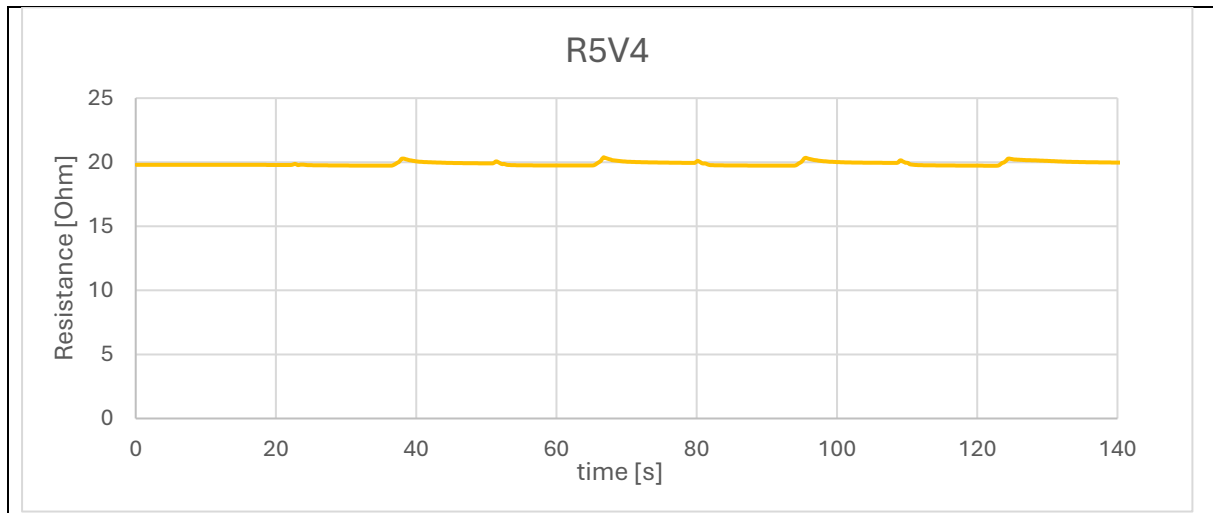


FIGURE 46: R5V4

Test results again show an almost flat line, indicating a very low resistance ratio. Small peaks are present, suggesting minimal recovery.

#### 4.5.3 Conclusion

Choosing satin for the new structure did not have the intended effect. It still occurs that there are many gaps in between the electrode yarns. It is especially noticeable when compared to R5V4, which used a twill to bind the yarns tightly together. Aside from that, all sensors show little to none change in resistive value, which indicates a crucial error in the woven structure.

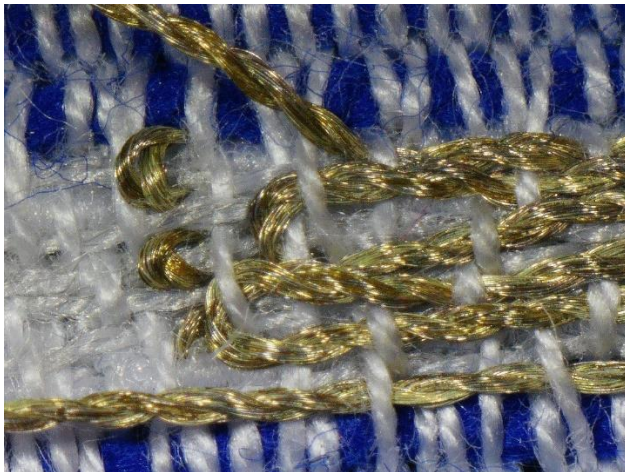


FIGURE 47

On closer inspection with the microscope, it was discovered that all sensors have electrode yarn bulging out the sides. It is suspected that this is caused by either the sequence of yarn weft insertion or it is a side effect of the structure and the bulging can not be removed. However, the threads bulging out can be moved further from each other. By making the surface of the bottom electrode layer larger than the top (figure x)

# 4.6 Round 6 : Increase the bottom electrode surface to eliminate short-circuiting

## 4.6.1 Hypothesis

This round the sensor will be woven with a paired twill pattern, the pairing of two electrode threads to each other the electrode layers will create a tighter structure. With the expectation that the electrode surface will be even and have more contact with each other for improved current flow.

Aside from that a new Map of bindings will be used to create a larger bottom electrode surface. It is expected that this will ensure that the electrode threads poking out the side will be distanced from each other (Fig. 48). Doing so will eliminate the probable main cause for short circuiting in the sensors thus far.

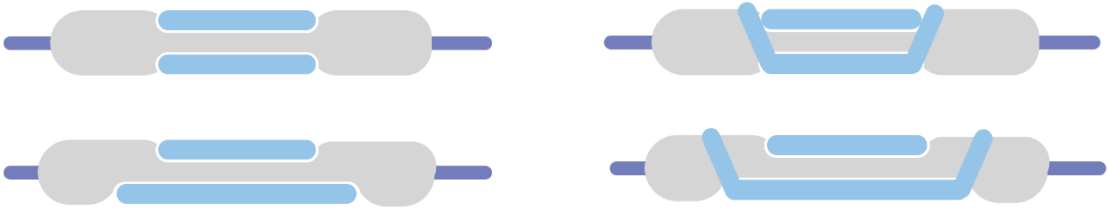


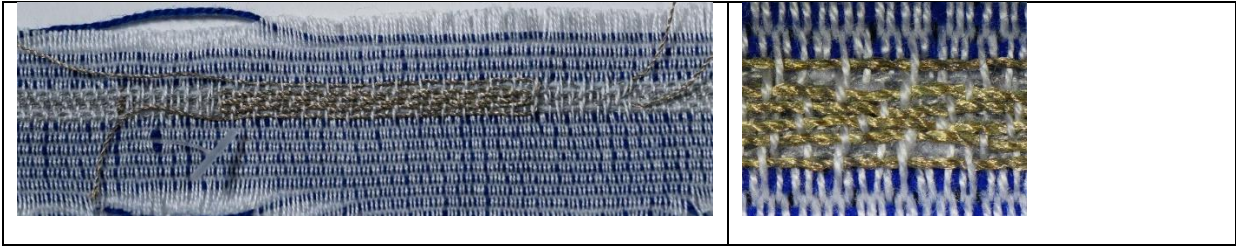
FIGURE 48: SIMPLIFIED CROSS SECTION OF SENSOR OLD (ABOVE) AND NEW (BELOW), IN NORMAL STATE (LEFT) AND COMPRESSED STATE (RIGHT)

To test whether the new MOB (Appendix B) is the cause for this intended effect, another sensor will be woven, using the regular twill pattern from R4 combined with the new MOB. If this sensor performs better than R4, the MOB will be the only change exacted.

## 4.6.2 Samples

### R6V1

The structure of the sensor has a few discrepancies apparent in the first and last electrode thread in only the upper layer. It seems the weave structure around the sensor has caused some of the warp threads to pull the electrode yarns to the side (Fig. 49).



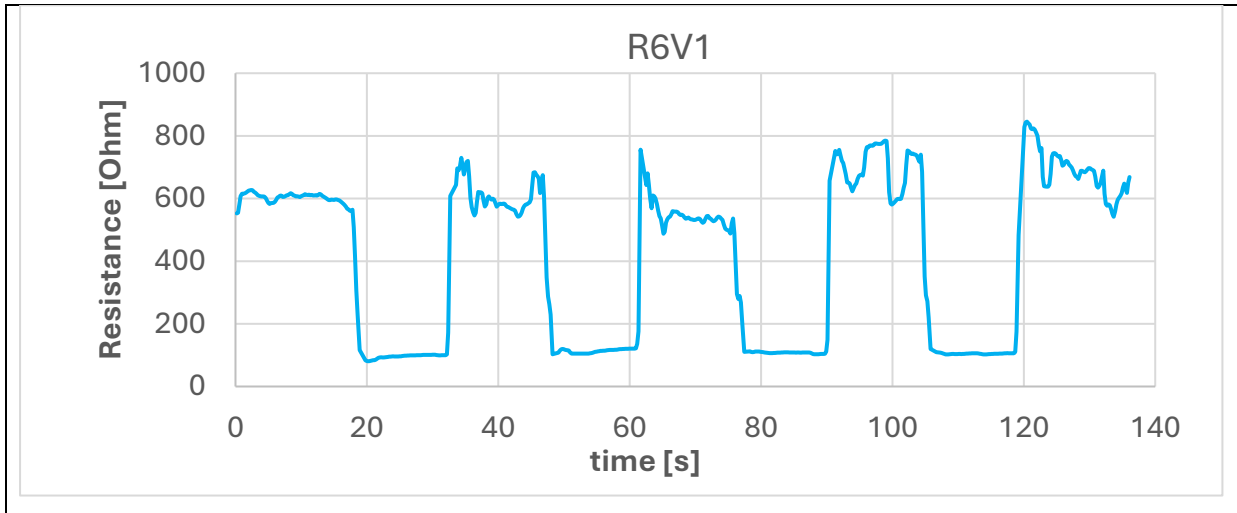
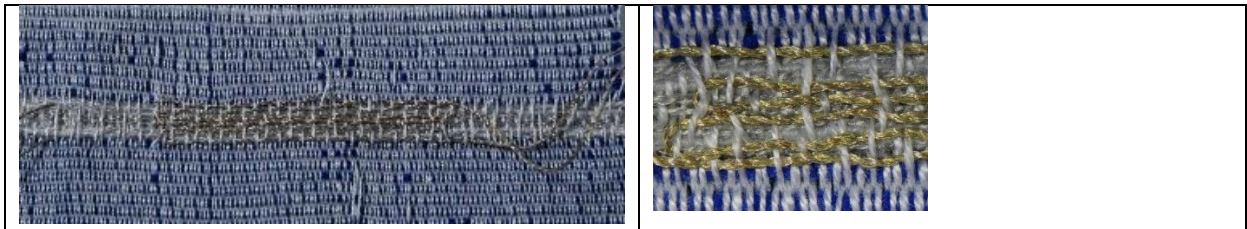


FIGURE 49: R6V1

This sensor shows improved results (Fig. 49). The graph clearly shows a drop from approximately 600 ohms to around 100 ohms, resulting in a high Resistance ratio. Repeatability is good, as the activated values consistently remain around 100 ohms. Recovery shows some noise in the return values, but on average they stabilize between 600–700 ohms, which is close to the original resistance ( $R_0$ ). This can be considered good recovery.

#### R6V2

This version uses a different weave diagram, which is based on a paired twill, instead of a regular twill. A paired twill (for diagram see Appendix B) with new MOB. Structurally, the sensor appears weak, with many gaps between electrode yarns and long warp floats.



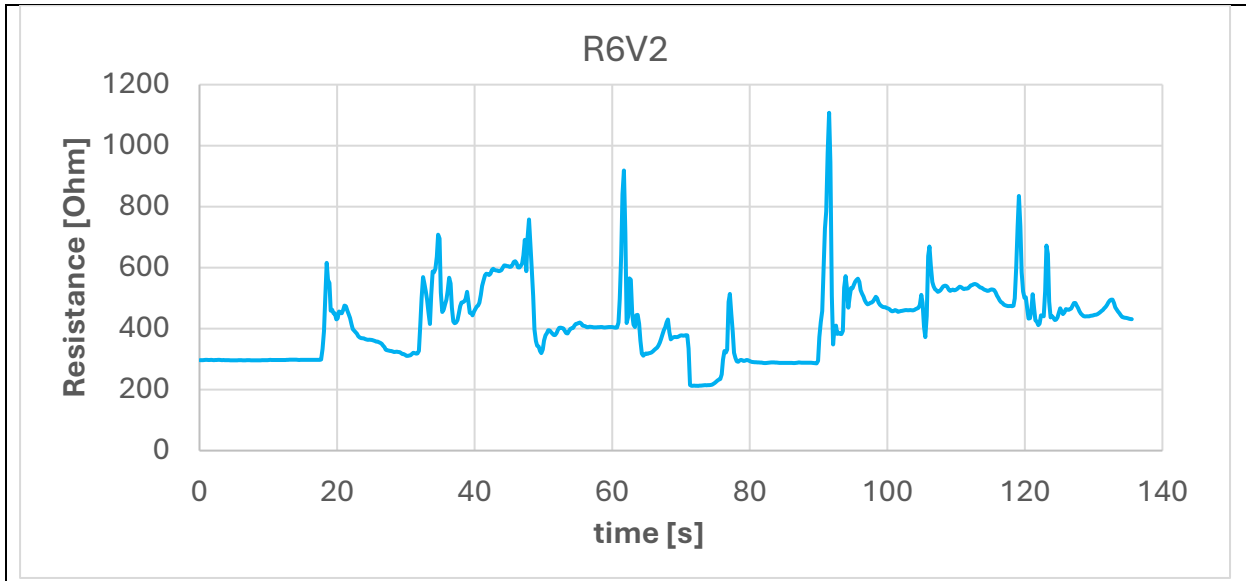
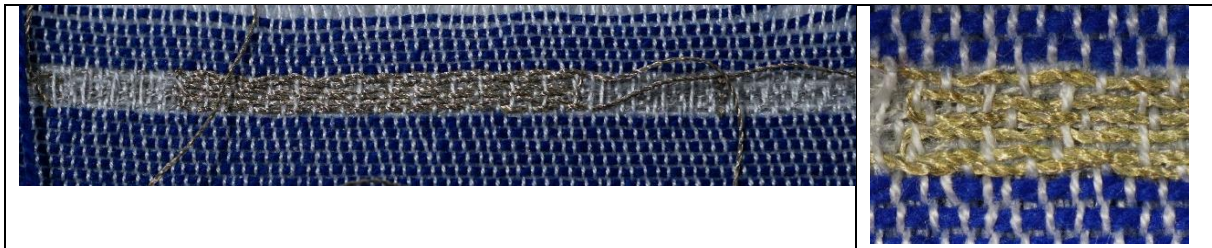


FIGURE 50: R6V2

Test results show no clear U-shapes (Fig. 50). The resistance values increase, suggesting a potential improvement in resistance ratio. However, due to the lack of clear U-shaped curves, the results are inconclusive.

### R6V3

This version also uses the paired twill diagram, and is combined with a twill pattern for the surrounding fabric instead of tabby to reduce warp float issues. Structurally, there is some improvement compared to V2, with fewer gaps between electrode yarns.



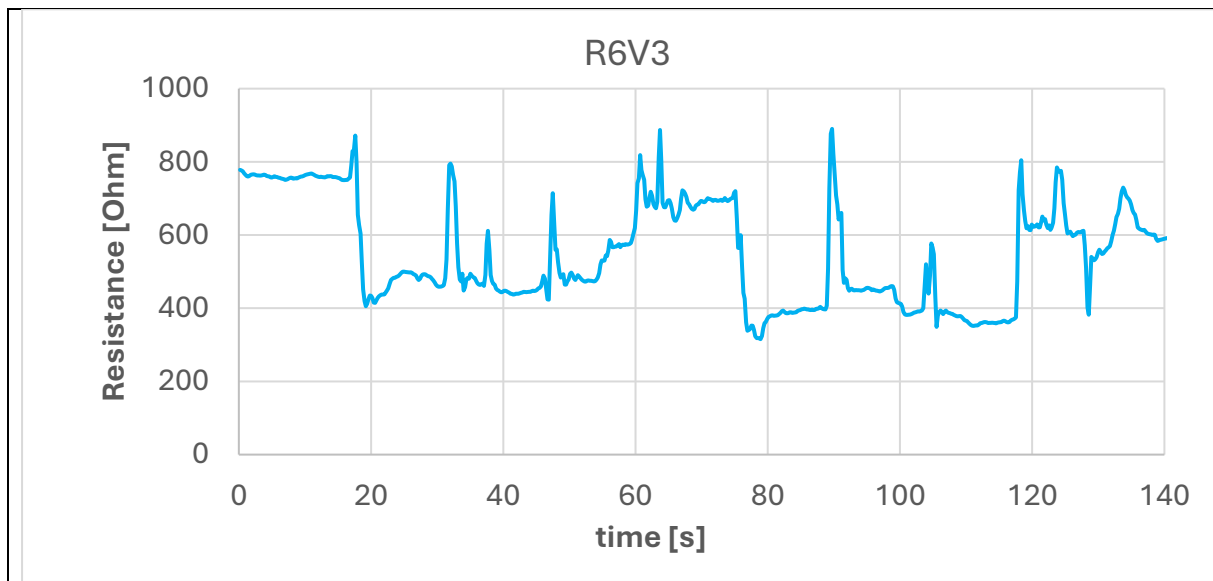


FIGURE 51: R6V3

Test results show an improved resistance range (Fig. 51). However, apart from one U-shape around 80 seconds, no clear U-shaped graphs are visible.

The first compression cycle shows a high Resistance ratio (with a drop from approximately 700 to 400 Ohm), but due to noise in the graph, repeatability and recovery cannot be reliably determined.

#### 4.6.3 Conclusion

When comparing the sensor from R4 with R6V1, the only difference is that R6V1 has the new MOB, therefore it can be concluded that this is the cause for improved performance. Thus this method will be used in the creation of sensors going forward.

# 4.7 Round 7 : Change structure to a paired satin to improve conductivity

## 4.7.1 Hypothesis

With similar hypothesis to R6, the following sensor will be made with the new MOB that creates a larger electrode bottom layer. This sensor differs from R6 in that it will again be based on a satin structure, such as in R5. As opposed to R5 the new structure will contain a paired satin, where the warp yarn joins two electrode yarns next to each other in the panel. The Map of Bindings and weave diagram for this sensor can be found in Appendix B.

## 4.7.2 Samples

### R7V1

This sensor is woven using a paired satin structure. Visually, the yarns are tightly packed, and there are no major gaps. However, the electrode yarns have a high degree of freedom, resulting in a curved appearance. Yarn segments protrude in areas with long floats.

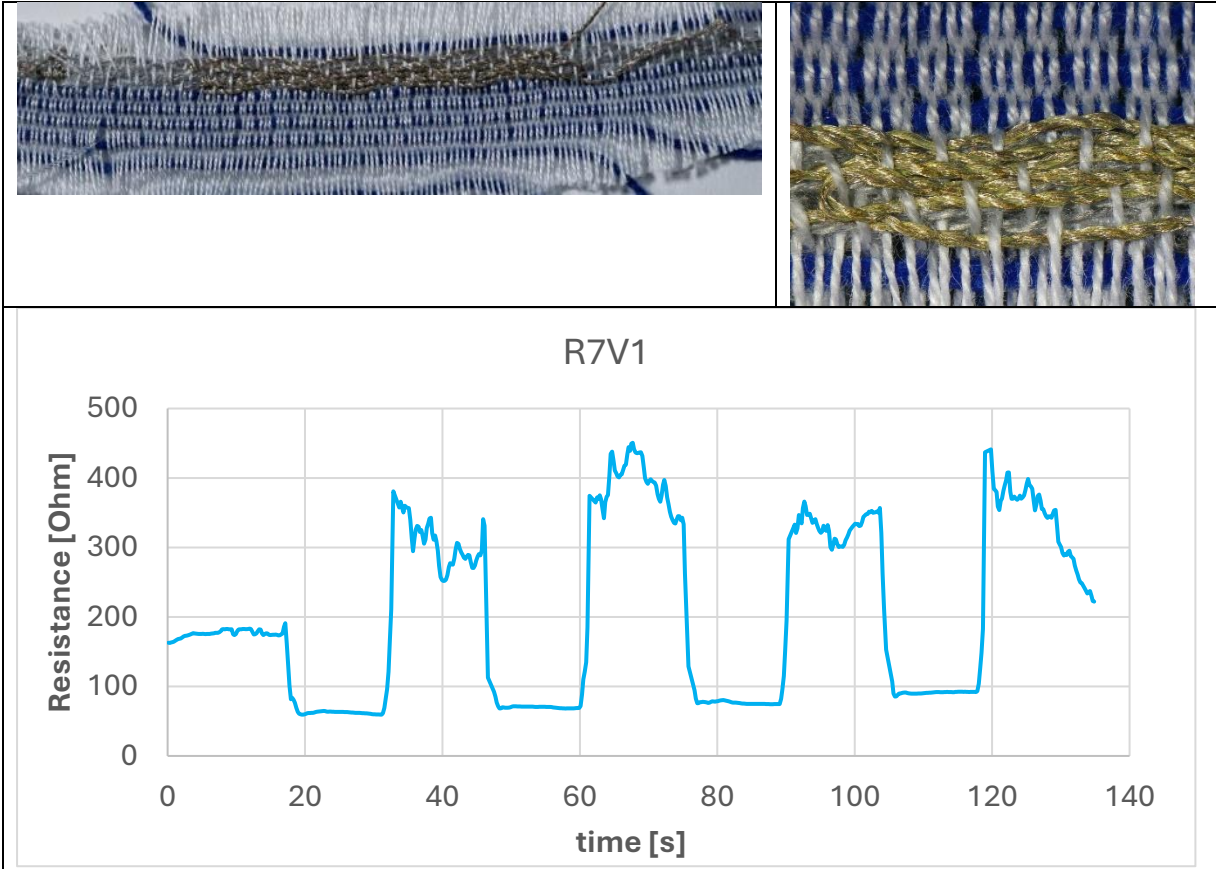


FIGURE 52: R7V1

Test results show good performance (Fig. 52). The sensor demonstrates a clear resistance ratio, with values dropping from approximately 300 ohms to 75 ohms during the second cycle. Repeatability is good, as activated values consistently fall between 75 and 100 Ohm. However, recovery is inconsistent. The return values do not stabilize at the same baseline ( $R_0$ ) and vary between cycles.

### 4.7.3 Conclusion

The sensor performs well, seeing its high initial resistance value and the large difference between R0 and each valley, indicating a high Resistance ratio. Overall the performance also has good repeatability, as shown when inflicting repeated pressure, that the sensors value stoops consistently to a value of 70 Ohm. Its return value does stagger slightly around 350 Ohm, with a standard deviation of approximately 40 Ohm.

Just like the samples from R6 these sensors have shown to be a significant improvement as compared to previous samples. Though the use of twill structure in R6 seems to create an overall higher initial resistive value, while showing the same resistive value when under pressure. This makes R6 a more sensitive sensor as compared to R7, but R7 has more consistent repeatability (Fig. 53).

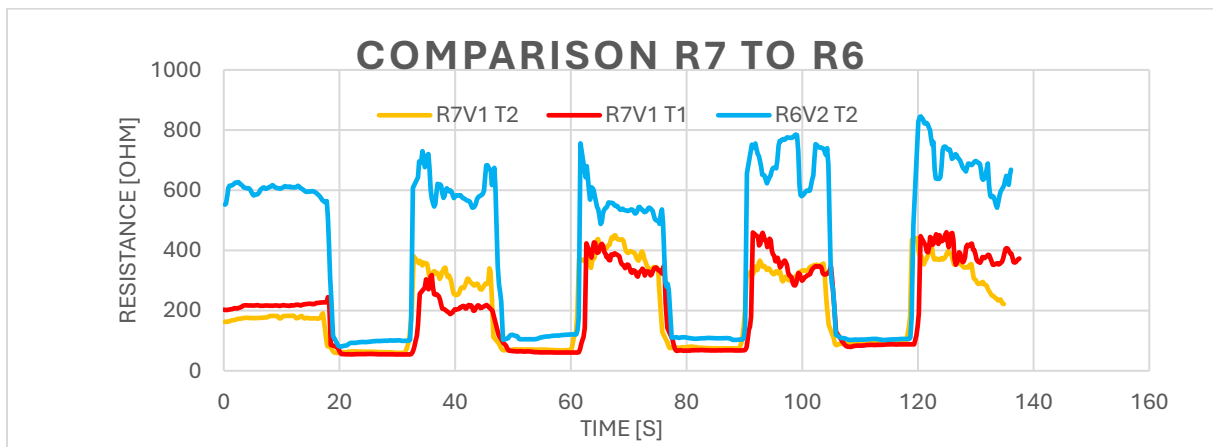


FIGURE 53: COMPARISON OF TEST RESULTS FROM ROUND 7 AND ROUND 6

For further prototyping and testing, the focus will shift back to creating a sensor with a tighter structure to ensure that yarns are more secure. Opting for a diagram based on the twill is a possible solution to this problem, as Round 6 has already shown that a twill based structure gives favourable results. Other possible solutions are changing the weave structure surrounding the sensor to minimize height differences and uneven tension during weaving.

## 4.8 Round 8 : Change structure to a paired twill to improve conductivity

### 4.8.1 Hypothesis

For this round, it was decided to return to a twill based design, as R6V1 has thus far shown the best results in terms of sensitivity. The paired twill design for R6V2 and R6V3, was improperly conducted, another attempt was made to create a structure that would pair the electrode yarns in duos for the upper and bottom layer.

Another improvement to R6V1, to attempt is to change the structure surrounding the sensor. R6V1 has shown some warp floats that pull apart the outer layer of electrode yarn. Changing the surrounding structure from a tabby to a compound twill, could change the occurrence of these floats. This is because a twill has a lower frequency of warp interlacement. The sensor itself is a quite thick compound it creates a raised bump where the sensor is woven, a surrounding compound will even out the surface of the fabric more and possibly prevent the warp floats from pulling on the electrode yarns. The Map of Bindings and weave diagram for this sensor can be found in Appendix B.

### 4.8.2 Samples

#### R8V1

The use of a compound twill surrounding the sensor has as intended effect that there are less warp floats occurring around the sensor. The texture of the sensor has also improved, as the part where the sensor is woven is less noticeable. This is a trait that is also preferable when weaving wearable garments.

The pictures show an improvement in structure for the electrode yarns, as seen in the microscopic pictures (Fig. 54) there are no visible gaps. What stands out is that on the back side of the sensor, there are resistive yarns in places where electrode yarns are supposed to be.

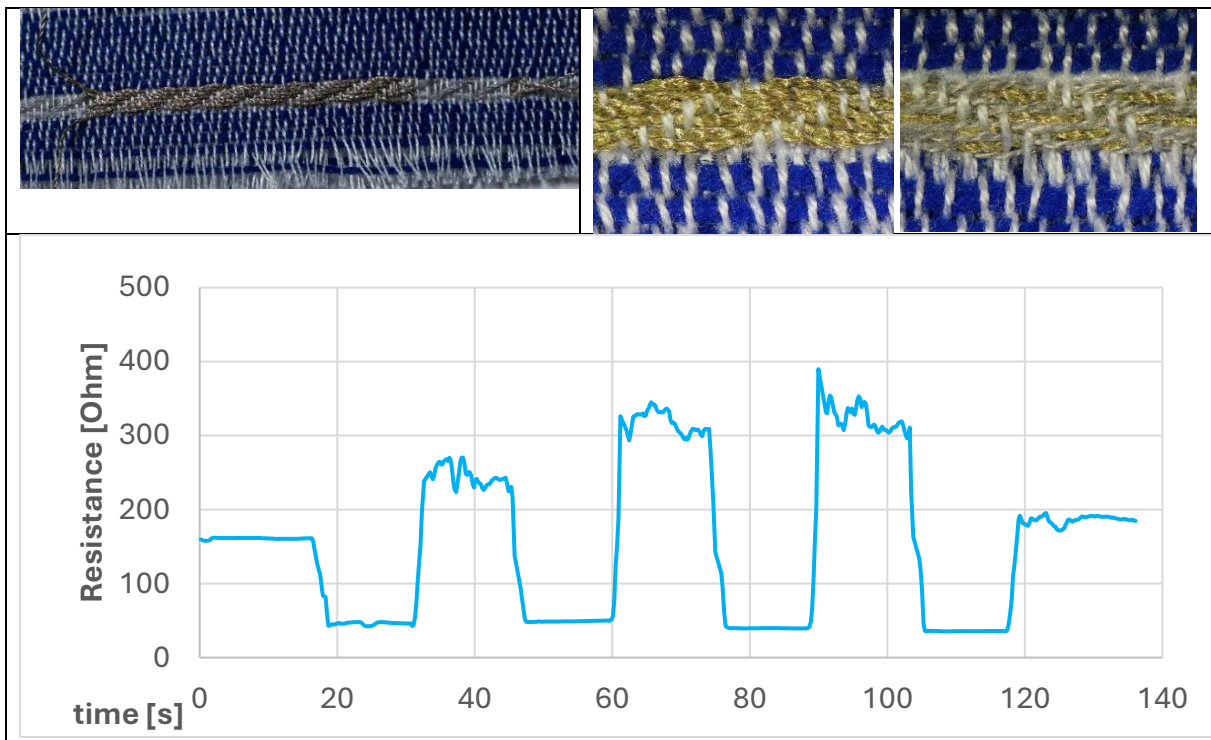


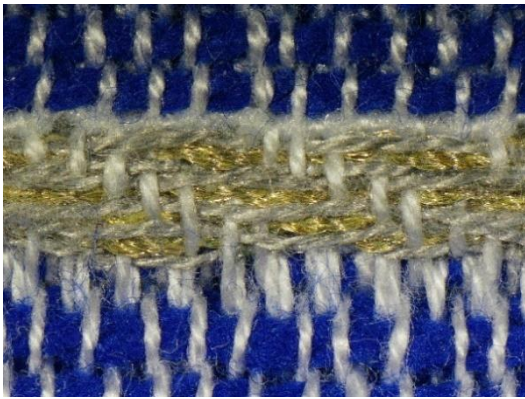
FIGURE 54: R8V1

The sensor performs well, but it is interesting that the normal value increases with every step. Also notable is the fact that the start and ending value are very different than the normal value during testing.

#### 4.8.3 Conclusion

It can be concluded that though the sensor performs well, showing a high Resistance ratio and repeatability. However, the sensor has a lower Resistance ratio when compared to R6V1.

Another aspect for discussion is the inconsistent recovery rates, which is apparent in both the recovery values as the initial normal resistive values. Compared to the recovery value, the lower normal resistive value,  $R_0$ , is especially noticeable at the start and end of the experiment. This phenomenon can be attributed to the uneven structure of the bottom layer of the sensor.



It is noticeable that the woven structure has some errors deviating from the design, due to resistive yarns from the bottom layer poking through, where there are supposed to be electrode yarns (Fig. 55). This could be due to an error in the weave diagram, adjustments are needed in either the order of which the yarns are inserted or the interlacing warps.

FIGURE 55: MICROSCOPIC PICTURE BACKSIDE OF SENSOR R8V1

## 4.9 Round 9 : Adjusting the paired twill for better recovery

### 4.9.1 Hypothesis

For this round, the weave diagram from Round 8 was woven on the paper loom and some errors in the diagram were found that interfered with the yarn placement. Adjustments were made to the weft insertion order and the diagram itself (Appendix B).

The new sensor should have identical structures for the upper layer electrode yarns and the bottom layer. Furthermore, to indicate the sensors on a demonstrator, a yarn with a contrasting colour is chosen to surround the sensor. In this round it is also explored what the effect is of swapping one yarn in the surrounding compound twill.

### 4.9.2 Samples

#### R9V1

The structure of the sensor's bottom layer has improved compared to Round 8, as seen in Figure 56, both layers show only electrode yarns.

The first version of the sensor uses an orange mercerized cotton as contrasting colour. There are some noticeable gaps in between the orange yarns, this can be caused by the yarns having a smaller diameter than the blue cotton yarns.

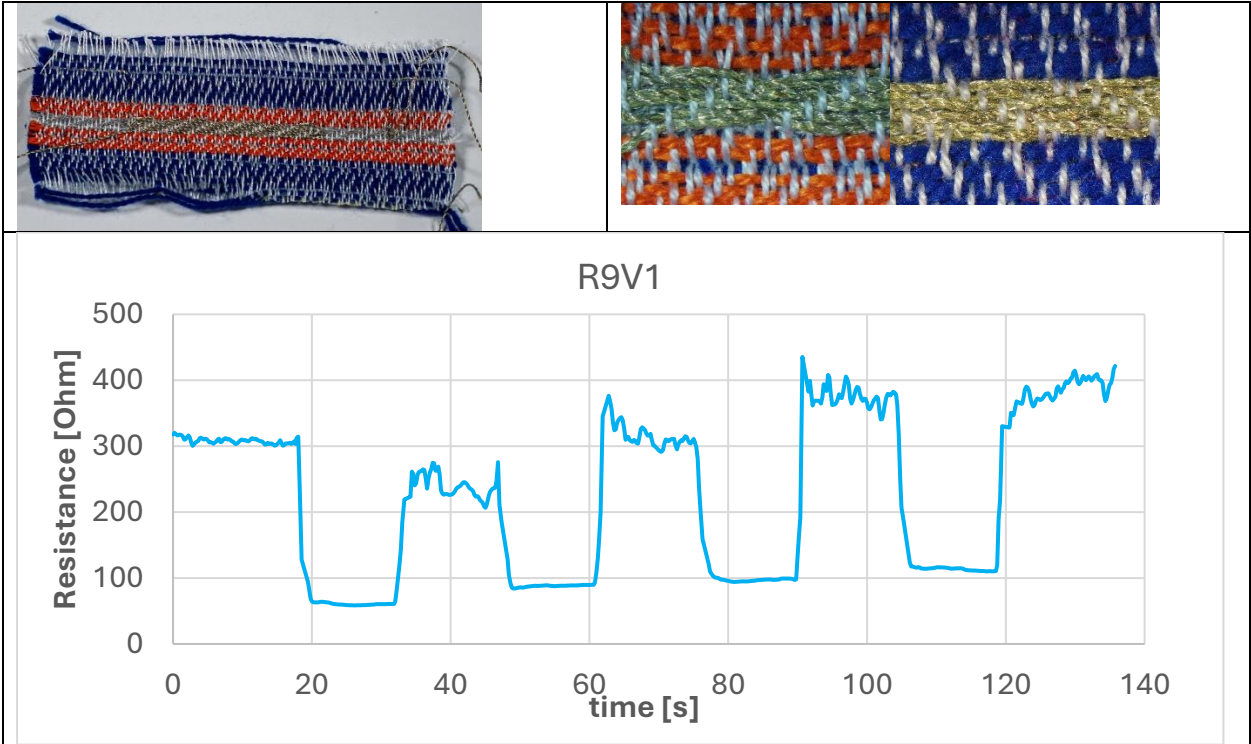


FIGURE 56: R9V1

Test results show good repeatability and medium recovery, but compared to Round 8 has a lower Resistance ratio.

### R9V2

For this sensor, the surrounding woven structure consists of a red cotton yarn and the usual blue cotton yarn. The red yarn improves on the orange mercerized cotton, as there are no visible gaps in between (Fig. 57).

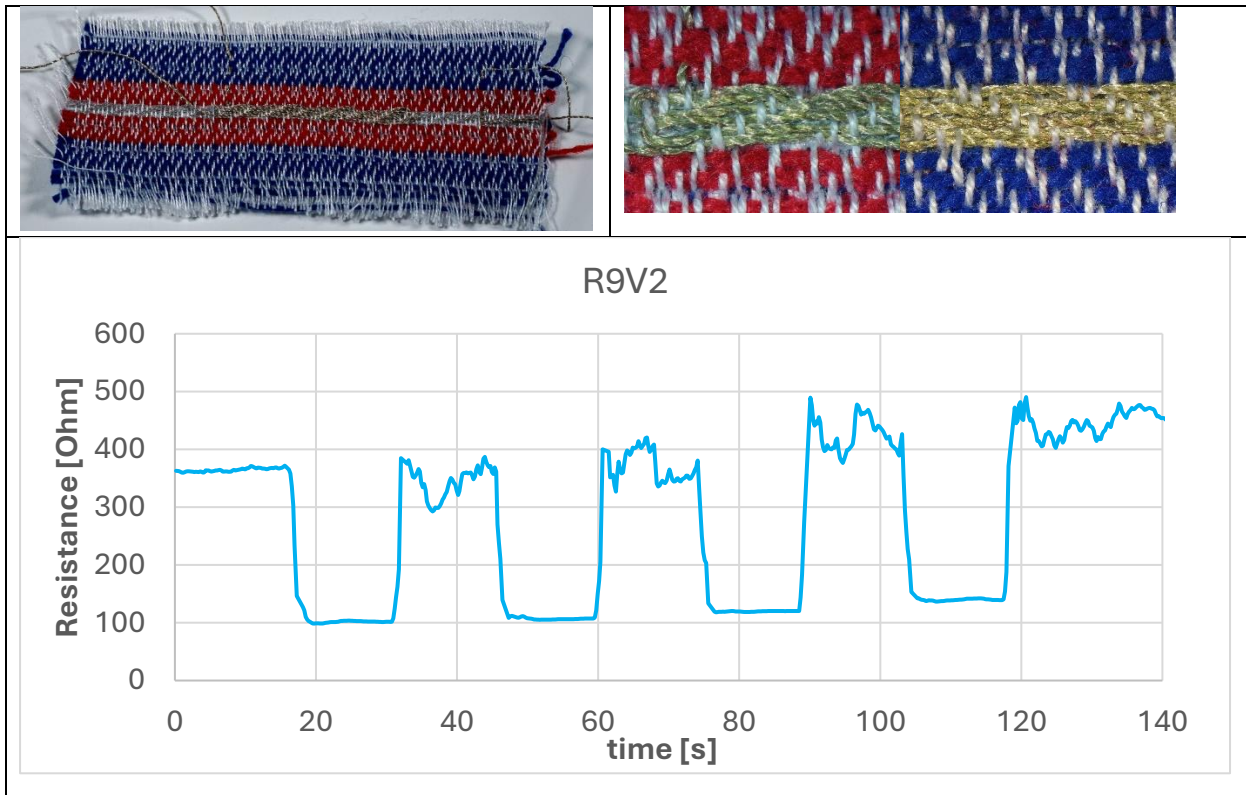


FIGURE 57: R9V2

Though only slightly noticeable, R9V2 has improving results over R9V1, showing on average a higher normal resistive value, resulting in a slightly higher Resistance ratio. The graph below (Fig. 58) shows that both R9 sensors have also improved compared to R8V1.

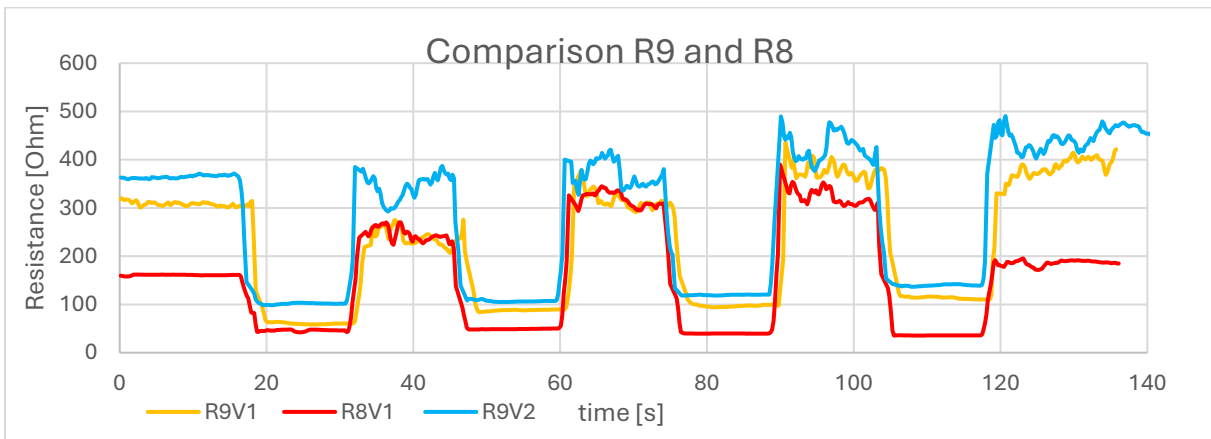


FIGURE 58: COMPARISON OF RESULTS FROM ROUND 8 AND ROUND 9

### 4.9.3 Conclusion

Both pictures of the sensor and the results of the test show that this is a well performing sensor with a secure structure, high Resistance ratio, good repeatability and decent recovery. Though there is some noise apparent in the recovery values, the average of each peak is congruent with the initial resistive value,  $R_0$ .

## 5. Key findings

### 5.1 Elongating the sensor pattern across the weft

The first key adjustment took place in Ch. 4.2, after noticing that the way the first sensor was woven created difference in warp tension. Not only could this negatively affect the loom by putting unnecessary tension forces on certain heddles, it could also cause the surrounding structure to pull on the sensor. As figure x shows, the difference in tension between the woven sensor and surrounding structure pulls on the layers, creating a slight and unpredictable compression.

Adjusting the sensor so that the yarns in the middle layers will be woven across the full length of the weft will create less tension difference (Fig 59). The electrode layers are still woven separately but are placed with less tension and height difference in the sensors' build.



FIGURE 59: SIMPLIFIED CROSS SECTION OF WOVEN SENSOR OLD DESIGN (LEFT) AND IMPROVED DESIGN (RIGHT)

### 5.2 Removing weft interlacement yarns

Starting from Ch. 4.3, the material composition of the sensor was changed, due to the suspicion that the dedicated weft interlacement yarns were the cause for the low RR. The weft interlacement yarns would add a stiffness and compression on the woven structure, not allowing the electrode layers to separate after compression (Fig 60). Since the weft interlacement yarns were not a necessary component, the decision was made to remove them all together and use the elastic to interlace the upper and bottom layer.

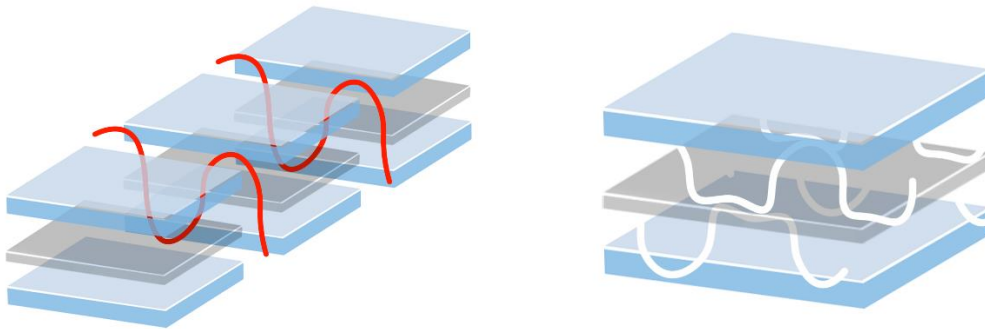


FIGURE 60: PLACEMENT AND USE OF WEFT INTERLACING YARN – OLD DESIGN (LEFT) AND NEW DESIGN (RIGHT)

The new structure uses the already existing elastic to alternate interlacements every 4 electrode yarns. (Fig. 61)

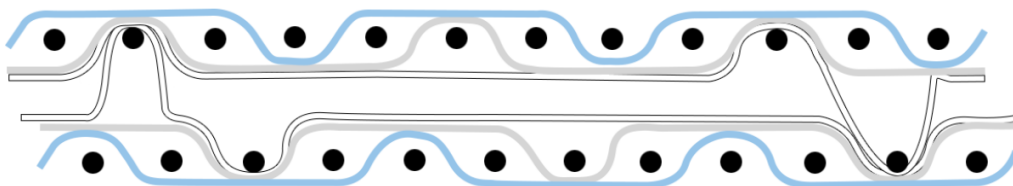


FIGURE 61: CROSS SECTION SHOWING WEFT YARNS INTERLACING THROUGH THE WARP STRUCTURE

### 5.3 Choosing yarns with the same diameter to weave a sensor

Choosing to use yarns of the same diameter creates a structure that is more symmetrical and secure. It allows the yarns to fit in between the warps better than when there would be a large difference in yarn diameter (Fig. 62). This adjustment was implemented in Ch. 4.4 and created a sensor that was visibly more secure than previous samples.



FIGURE 62: CROSS SECTION OF WEFT YARNS, OLD COMPOSITION (LEFT) AND NEW COMPOSITION (RIGHT)

### 5.4 Lowering the risk of short circuits by elongating the bottom electrode layer

The next key adjustment was added in Ch. 4.6. After weaving multiple sensors that had a very small RR, it was concluded that there was something fundamental in the structure that caused a short circuit. A closer inspection with the microscopic camera discovered, whenever the electrode yarns of the bottom layer turned weft it would poke out through the top layer, possibly making contact with the upper layer (Fig. 63).

To negate this effect the weaving pattern was adjusted to elongate the bottom electrode layer in the horizontal direction. The new adjustment creates more distance between the ends of both the upper and bottom layer, where conductive yarns turn weft. Whenever the yarns of the bottom electrode yarns do poke through the top layer, they are a secure distance from the upper electrode yarn.

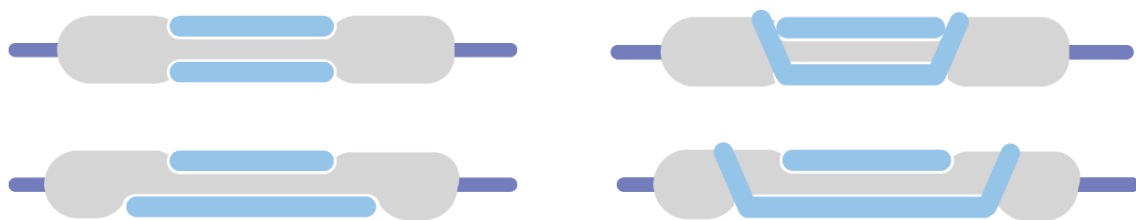


FIGURE 63: SIMPLIFIED CROSS SECTION OF SENSOR OLD (ABOVE) AND NEW (BELOW), IN NORMAL STATE (LEFT) AND COMPRESSED STATE (RIGHT)

## 5.5 Adjusting the surrounding pattern to reduce strain of the warp yarns

Changing the pattern of the fabric surrounding the sensor from a tabby weave to a compound twill weave has made a noticeable difference in the sensors appearance, see Ch. 4.8. The sensors electrode yarns appear more packed and uniform. Before there appeared to be floating warp yarns pulling the electrode yarns apart. With the compound twill, not only do there not appear any long warp floats, the feel of the surface is more even proving that the sensor is more evenly packed in the fabric (Fig. 64).

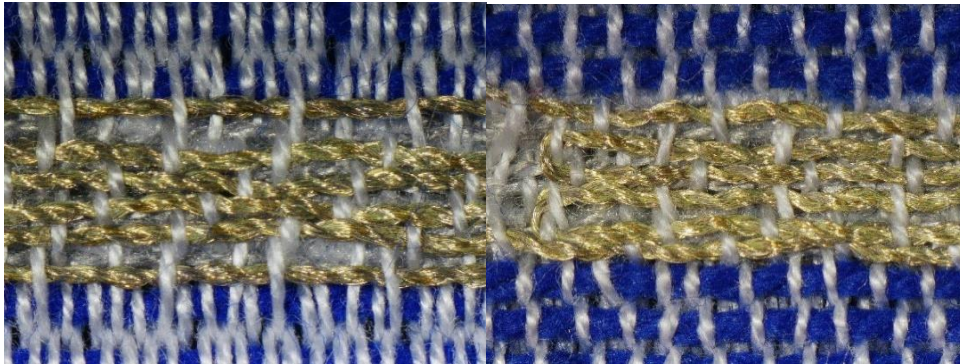


FIGURE 64: MICROSCOPIC PICTURE OF SENSOR SURROUNDED BY A PLAIN WEAVE FABRIC (LEFT) AND A SENSOR SURROUNDED BY A COMPOUND TWILL BASED FABRIC (RIGHT)

## 5.6 Choosing a paired twill diagram to weave

To remedy the issues of yarns not being packed together and low RR, for the weave different structures were tried in

### *Satin*

The purpose of the satin (Fig. 65) was that due to lesser warp interlacements more of the electrode yarns surface becomes exposed, see Ch. 4.5 Round 5. This creates more contact between the yarns and better current flow, creating a higher RR. However this was not the case, likely due to gaps in between the yarns.

### *Twill*

The twill pattern also showed gaps in between the electrode yarns (Fig. 65), however in performance it was slightly better than the satin, see Ch. 4.6 Round 6. The twill structure has more warp interlacements but still leaves a large amount of electrode yarn surface exposed.

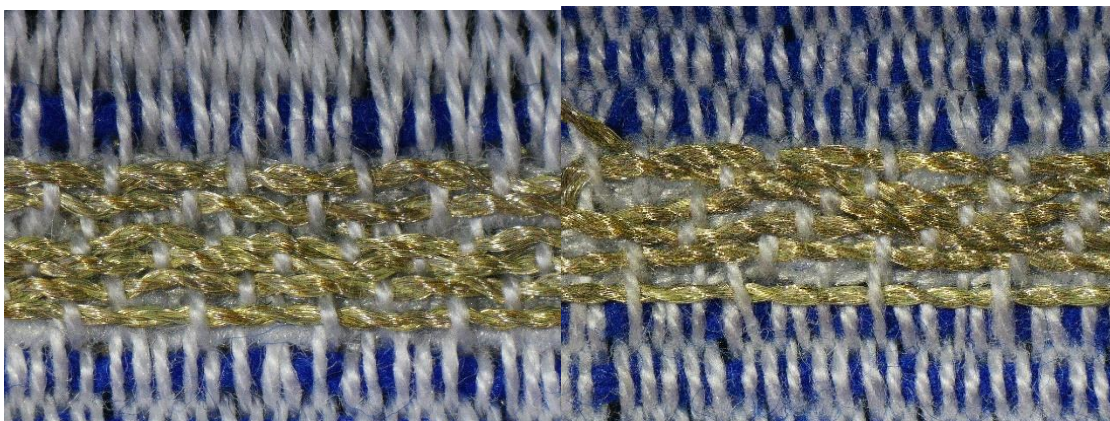


FIGURE 65: SENSOR BASED ON A SATIN (LEFT) AND SENSOR BASED ON A TWILL (RIGHT)

After these attempts, a theory arose that pairing two electrode yarns under one warp float would increase the overall resistive value. This is due to the yarns being more tightly packed together and increasing surface contact between the yarns.

#### *Paired satin*

The paired satin structure (Fig. 66) has improved upon the regular satin, since it the electrode yarns clearly appear more packed together see Ch. 4.7 Round 7. It proves that a structure that pairs up the electrode yarns does improve the structure of the upper and bottom electrode layers. However, one disadvantage of the satin is that the lesser warp interlacement cause the electrode yarns to shift and deform the sensor.

#### *Paired twill*

The paired twill (Fig. 66) shows the best results, the qualities observed in this sensor are tightly packed electrode layers and an even surface structure, see Ch. 4.8 Round 8. Pairing the electrode yarns has significantly improved the structure. As opposed to the satin, the twill secures the yarns in place while still exposing much of the electrode yarns surface.

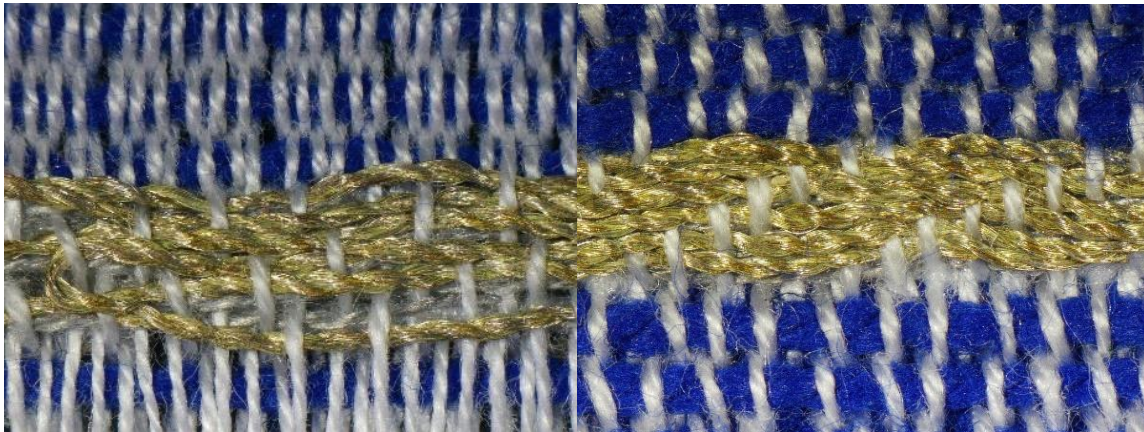


FIGURE 66: SENSOR BASED ON A PAIRED SATIN (LEFT) AND SENSOR BASED ON A PAIRED TWILL (RIGHT)

## 6. Qualities of a woven sensor

### 6.1 Generalised requirements

Following the research and key findings, some generalised requirements for creating a woven sensor can be established.

#### Structure

- A good separation of the different layers

A woven pressure sensor consists of **5 layers**:

- Upper electrode layer
- Upper resistive layer
- Elastic
- Lower resistive layer
- Bottom electrode layer

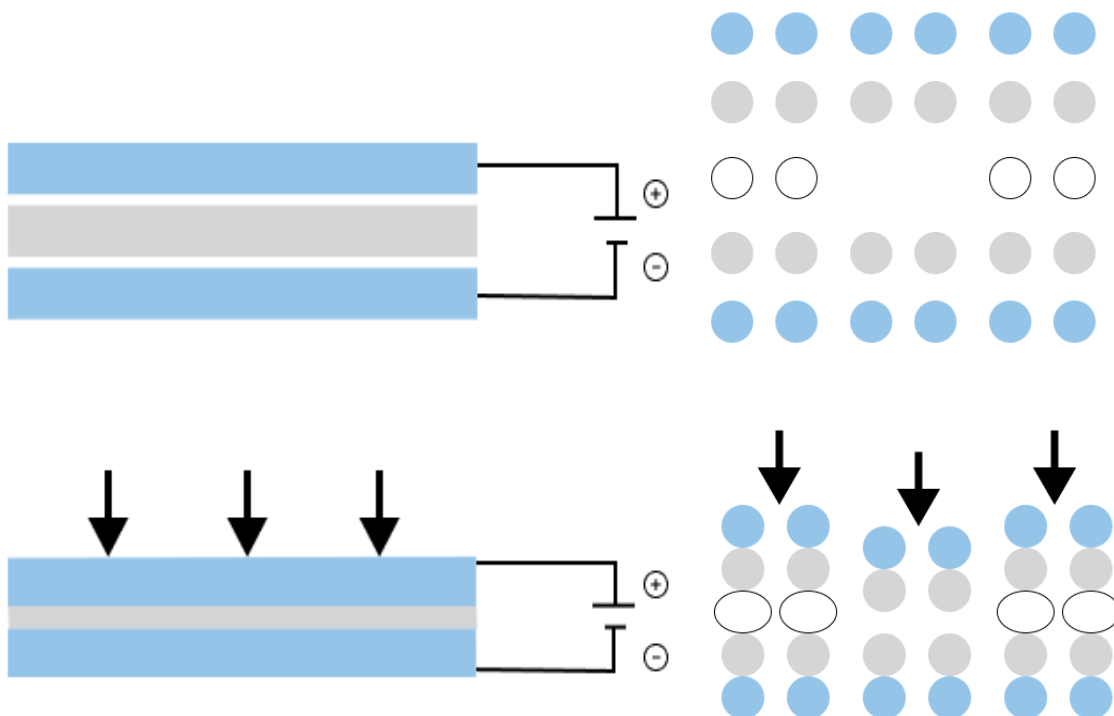


FIGURE 67: SCHEMATIC SHOWING THE WORKING PRINCIPLES OF A WOVEN PRESSURE SENSOR

When the upper layer make contact with the bottom layer the resistive value drops (Fig. 67). To create a sensor with a high RR, this difference in value must be as large as possible. This means that there must be as little contact between the upper electrode layer and the bottom electrode layer.

#### Tightly packed electrode yarn surface

A visual property of a well woven sensor is when the electrode yarns on the surfaces are tightly packed together. Tightly packed yarn are a sign of a secure structure, where all yarns are aligned as intended and they do not shift out of place, which maintains the structure of different layers. Another property of tightly packed yarns is that it assists with better current flow, as the effective contact surface between conductive yarns is increased.

The surrounding fabric structure has to match the sensor in thickness

As mentioned in Ch. 5.5, it is important for the sensors thickness that the surrounding fabric has the same thickness as the sensor, to prevent tension in the warp yarns that cause the sensors electrode yarns to be pulled apart.

### *Materials*

Firstly, when weaving a sensor it is important that all materials have roughly the same diameter. This will help create symmetry in the structure and maintain a secure structure where yarns do not shift from their place.

Secondly, for electrode yarns it is important that the resistive value is low. The Statex Shieldex yarns used for the woven sensors in this research has a value of 600 Ohm/m. Moreover, the resistive yarn in turn has to have a higher resistive value than the electrode yarns. The Bekaert Bekinox 60/40 PES has a resistive value of 1000 Ohm/m. However, a value that differs too greatly from the electrode yarns, could inhibit the current flowing from the upper electrode layer to the bottom layer. This is because the high resistive yarn would distribute the current among itself instead of conducting it to the bottom layer.

Lastly, a thin yarn with a high amount of elastic properties is preferred to be used in a sensor. Elastic properties are determined by the ratio of elastane the yarn is composed of. A higher ratio of elastane is thus preferable for use in a woven sensor.

### *Process*

Firstly, the order of yarns weft inserted does not make much difference. As long as the interlacing warp allow for weft yarns to slide under each other, the specific order, in which the weft yarn is inserted, does not make a difference.

Secondly, the importance of beating the reed during weaving has to be kept in mind. It has previously been stated what the intended effect is of tightly packed yarn in a woven sensor. To create an even surface of electrode yarns and ensure the overall structure of the sensor is secure, beating the reed during weaving will ensure the inserted weft yarn is pressed tightly to the fabric before interlacing with the warp.

Lastly, the weaver has to ensure that yarns do not cross each other during weft insertion. It is especially relevant for electrode yarns and other conductive yarns, because contact can cause short circuiting. The effect of yarns crossing during weft insertion and negating this risk, were demonstrated in Ch. 4.6 And Ch. 5.2.

## 6.2 Performance metrics of the woven sensor

A well working pressure sensor is defined by its ability to register pressure quickly and accurately. For resistive pressure sensing technology, a quick response means a sensor of which the output signal is read by an immediate drop in resistive value when under compression. To define accuracy, the output signal of its resistive value must maintain constant when under compression and when uncompressed.

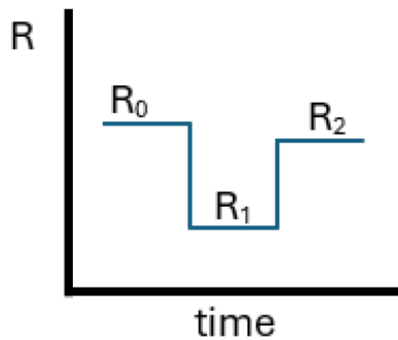


FIGURE 68: EXPECTED GRAPH OF A SENSOR WHEN COMPRESSED AND RELEASED

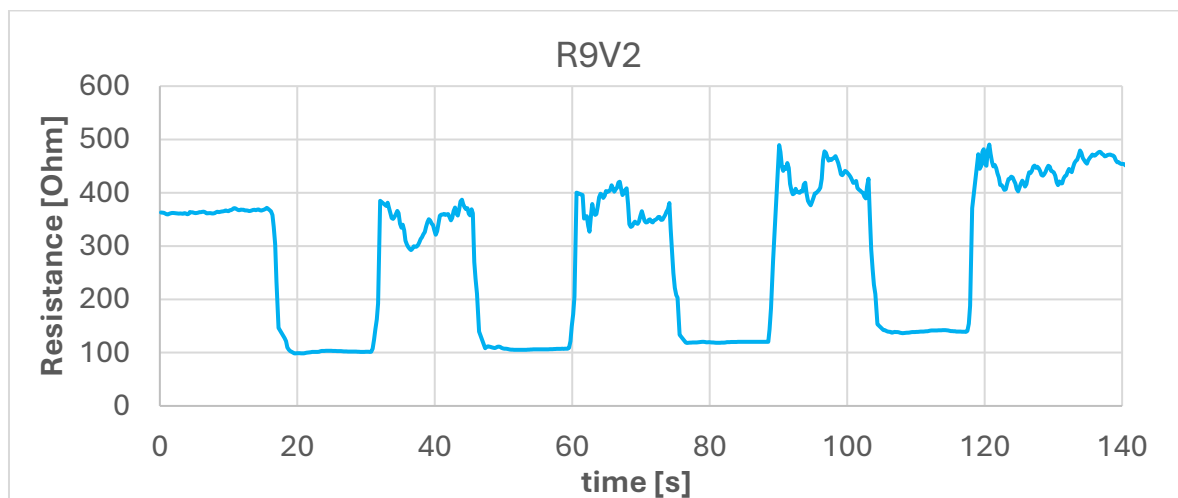


FIGURE 69: TEST RESULTS FINAL SENSOR

A sensor's performance is further defined by the following qualities as mentioned in 3.5.1

Performance metrics:

### Resistance ratio

The Resistance ratio (RR) required for a well performing sensor is defined at a minimum of 20%. Based on the values in Figure X, the RR of the final woven sensor stands at 64%, which is well over the minimum value.

### Recovery

For the latest sensor, it is difficult to determine its recovery rate, since the graph shows some noise in the uncompressed state. However, when simplifying the graph by taking the average of each peak, a recovery rate can be calculated:

$$375 - 370 / 375 = 5 / 375 = 0,01 = 1\%$$

Seeing as the optimal Recovery rate is 0%, this is an excellent result.

### Repeatability

Maintaining the same Resistive value over multiple cycles of compression is a requirement for good repeatability. When looking at the Figure X, it is noticeable that under compression the sensor maintains the same value for the first three cycles, and has one increase from 100 to 140 Ohm in the last cycle. However, the RR of each cycle remains the same, showing consistent repeatable results.

### Sensitivity test

With the accomplishment of designing a sensor that has good repeatability, recovery and a high resistance ratio, it is imperative that the sensitivity of this sensor would also be tested. Sensitivity is an especially important factor for programming a device that uses the sensor's input to actuate functions. A sensor that is sensitive is able to have a ranged function that changes depending on the size of force acted during compression.

The sensitivity test is performed by placing sensor R9V2 in the Rheometer, only instead of repeatedly pressing down with 10 N, the experiment exerts force in increments of 2 N. Starting the test with the foot pressing down at 2 N and each time it comes down again with increased force. The results of experiment (figure x) can be interpreted as the sensor showing clearly different results for each different amount of force in compression.

TABLE 2 MEASURED RESISTIVE VALUE AT EACH COMPRESSION

Force (N)	Resistance (Ohm)
0	520
2	410
4	380
6	300
8	250
10	230
12	210

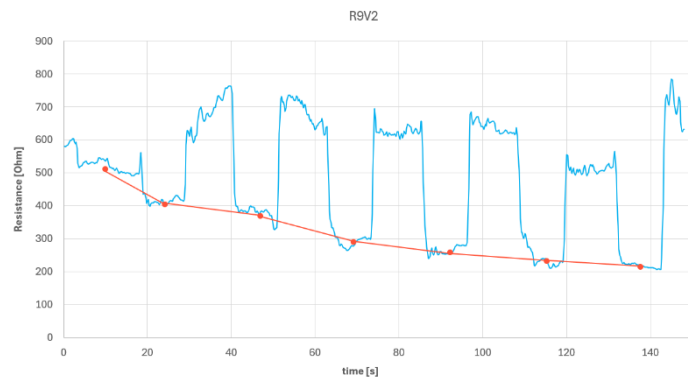


FIGURE 70: TEST RESULTS SENSITIVITY TEST

From this test, it can be concluded that the sensors current design has a high sensitivity as there is an average of 48,33 Ohm difference per step of increased force compression.

### Hysteresis

Hysteresis in textile-based sensors can arise from several factors, one of which is the structure of the yarn. The arrangement and stability of yarns within the sensor play a critical role in how it responds to compression and decompression.

A well-structured and secure sensor has reduced noise during compression, a good recovery after deformation, and repeatability across measurement cycles. These characteristics indicate a more stable and predictable output. Together, these effects help mitigate hysteresis, suggesting that optimizing yarn structure is a promising direction for the future design and development of woven sensors.

## 7. Demonstration fabric

This chapter will delve into the design and creation of a collection of sensors that can be applied in a usable interface. This is a piece of fabric containing an array of sensors, from here on named a demonstrator.

### 7.1 Goal of the demonstrator

The goal of creating a demonstrator is to observe how placing multiple woven sensors in a fabric would influence the performance of each individual sensor and to create a prototype that simulates how sensors can be used in an application.

#### 7.1.1 List of Requirements

To start designing a demonstrator, it is necessary to formulate a list of requirements and wishes to take certain parameters into consideration.

1. Must allow for each individual sensor to register pressure and generate its own signal
  - a. Each individual sensor must create a signal so it can be determined where on the fabric pressure is registered
  - b. Allowing each individual sensor to output a mappable signal also creates more opportunities for different functions
2. Not have too many threads as in and output
  - a. As it becomes complicated too quickly when you have to integrate it into a fabric/wearable product
3. Allow for easy duplication of sensors
  - a. Aligning the sensors horizontally allows for the electrode yarn to be more easily woven into the fabric

#### 7.1.2 Design

When designing the layout for the demonstrator, two possible configurations were considered for integrating the sensors into the fabric:

- Sensors placed continuously and connected directly to each other
- Sensors spaced in a grid pattern

The chosen approach is to combine these two considerations in a grid layout where the backsides of the sensors are connected. This configuration makes it easier to replicate multiple sensors within a woven fabric while keeping the structure manageable. By connecting the sensors at the back, the design avoids the added bulk that would result from multiple individual connections to the electronics, leading to a cleaner and more scalable integration within the textile.

The plan for the demonstrator is to create a grid consisting of several sensors placed apart from each other. The upper electrode layers will be woven in patches by means of a partial weft, but all sensors share the same bottom layer as that is horizontally spread out, to minimize the amount of thread needed to create connections to the interface. Each row is labelled with a letter, making it recognizable that they share the same bottom layer. Each column is then given a number, creating a labelling system for each individual sensor in the demonstrator (Fig. 71).

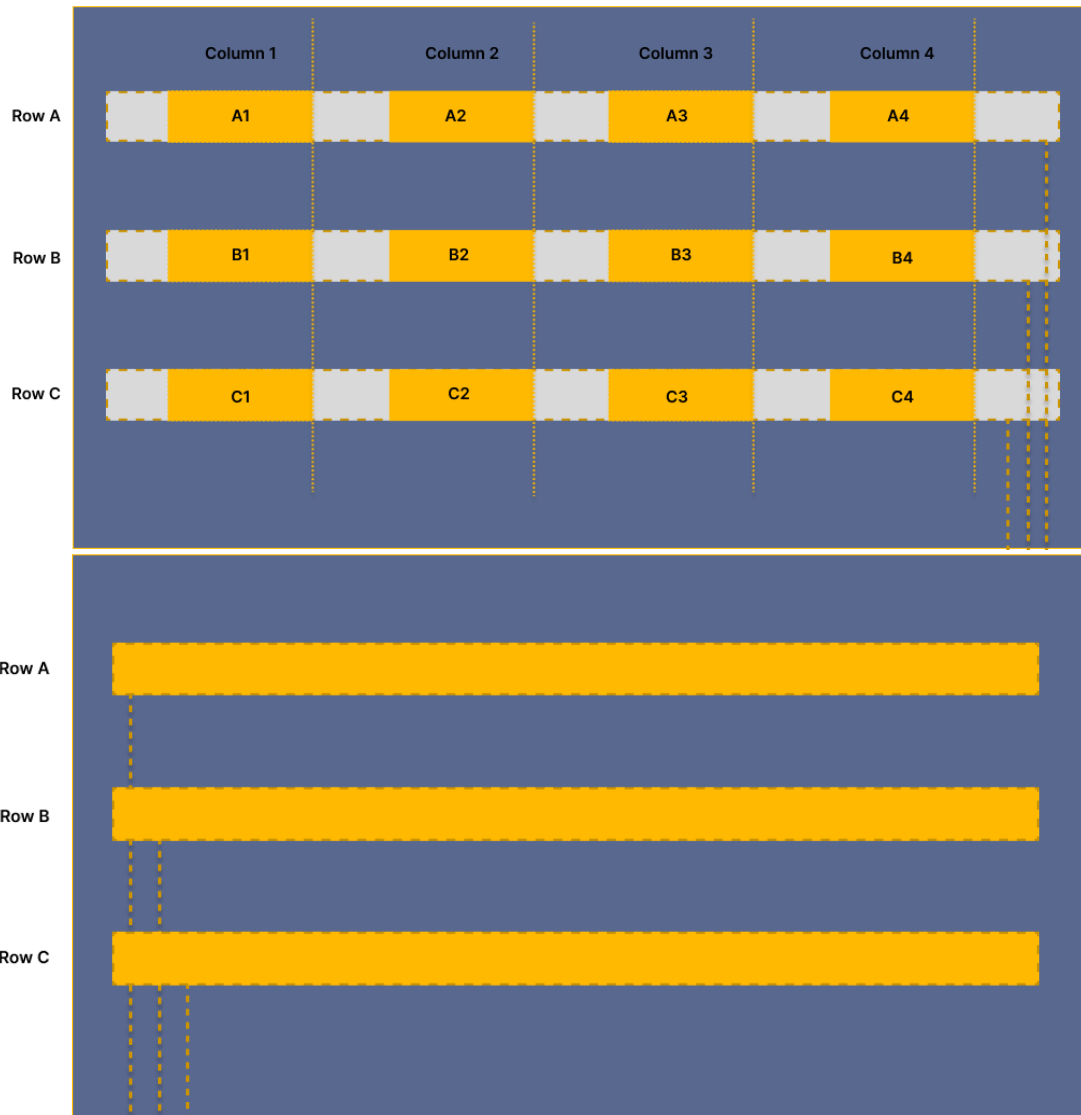


FIGURE 71: SCHEMATIC DESIGN FOR THE DEMONSTRATOR – FRONT (ABOVE) AND BACK (BELOW)

The hypothesis of connecting the sensors in series, is that due to the distance the current has to travel to each connection point, there would be a difference in resistive value between the sensor closest to the output and the farthest. Since the electrical current has to flow through more length of electrode yarns, sensor A1 would have an overall higher resistive value than C4 in both inactivated and activated state.

To verify that the sensors are able to function well, the demonstrators will also undergo pressure testing. Testing is done by placing each individual sensor of the fabric in turns under the presser foot of the Rheometer and connecting the ends corresponding to the sensor to the DAC in- and output. Figure 72 shows how the current would flow through the fabric, when compressing one sensor.

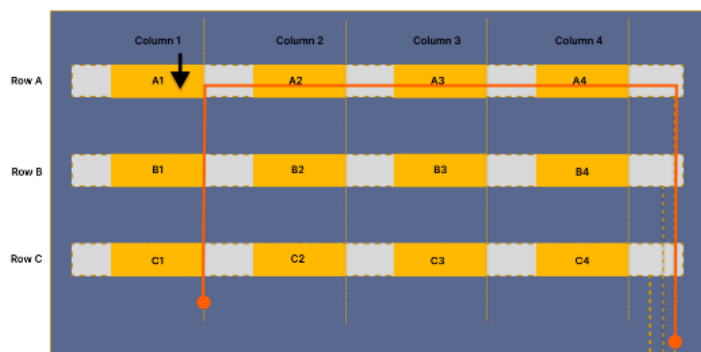


FIGURE 72: SCHEMATIC OF THE CURRENT FLOWING THROUGH THE FABRIC WHEN A SENSOR IS ACTIVATED

Comparable to how all iterations of sensors were tested, only for the demonstrator it is necessary to level the fabric evenly.

## 7.2 Prototyping

### 7.2.1 Demonstrator 1: Placing the sensors in series on a fabric

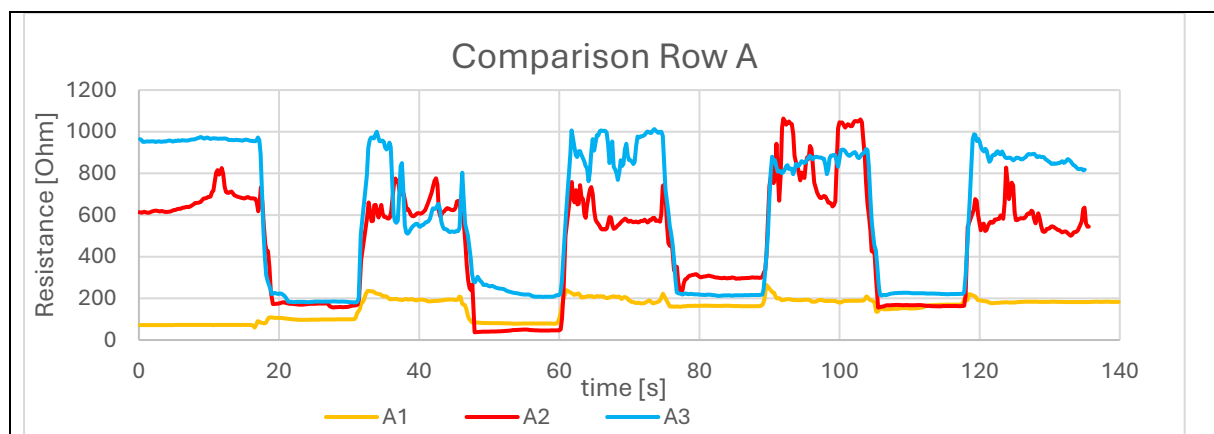
The first demonstrator (Fig. 73) was made by continuously weaving with four separate shuttles of conductive yarn. Weave diagram and Map of Bindings of this demonstrator are found in Appendix C. After each row of sensor was finished, a few rows of compound weaving with cotton were woven. After which the same shuttles of conductive yarn for both the upper electrode layer and bottom electrode layer were used again.



FIGURE 73: DEMONSTRATOR 1

Initial testing showed that it is unfavourable to have the bottom electrode layer connected in series. So later the floats were cut to allow for each row to have the bottom layer free from interference from other rows.

The test results (Fig. 74) show a large difference in overall resistive values between Row A and the other rows. It is difficult to discern what the cause of this phenomenon is. One explanation could be that through human error some of the rows were not woven properly. The floating conductive yarns could also interfere with the sensors being able to create a consistent signal. This conclusion can be drawn from the fact that Row C, the most bottom row, has a fairly consistent graph, which could be because the current flows more directly to the sensor.



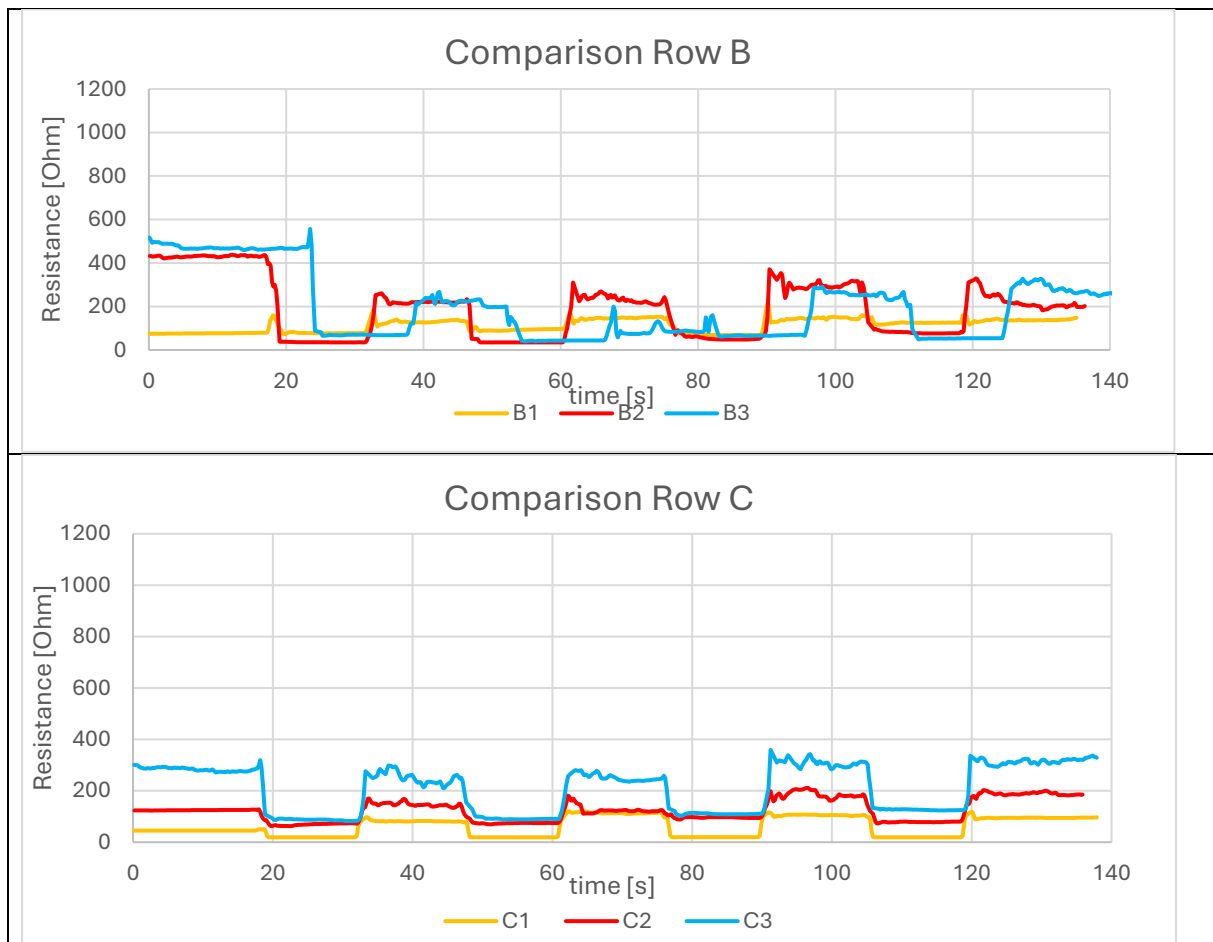


FIGURE 74: TEST RESULTS DEMONSTRATOR 1

Good quality of this sensor is the structure of the sensor and the surrounding fabric looks secure and has embedded the sensor seamlessly in the fabric. Though not consistent, the output signal of most of the sensors show good Resistance ratio and repeatability.

Areas of improvement are removing the floats and making the sensors more recognizable as the colour of the conductive yarn does not communicate effectively that it is a sensor. Aside from that the output signal of the sensors should be more consistent and preferably in the same range of resistive value.

### 7.2.2 Demonstrator 2: Placing the sensors in parallel

The following demonstrator has the sensors placed in parallel, meaning the individual sensors are not connected through the same conductive thread each column (Fig. 75). This method ensures that each individual sensors signal are optimized by creating more direct connections to the current, however it also creates more threads for connection, which is not preferable when used in a product. This is because more connections makes a system more unnecessarily complicated. A decision was made to deviate from the original design to test whether a sensor in a woven matrix would still behave as an individual sensor. The weave diagram and Map of Bindings for this demonstrator are found in Appendix D. Due to the connections otherwise not fitting, this demonstrator has only two rows as compared to the last. This creates a 4 by 2 matrix of woven sensors (Fig. 76).

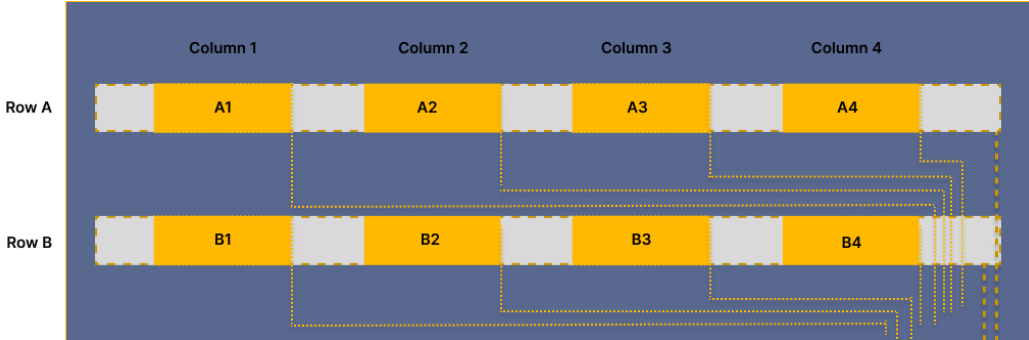


FIGURE 75: SCHEMATIC DESIGN DEMONSTRATOR 2



FIGURE 76: DEMONSTRATOR 2

The test results (Fig. 77) show an improvement in the sensors' overall resistive value. However, the output signal still shows some noise, especially at the return value.

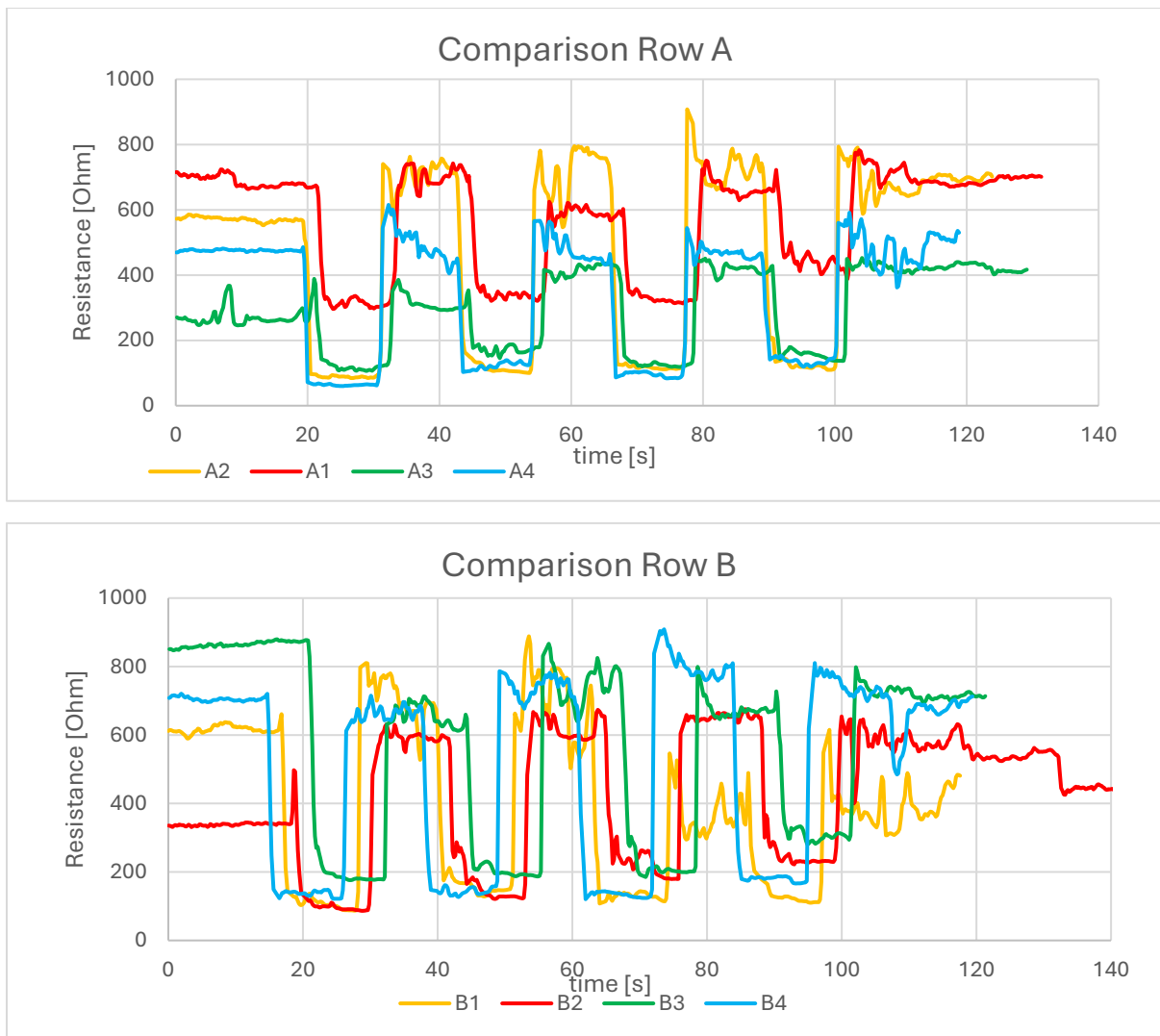


FIGURE 77: TEST RESULTS DEMONSTRATOR 2

Good qualities of this demonstrator is that separate connections to each individual sensor make it easier to differentiate between sensors. Aside from that the increased resistive value range also give more freedom to map the signal to a programmable code.

Disadvantages are that this design is not scalable to more sensors in a fabric, it is unrealistic to weave in more of the loose conductive threads of these separate connections. More separate connections also makes it complicated to connect the ends to electrical hardware and for some boards impossible, because they would not have enough input slots.

### 7.2.3 Demonstrator 3: Final prototype

For this demonstrator, the decision was made to return to the original design. As previous demonstrations have shown, weaving the sensors in parallel and series did not improve the sensor signal. Therefore, the decision was made to weave the sensors in series again, arranged in the fabric as a 4×3 matrix. The weave diagram and Map of Bindings for this demonstrator can be found in Appendix E.



FIGURE 78: DEMONSTRATOR 3

In this version, the sensors are spaced further apart, and the long floats between sensors are more neatly integrated into the fabric (Fig. 78). The same principle applies where the sensors in each column are connected by one continuous electrode yarn, in the upper electrode layer. For each row, all sensors share one long horizontal bottom electrode layer. Additionally, the sensors are once again woven with red borders around them, making them more recognizable within the fabric.

For full data see Appendix XX.

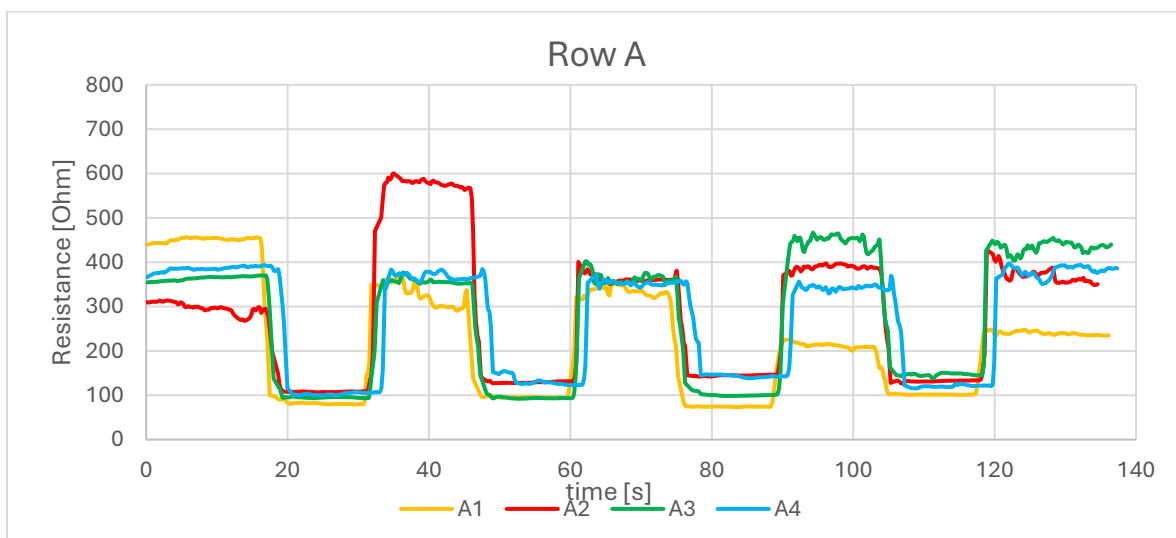




FIGURE 79: TEST RESULTS DEMONSTRATOR 3

As shown in the test results (Fig. 79), one of the main strengths of the sensor is its very good repeatability and recovery. There are clear, distinctive U-shaped graphs for all rows. The only exception is that rows B and C also show a clear difference between individual sensors in value, making them easier to program.

A disadvantage of this fabric is that while assessing the recovery, the sensors still exhibit some noise in the return values. For example, C3 shows the most consistent graph, with return value at 325 Ohm. However this is the only example, of the twelve sensors, as for example C2 shows an increase in return value after every compression cycle. C1 also shows several small peaks instead of a flat line, where the peaks create a standard deviation of 150 Ohm.

For row A, the recovery is initially perfect. However, after the first few cycles, it begins to shift.

These are relatively minor issues that could be addressed with further research, which is recommended and discussed in Chapter 8.

## 7.3 Programming device

### 7.3.1 Electronics

To demonstrate how a fabric with woven pressure sensor can work, a user test setup where there is visual feedback for the sensor input is a possibility. The demonstrator's design consists of the following electrical components:

- Arduino board (Fig. 80)
- 3 connections for input, one for each row
- 3 resistors to allow calculation of total resistive values
- 4 connections output, one for each column
- Breadboard

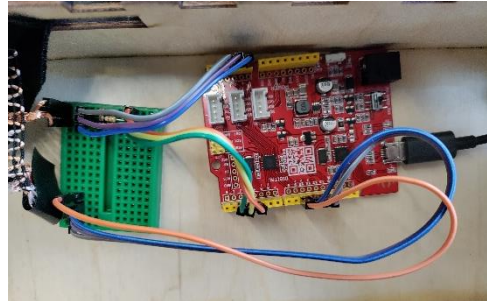


FIGURE 80: PICTURE OF ELECTRONICS CONNECTED TO ARDUINO

Appendix F shows the schematic of how the sensors are connected to the breadboard.

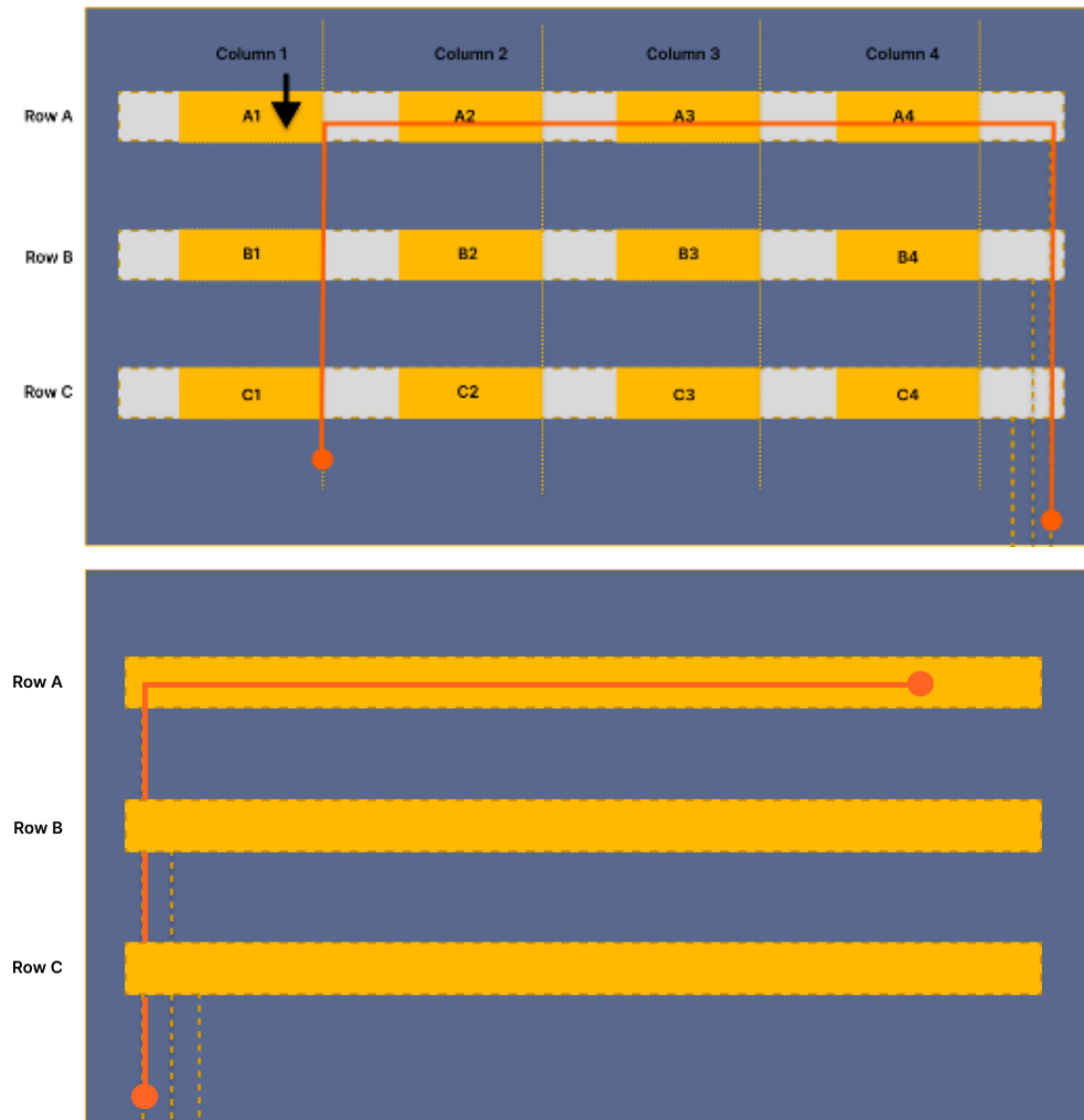


FIGURE 81: SCHEMATIC OF CURRENT FLOWING THROUGH DEMONSTRATOR WHEN ACTIVATED

The setup is programmed to input the current through the three bottom electrode layers. When a sensor is pressed it will flow through the column of said sensor back to the Arduino (Fig. 81). From that output a signal can be read and through processing in the code it can be determined which sensor in the column is being compressed.

### 7.3.2 Software

The software written for the demonstrator consists of an Arduino script and a Processing code.

The Arduino script reads the data signals from the demonstrator fabric and writes it into a set of 12 values, corresponding to each sensor (Appendix G).

With the add-on software Processing, these 12 values can be mapped to influence a video simulation. For this particular demonstrator the decision was made to create a set of coloured dots, that each can be shaped by pressing a sensor (Fig. 82).

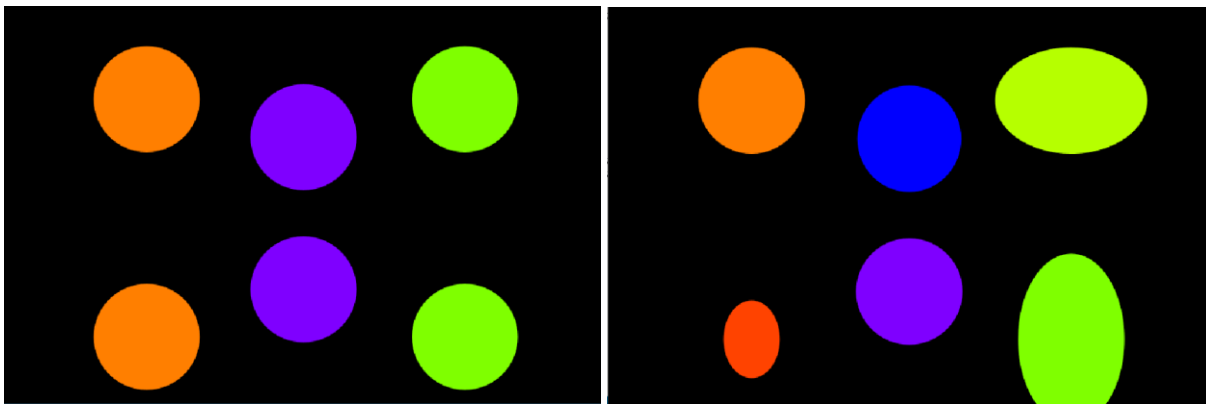


FIGURE 82: SCREENSHOT OF PROCESSING VISUALISATION IN NON-ACTIVATED STATE (LEFT) AND ACTIVATED (RIGHT)

Since the sensors are connected in series, whenever the output of one sensor is measured at any times other sensors can affect the data that is read. Pressing multiple sensors at the same time or another sensor that is not being measured will create noise in the data. This is noticeable in the simulation whenever a sensor is pressed, only one dot on the screen is meant to deform, however randomly others will also react.

## 7.4 Senzhi

The completed system will continue to be referred to by the name: Senzhi. The name is derive from the word "sense" and the Chinese character of weaving "zhi". Just as the qualities of the sensing and the fabric being woven are intricately intertwined, so are these verbs to create a new term.



FIGURE 83: SENZHI

Senzhi is a system that consists of a fabric with integrated woven pressure sensors, which is programmable via Arduino to interact with a digital interface (Fig. 83). The working principle of the woven sensor is again explained in Figure 84, to highlight how fully integrated the pressure sensor is in the fabric.

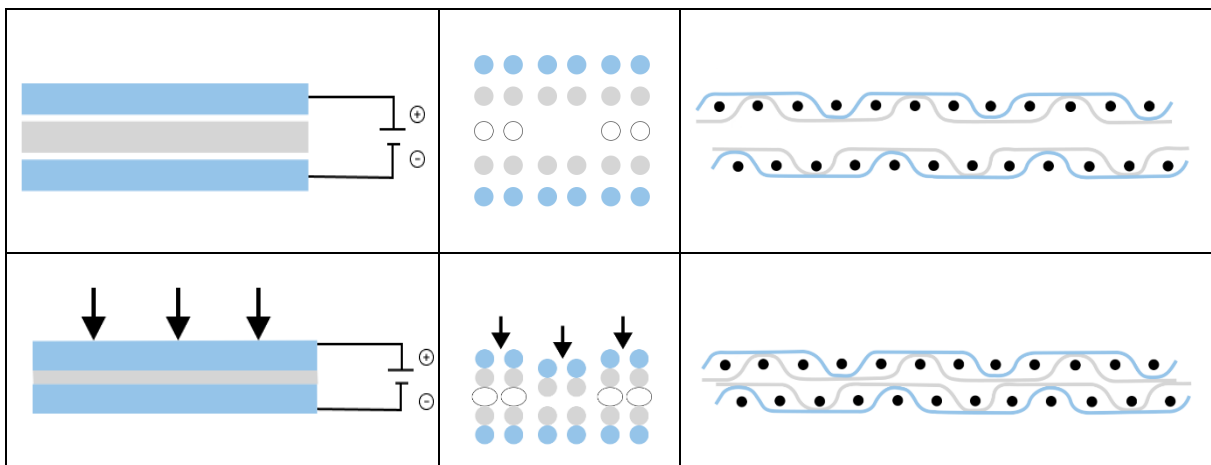


FIGURE 84: SCHEMATIC SHOWING THE WORKING PRINCIPLE OF A WOVEN SENSOR, SIMPLIFIED (LEFT), YARN COMPOSITION (MIDDLE) AND WARP CROSS-SECTION (RIGHT)

## 7.5 Evaluation

### 7.5.1 User testing

The purpose of testing the demonstrator with human participants is to discover and determine its experiential qualities. Understanding how woven sensors are perceived on a cognitive level is important to identify, which possible user contexts it can be applied to.

The test will consist of two phases, during the first phase the user is observed while interacting with the demonstrator. Observations are important to obtain knowledge on their perfunctory emotional response. When designing to enhance emotions and allow the product to connect to the user through intuition a product must address three levels of cognitive responses: Visceral, Behavioural and reflective. (Norman, 2005) Of these levels, in the woven sensors, current developmental state, the most relevant is visceral. This term embodies the sensory qualities and relates to the users immediate responses, which are involuntary and subconscious. Only in later stages when the sensor's are incorporated in a larger user context, for example as part of a working consumer product, can the user engage behavioural and reflective.

It is a deliberate choice to give the participant as little information about what the demonstrator does before the interacting with it. This is done to encourage the users visceral responses. By deliberately not telling how the fabric with sensors relates to the visualization on screen will create ambiguity of information (Gaver et al., 2003). This means the user is required to fill in the incomplete information with their own interpretation and formulated expectations.

In turn it will encourage the user to think more extensively about the demonstrator for the second phase, which is a short interview. The user is asked to review how they interpret the relation between the sensor and the visualization on the screen. Ambiguity of information will motivate the user to think about this during the interaction. The user is also asked to come up with a possible implementation for a fabric with integrated sensors, which requires the user to use their imagination.

### 7.5.2 Method

After signing the informed consent form (Appendix H), the participant first takes place at a table with the sensor laying in front of them. Then they get a short introduction to the test.

Introduction script:

*"Thank you for your willingness to participate in this user test. Before you lies a patch of fabric embedded with pressure sensors, you are allowed to interact with it however you like. When interacting you can do no wrong as there is no right or wrong. You are asked to think out loud for the duration of the demonstration."*

After the introduction, the participant is allowed to interact with the fabric for the duration of 2 minutes. This interaction is filmed to retain their dialogue when thinking out loud and to connect that dialogue to their actions. Said actions that are most interesting to observe are how they interact with the fabric and what remarks they have when they notice interaction with the visualization on screen.

After the 2 minutes have passed, the participants are asked to answer the following interview questions:

1. How clear was it that interacting with the fabric influences what happened on screen?
2. How do you think the sensors on the fabric influence the visualization on the screen?
3. In what kind of context do they imagine this type of fabric to be used?

### 7.5.3 Results

#### Observation

Below is a table of all interactions with the fabric and how many participants performed said action.

TABLE 3: USER TEST RESULTS – OBSERVATION OF ACTIONS

Action	Amount of users who performed this action
Pressing with one finger	4
Pressing with whole hand	4
Dragging finger along the fabric	4
Rolling the fabric	3
Wringing	1
Flipping over	1
Lift it up	4
Repeatedly pressing one sensor	2

One remark shared by two participants is “one (sensor) is more sensitive than others”. Other than this another notable remark is that the visualization behaves differently depending how the fabric is folded on itself.

#### Interview

For the first question “How clear was it that interacting with the fabric influences what happened on screen?” all participants remarked that it became clear quickly that the fabric would influence how the dots moved on the screen. Though two participants commented that due to a few individual sensors responding less, they doubted the effect on the visualization a little.

For the second question “How do you think the sensors on the fabric influence the visualization on the screen?” all participants noticed that the visualization changed the shape of the ellipses, and noted that the size and colour of the ellipses would change.

Only one of five participants (User 4) noticed that pressing the sensors would lengthen or widen the ellipses on the screen. They observed the pattern during the demonstration and in the interview mentioned that “some blobs were very wide and some became thin”.

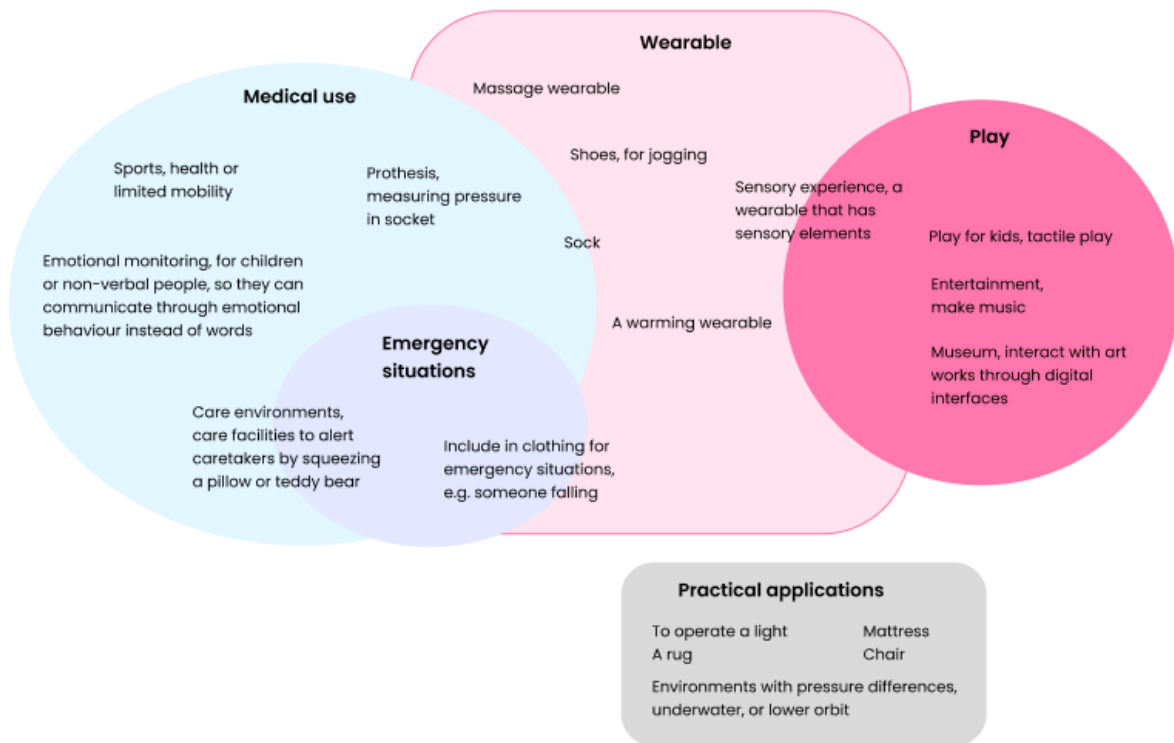


FIGURE 85: INTERVIEW ANSWERS OF SUGGESTIONS FOR APPLICATIONS OF THE WOVEN SENSOR FABRIC

The last question “In what kind of context do they imagine this type of fabric to be used?” brought about many suggestions by the participants. Figure 85 shows all these suggestions categorized by themes. These themes will be further utilized to formulate recommendations in Ch. 8.2.3 Applications. The complete annotation of the observation and interview results can be found in Appendix I.

#### 7.5.4 Conclusion of the user test

The results indicate that participants quickly understood that interacting with the fabric affected the on-screen visualization. All participants recognized the connection between their actions and the movement of the dots and the transformation of the ellipses, suggesting that the interaction is generally intuitive. However, some uncertainty arose due to inconsistent sensor sensitivity, as two participants noted that certain sensors appeared less responsive than others. This occasionally led participants to question whether their actions were being fully registered by the system.

In terms of physical interaction, participants naturally explored the fabric through a variety of gestures. Pressing with one finger, pressing with the whole hand, dragging along the fabric, and lifting the fabric were performed by all users, indicating that these actions feel natural when interacting with a textile interface. More complex manipulations such as rolling, wringing, or flipping the fabric occurred less frequently, suggesting that users initially rely on simpler and more direct interactions.

Participants were generally able to identify how their interactions influenced the visualization, particularly noticing changes in the shape, size, and colour of the ellipses. However, only one participant recognized the more specific relationship between pressing sensors and the widening or lengthening of the shapes. This suggests that while the overall effect of the interaction is clear, the precise mapping between sensor input and visual output is not immediately obvious.

Overall, the prototype successfully communicates the basic interaction between the fabric and the visualization, but improvements in sensor consistency and clearer feedback could help users better understand the specific relationships between their actions and the resulting visual changes.

## 8. Discussion

### 8.1 Limitations

#### 8.1.1 Technical limitations

Because there are many interacting elements within a woven sensor, it is difficult to determine the exact cause of errors in the results. When analysing and designing new weave structures, efforts are made to isolate as many factors as possible to ensure that the correct parameters are being tested. However, despite these efforts, numerous variables still influence both the weaving and testing processes. This is particularly true for hand weaving, where the process introduces additional variability and leaves considerable room for human error.

Though the sensors work well individually, it is difficult to determine how the sensors work in a matrix integrated into cloth.

Firstly, the demonstrator's test result still show inconsistent normal resistive value. There is some noise in the normal resistive value  $R_0$  and the return values following. In some graphs the average standard deviation stands at 150 Ohm. This makes it harder to program a threshold for the sensors in the code.

Secondly, the sensors affect each other when connected in series. The upper electrode layers are all connected through one continuous electrode yarn. This continuous connection could impact the effectiveness of the individual sensor in several ways, the electrical current travels through all these sensors. All sensors in a row are also connected through the bottom electrode layer. Which is also woven with one continuous electrode yarn. This larger area of sensor electrode layer increases the risk of discrepancies and errors.

Lastly, the inherent architecture of the fabric system makes it difficult to map the signals. The Arduino code can only read from three data points of the fabric as there are three rows. Increasing the amount of sensor per row would complicate the code as it has to create a matrix of the signals read. More signals coming through per row would mean more signals coming through per data input, which would require more expert knowledge to program.

#### 8.1.2 Materials

During the prototyping rounds, it became apparent that the optimal materials were not always available for certain sensor designs. For instance, when working with elastic yarns, there are very few commercially available options made from 100% elastane. The only available example has a very thin diameter, while thicker elastic yarns are typically blended with polyester. These blended yarns are less desirable, because the polyester fibres are not elastic and therefore reduce the overall elastic properties of the yarn. However, since these are the only options readily, they had to be used in this project.

Another limitation concerned the efficiency of the devices and techniques used during production. The sensors were woven on a TC2 digital jacquard loom that is 72 cm wide, while each sensor only occupied approximately 2 to 3 cm of that width. As a result, producing a single sensor required setting up and weaving across a much larger width than necessary. This process not only increased the time required for each iteration but also resulted in a considerable amount of unused or scrap material.

### 8.1.3 Time span and planning

Within the 100-day timeframe of the master's thesis, it was possible to develop only nine iterations of the woven sensor before moving on to the demonstrator stage. The time required to develop a functioning sensor consequently left limited time for the development of a larger, fully realized demonstrator. This limitation was partly the result of ineffective planning and personal circumstances. However, it also stemmed from the initially broad scope of the thesis, which required significant time to narrow down and focus on specific directions.

## 8.2 Recommendations

### 8.2.1 Further research

When considering the transition to an automated industrial loom process, it is important to account for the fact that such looms typically cut threads at the edges rather than allowing them to remain continuous throughout the fabric. This must be taken into consideration when designing the electrode layers of the sensor, as continuity of conductive pathways may be affected. A potential recommendation is to replace the standard warp threads with conductive yarns to maintain electrical functionality within the structure.

In addition, industrial textiles generally undergo a finishing process to stabilize the fabric and ensure that the fibres remain in place. While this improves durability and handling, it may also influence the performance of the sensor. Therefore, the impact of finishing treatments on sensor functionality should be further evaluated.

Furthermore, washability testing is an important aspect to consider. Assessing the durability and performance of the sensor after washing will provide insight into its practical applicability.

Finally, further experimentation with a wider range of materials is recommended. Exploring different yarn types and material combinations may lead to improvements in performance of the sensor.

### 8.2.2 Potential follow-up research factors

Despite the progress made in the development of woven pressure sensors during this project, several factors remain unknown and require further research. These unresolved aspects highlight where additional experimentation could lead to performance improvements or new design possibilities.

Some potential solutions have not yet been tested, primarily due to limitations in time and available resources. One such area involves experimenting with different conductive yarns. Variations in material composition, coating, or resistance could influence sensor sensitivity, signal stability, and durability. Systematically comparing alternative conductive yarns may reveal options that enhance performance or mechanical compatibility within the woven structure.

Similarly, the use of different resistive yarns remains an open subject for exploration. Since resistive yarns play a crucial role in pressure-sensing mechanisms—particularly in piezoresistive designs—they directly affect sensor accuracy and repeatability. Testing alternative resistive yarns could improve resistance ratio, sensitivity range, or recovery.

Another unexplored factor is the implementation of larger conductive surface areas within the fabric. This may improve pressure distribution, and overall signal uniformity, especially in applications

requiring large-area sensing. However, such modifications may also introduce new challenges related to, signal interference, increased chance of short circuiting, or structural rigidity.

Another limitation encountered during this project was the restricted availability of suitable elastic yarns. All commercially available elastic yarns identified during the research period consisted of a blend of elastane combined with polyamide (PA). The addition of PA increases the overall yarn diameter and reduces the elastic performance compared to pure elastane. For the intended sensor construction, a 100% elastane yarn with a diameter comparable to that of Shieldex would have been preferable, as this could have provided improved elasticity without unnecessarily increasing bulk.

Finally, the substitution of warp yarns represents another relevant area for further research. The loom used in this study had been pre-warped with mercerized cotton and was shared for multiple purposes, making it impractical to rearrange or replace the existing warp configuration. The possibility of replacing the mercerized cotton warp with conductive yarns was discussed. Such a modification could potentially enable the weaving of larger continuous electrode surfaces, thereby quickly expanding the functional sensing area and offering new structural design possibilities.

Overall, these unknown factors represent promising directions for future research and optimization, with the potential to significantly refine the performance and scalability of woven pressure sensor systems.

### 8.2.3 Applications

#### *Senzhi clothing*

During the user testing results, wearable applications were often mentioned (Ch. 7.5.3) with some applications related to medical use or integration in clothing. This is why the following application is presented as the Senzhi shirt and Senzhi shorts (Fig. 86). The sensor elements are incorporated into the back side of the clothing, as it gathers data of the wearers sitting posture.



FIGURE 86

### *Senzhi bear*

To enhance product experience, this design is an attempt to connect technology to the human emotion. This can be done by shifting the purpose of technology from function to meaning, and to create an object that has less emphasis on what it can do to what the user interprets what it can do.

Hassenzahl defines three aspects of experiential design, Why, What and How. To define these three aspects for a woven pressure sensor is entirely different than defining them for a teddy bear. Still they can be one and the same. Touch is a very intimate act, especially in healthcare contexts where physiology already is a major factor. The design of the Senzhi bear (Fig. 87), allows a new way to collect data through touch without presenting the patient with even more medical products.



*FIGURE 87. SENZHI BEAR*

## 9. Conclusion

The aim of this research was to explore the design, development, and integration of woven pressure sensors within textile structures, culminating in the creation of a functional demonstrator system. Through iterative prototyping, material experimentation, and structural refinement, this study has shown that it is possible to successfully embed responsive and programmable sensing capabilities directly into woven fabrics.

The key findings demonstrate that the performance of woven sensors is highly dependent on both structural and material parameters. Adjustments such as elongating the sensor pattern across the weft, removing unnecessary interlacement yarns, selecting yarns of equal diameter, and optimizing electrode layer geometry significantly improved sensor stability and resistance ratio. In particular, the introduction of paired twill structures proved to be a critical advancement, resulting in tightly packed electrode surfaces and a more secure and consistent sensor architecture. These refinements collectively enabled the development of a sensor with strong performance metrics, including a high resistance ratio of 64%, excellent recovery, good repeatability, and notable sensitivity to incremental force changes.

Beyond individual sensor performance, this research also addressed the challenge of scaling sensors into a functional textile system. The development of three demonstrators highlighted the trade-offs between electrical performance, structural integration, and system complexity. While parallel configurations improved signal clarity, they proved impractical for scalable textile integration due to the increased number of connections. Conversely, series configurations offered a more feasible approach for embedding multiple sensors within a fabric, although they introduced challenges such as signal interference and reduced precision in sensor mapping. The final demonstrator, *Senzhi*, represents a balanced solution, successfully integrating a 4×3 matrix of sensors into a cohesive textile interface that can interact with digital systems in real time.

User testing further validated the potential of woven sensors as intuitive and interactive interfaces. Participants naturally engaged with the textile through familiar gestures such as pressing, dragging, and folding, and quickly understood the relationship between physical interaction and digital response. However, inconsistencies in sensitivity and signal noise occasionally reduced clarity, indicating that further refinement is needed to enhance reliability and user experience.

Despite these promising outcomes, several limitations remain. Variability in resistive values, interference between interconnected sensors, and constraints in data acquisition highlight the need for improved electrical isolation and more advanced signal processing methods. Additionally, material limitations and the constraints of the weaving process impacted the range of achievable designs.

In conclusion, this research demonstrates that woven pressure sensors are a viable and compelling approach for creating interactive textiles. By integrating sensing functionality directly into the fabric structure, the *Senzhi* system illustrates the potential for textiles to act as responsive interfaces. While further development is required to address current limitations, the findings provide a strong foundation for future research and open up new possibilities for applications in wearable technology, healthcare, and interactive design.

## Last remarks

I would like to take this opportunity to mention that this research was not performed under the best circumstances of my life. The process tenuous and were it not for external factors, I may have had delivered different results. Nonetheless, I believe that the results shown in this report contain valuable knowledge to push forward research in woven textile technology. I would like to say that enduring and persevering through the circumstances and still being able to deliver these results shows strength and I hope this will inspire future researchers to push through difficult times.

## Acknowledgements

I would like to thank Kaspar Jansen and Holly McQuillan for their guidance and support during this graduation project. Their expertise, knowledge and patience have given me the opportunity to learn many new skills and improve upon my already existing knowledge. Working with you both has been a joy and a privilege, which I am incredibly grateful of. At times I felt that we had more of a partnership dynamic than that of supervisors and supervised, which was exactly what I needed to work through this project.

I would further want to thank the staff of Applied labs for providing valuable technical support to this project. Special thanks to Adrie Kooiman for assisting in the Arduino code and providing the blueprint for Senzhi. And special thanks to Tim de Jong, for assisting in writing the Processing code and repairing the TC2.

I would also like to thank my fellow Applied labs graduation students, for providing me with laughter and sympathy. Revelling together during our shared struggles has inspired me to continue working with a positive mindset.

Last of all, I would like to thank my friends for being the greatest support I could wish for and putting up with my many antics.

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## Appendix A: Glossary

Jacquard – technique of weaving where heddles move independently

Resistance ratio – measured difference in resistive value as a percentage of the total resistive value of a sensor

Hysteresis – a phenomenon of noise and inconsistency in a graph of resistance over time

Tabby/plain weave – weave diagram of interlacing warp and weft

Twill – weave diagram of interlacing warp and weft in a diagonal pattern

Satin – weave diagram that leaves long weft floats

Electrode yarn – conductive yarn with a low resistive value

Resistive yarn – conductive yarn with a high resistive value

Warp – Vertical spun yarn in a loom

Weft – yarn that is inserted horizontally during weaving

Interlacement – crossing yarns that keep the structure in place

Float – a length of yarn that extends over interlacements

Map of bindings – a color coded map that is used in Adacad to generate a Bitmap

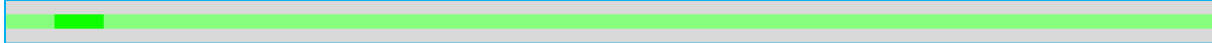
Bitmap – an image made up of pixels, each pixel representing a warp or weft yarn, used in the TC2 to weave fabrics

TC2 – Thread Controller 2, a digital jacquard loom

# Appendix B: Weave diagram and Map of Bindings

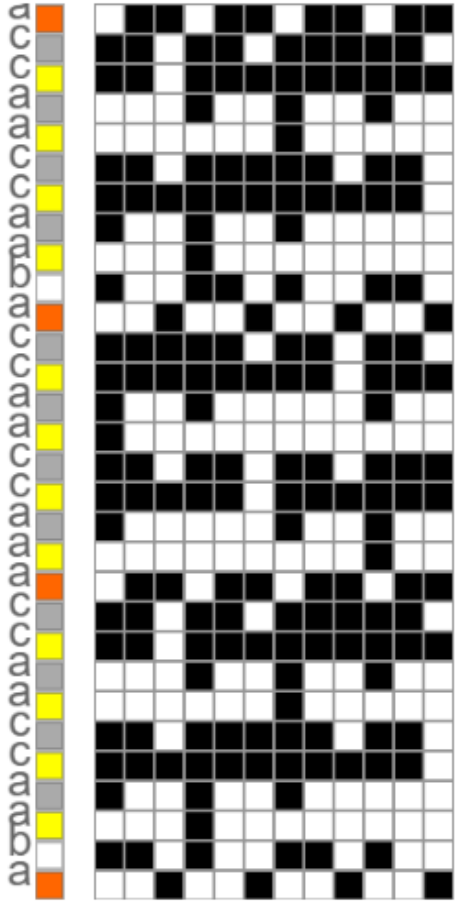
## 9.1 Round 1

MOB



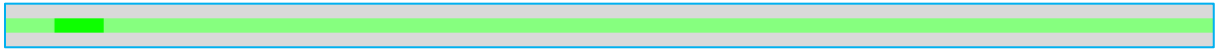
Diagram

Sensor (Bright green)



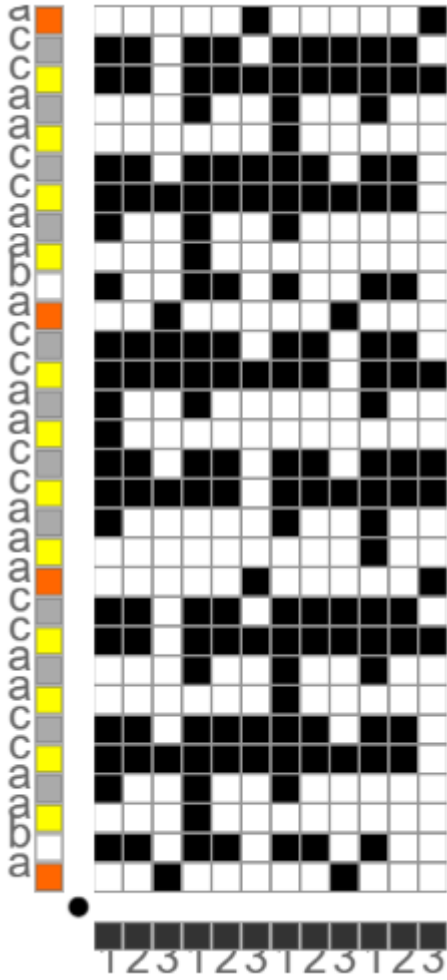
## 9.2 Round 2

MOB

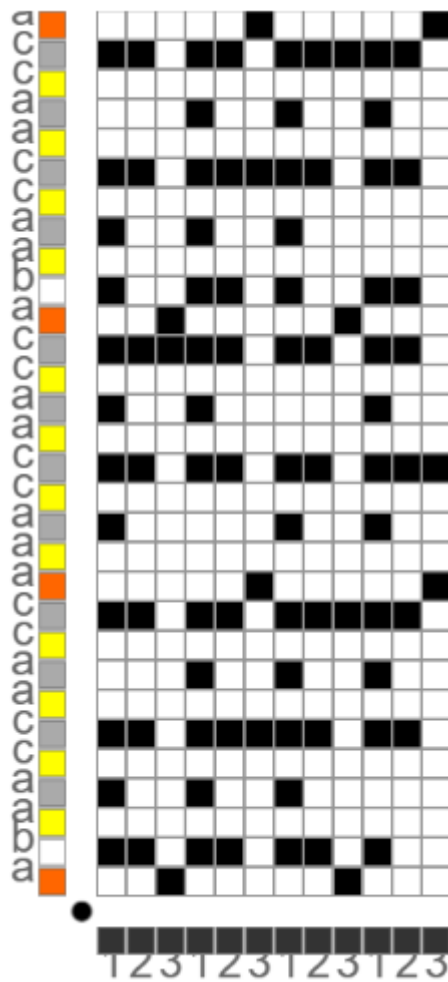


Diagram

Sensor (Bright green)

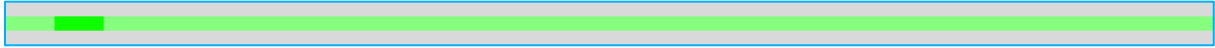


Sides (Pale green)



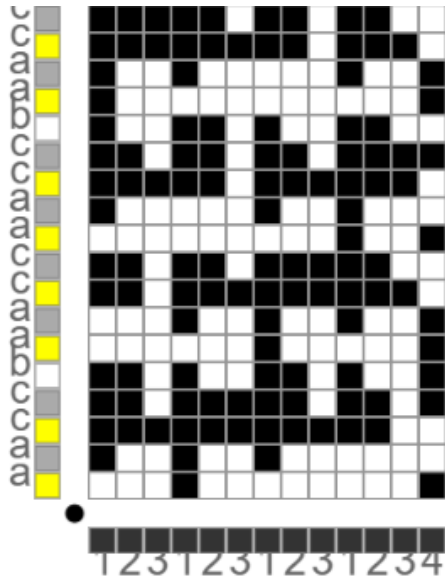
### 9.3 Round 3

MOB



Diagram

Sensor (Bright green)



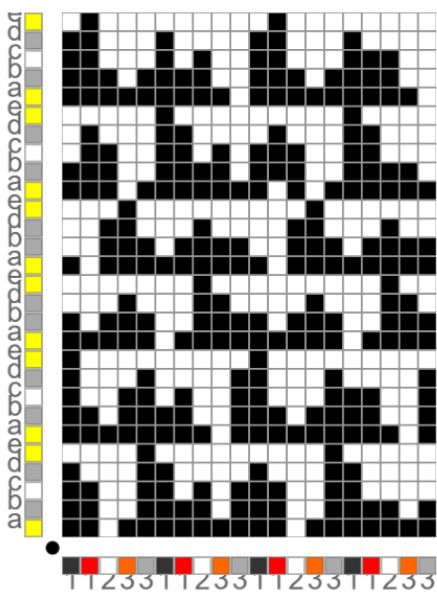
### 9.4 Round 4

MOB

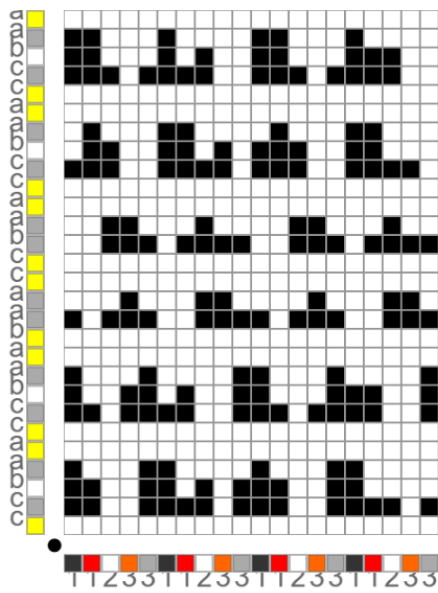


Diagram

Sensor (Red)



Sides (Orange)



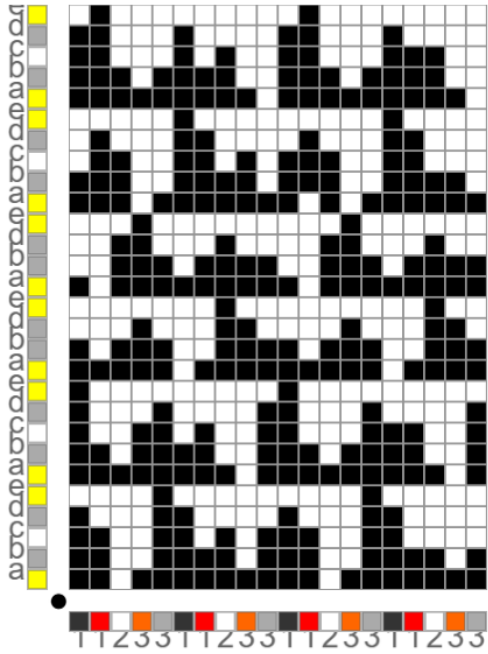
## 9.5 Round 5

MOB

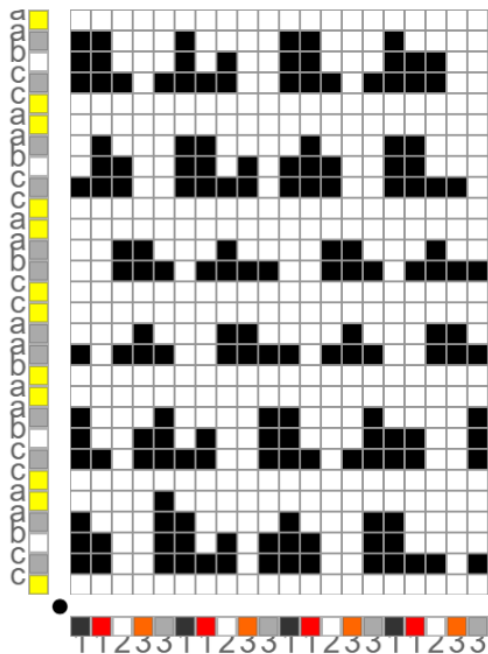


Diagram

Sensor (Red)



Sides (Orange)



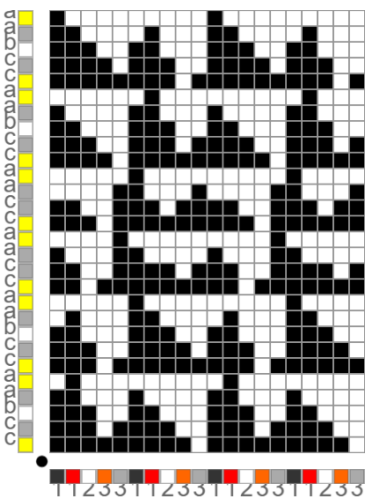
## 9.6 Round 6

MOB

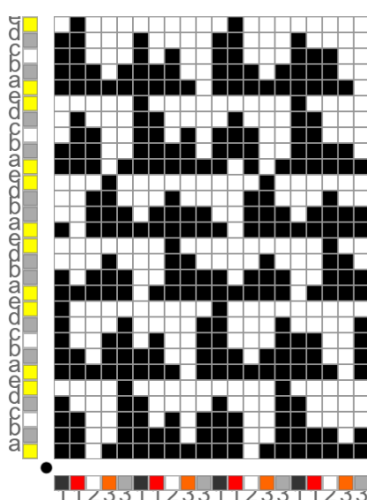


Diagram

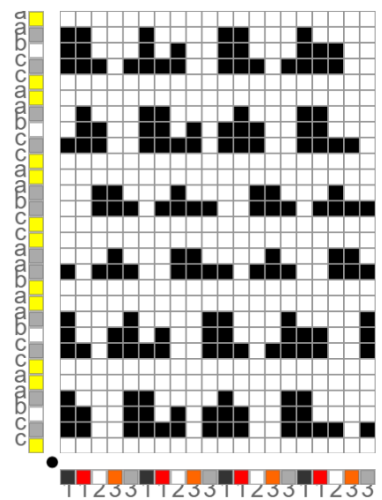
Sensor (Red)



Bottom sensor (Blue)



Sides (Orange)



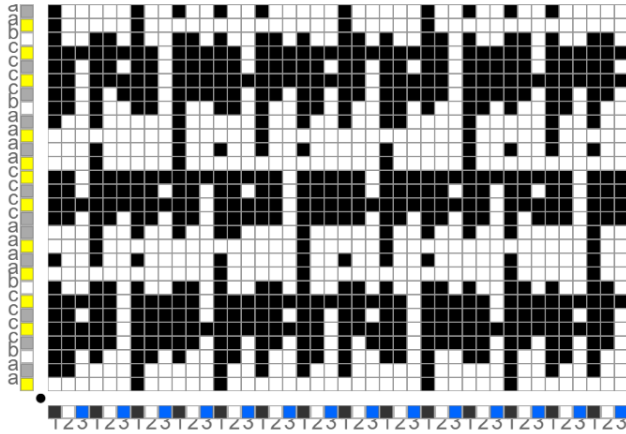
## 9.7 Round 7

MOB

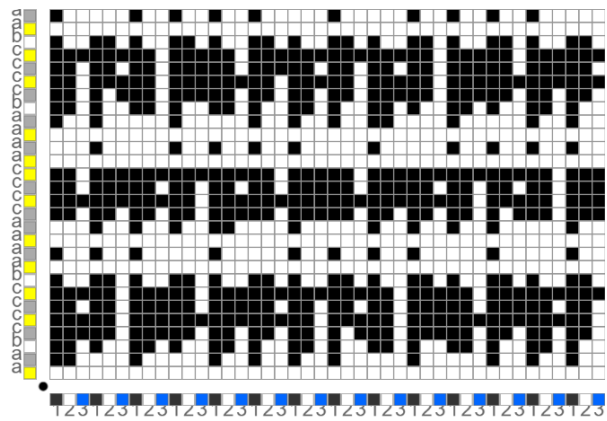


Paired satin

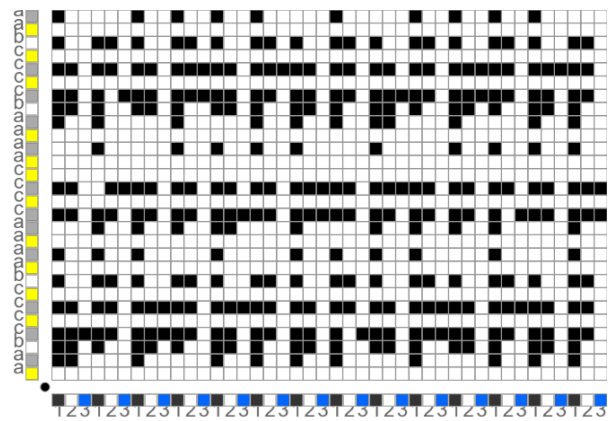
Sensor (Red)



Bottom sensor (Blue)



Sides (Orange)



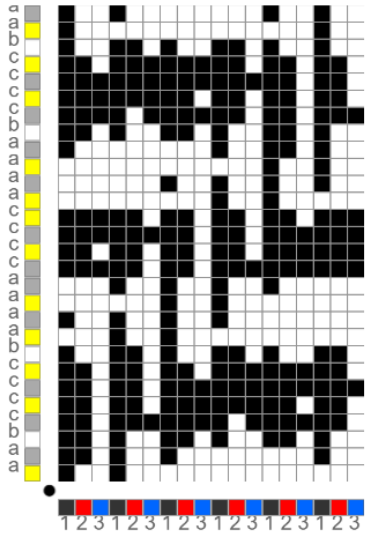
## 9.8 Round 8

MOB

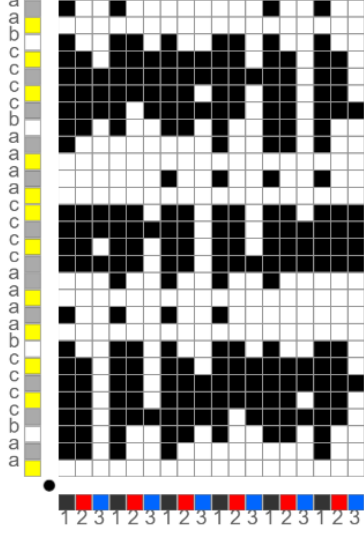


Paired twill

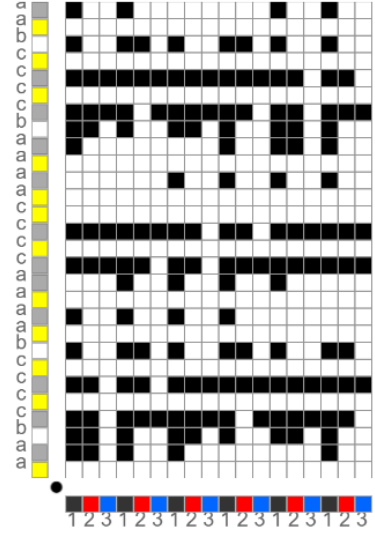
Sensor (Red)



Bottom sensor (Blue)



Sides (Orange)

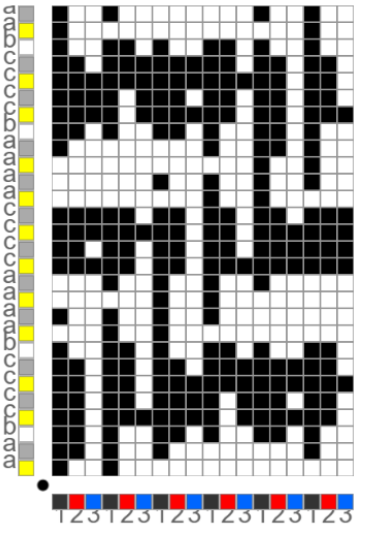


## 9.9 Round 9

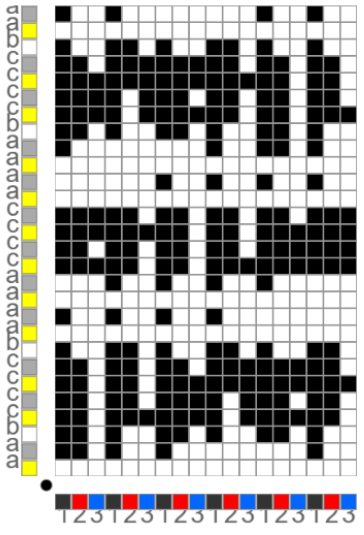


Paired twill

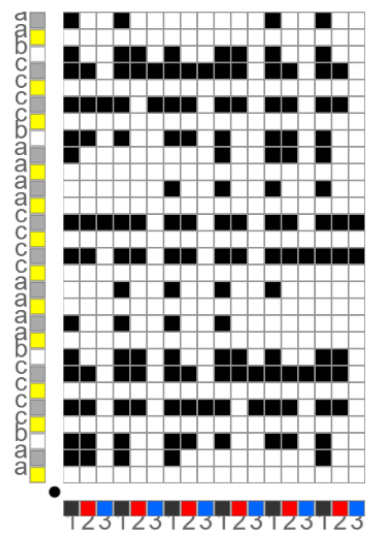
Sensor (Red)



Bottom sensor (Blue)



Sides (Orange)

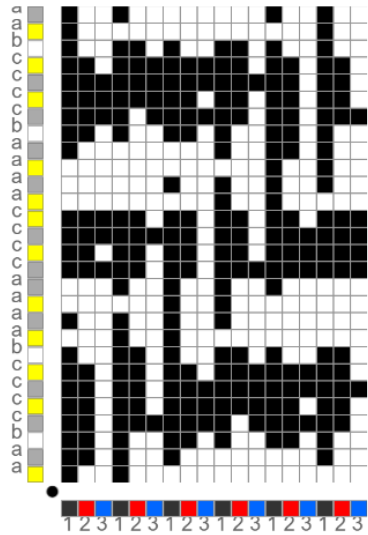


# Appendix C: Demonstrator 1

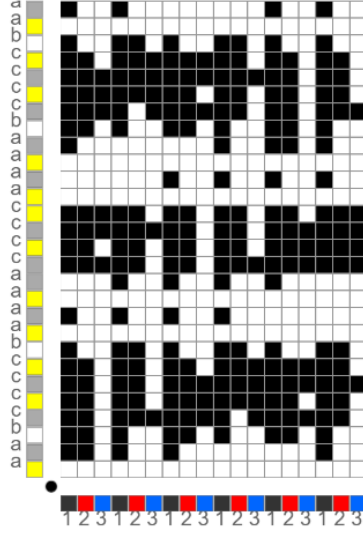
Map of bindings



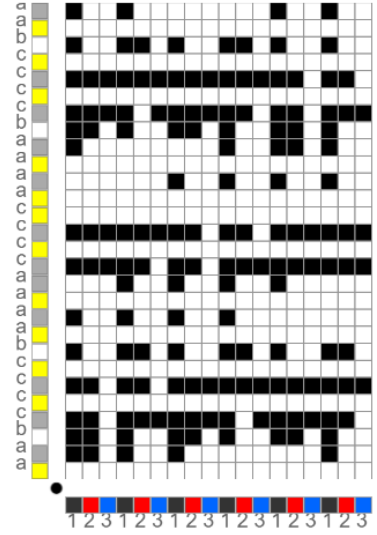
Sensor (Red)



Bottom sensor (Blue)

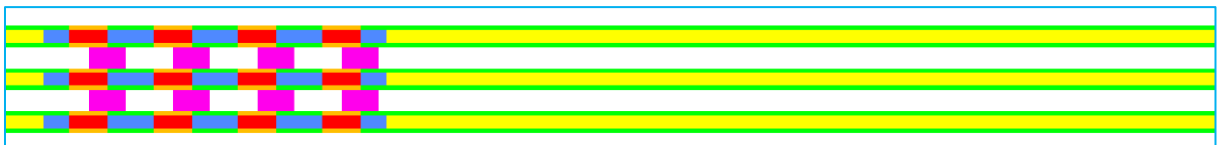


Sides (white)

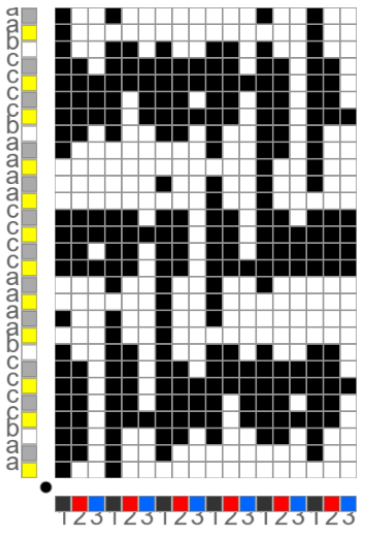


# Appendix D: Demonstrator 2

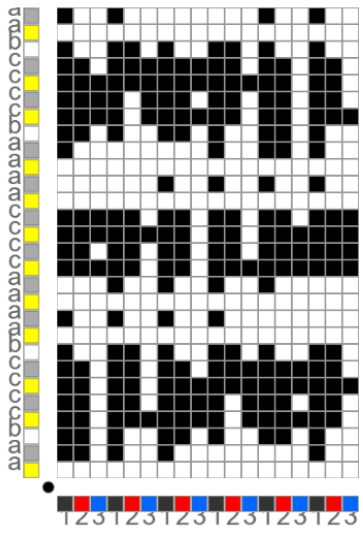
Map of bindings



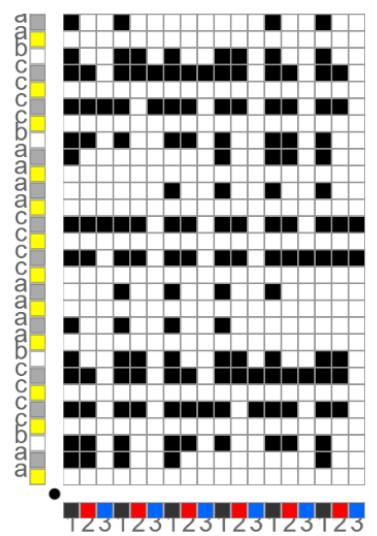
Sensor (Red)



Bottom sensor (Blue)

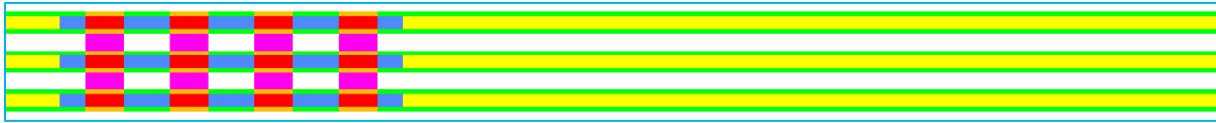


Sides (Yellow)

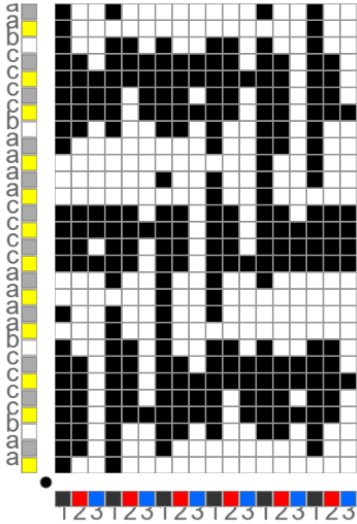


# Appendix E: Demonstrator 3

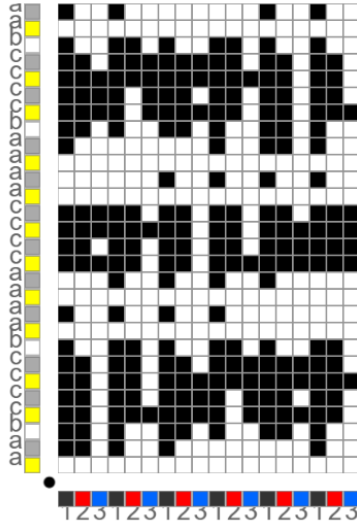
Map of bindings



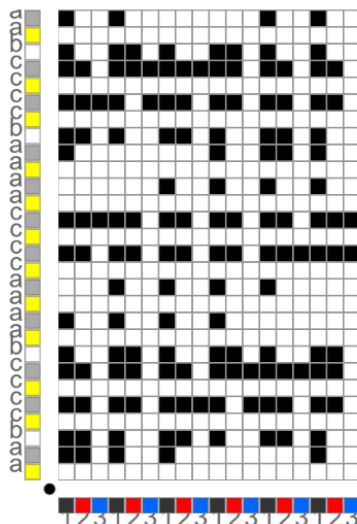
Sensor (Red)



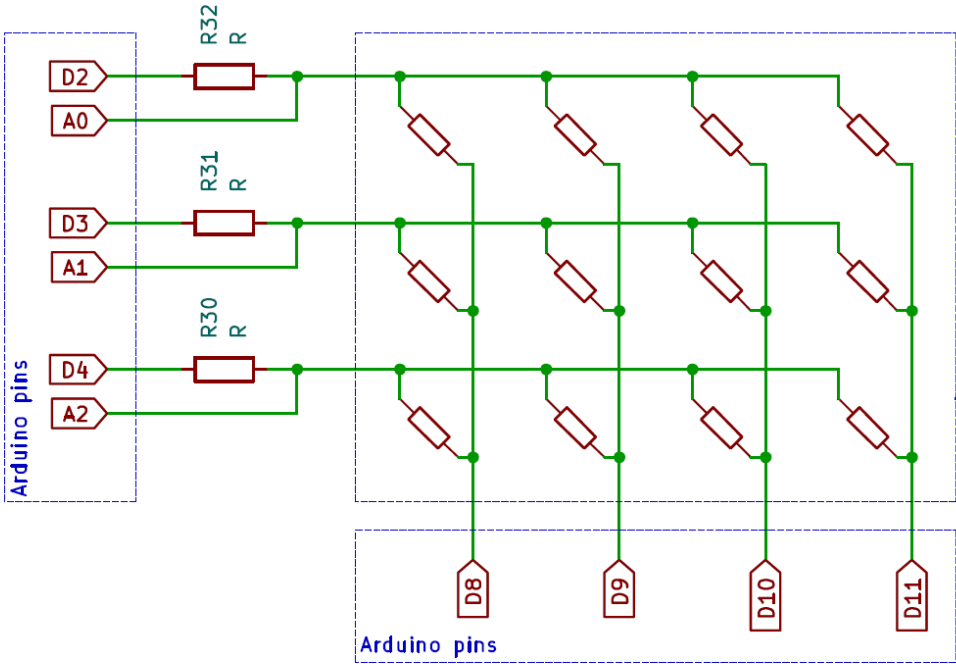
Bottom sensor (Blue)



Sides (Yellow)



# Appendix F: Schematic electronic system



## Appendix G: code

### 9.9.1 Arduino

// reference: <https://www.arduino.cc/education/visualization-with-arduino-and-processing/>

```
const byte sourcePins[] = (Aigner et al., 2022);
const byte sinkPins[] = (Aigner et al., 2022 II );
const byte sensePins[] = { A0, A1, A2 };

void setup() {
  Serial.begin(115200);
  while (!Serial && (millis() < 5000))
    ; // Wait up to 5 secs for Serial to be ready

  // mickeymouse programming
  Serial.println("define pins");
  for (int i = 0; i < sizeof(sourcePins); i++) {
    pinMode(sourcePins[i], OUTPUT);
  }

  for (int i = 0; i < sizeof(sinkPins); i++) {
    pinMode(sinkPins[i], OUTPUT);
  }
  // while (true) {
  //   Serial.println(Measure(sourcePins[0], sinkPins[0], sensePins[0]));
  //   delay(100);
  // }

  Serial.println("A1, A2, A3, A4, B1, B2, B3, B4, C1, C2, C3, C4");
}

int avg[3][4];

// measure doet N metingen,
// Een van de rijen (A, B, C wordt gemeten,
```

```

// de andere rijen worden steeds output, en hoog (5V) gemaakt)
// dat zou de onderlinge invloed moeten verkleinen
int N = 8;
int Measure(int src, int snk, int sns) {
    // maak sourcepin - de pin aan de referentieweerstand - hoog
    digitalWrite(src, HIGH);
    // sink is de colom-draad, die wordt OUTPUT en (default) LAAG
    pinMode(snk, OUTPUT);
    // sensor (analoge pin) wordt INPUT (maar misschien doet AnalogRead dat ook?)
    pinMode(sns, INPUT);
    // wacht tot de signalen stabiel zijn.
    delay(5);
    int res = 0;
    // doe N metingen
    for (int i = 0; i < N; i++) {
        res += (analogRead(sns));
    }
    // zet alle pinnen weer terug
    digitalWrite(src, LOW);
    pinMode(snk, INPUT); // make Hi-Z
    pinMode(sns, OUTPUT);
    digitalWrite(sns, HIGH);
    return res;
}

```

```

void loop() {
    for (int row = 0; row < sizeof(sourcePins); row++) {
        for (int col = 0; col < sizeof(sinkPins); col++) {
            // doe een meting
            int r = Measure(sourcePins[row], sinkPins[col], sensePins[row]);
            // exponentieel filter - zorgt voor een 'smooth' output
            avg[row][col] = 0.9 * avg[row][col] + 0.1 * r;
        }
    }
}

```

```

// print alleen veranderingen (average - huidig resultaat)
Serial.print(avg[row][col] - r);
// print average resultaat
// Serial.print(avg[row][col]);
Serial.print(", ");
}
}
Serial.println();
delay(50);
}

```

### 9.9.2 Processing

```
import processing.serial.*;
```

```

Serial myPort; // Create object from Serial class
static String val; // Data received from the serial port
int sensorVal;
int[] arrVal={0,0,0,0,0,0,0,0,0,0,0,0};

int threshold = 60; // adjust to make it more/less sensitive

```

```

void setup()
{
  size(720, 480);
  noStroke();
  noFill();

  String portName = "COM6";// Change the number (in this case ) to match the corresponding port
  number connected to your Arduino.

  myPort = new Serial(this, portName, 115200);
}

```

```

void draw()
{
  if ( myPort.available() > 0) { // If data is available,
    val = myPort.readStringUntil('\n');

    try {
      if (val != null){
        //println(val);
        //println(split(val, ','));
        arrVal = int(split(val, ","));
        arrVal = expand(arrVal,13);

        for (int i = 0; i < arrVal.length; i++) {
          if (abs(arrVal[i]) < threshold) {
            arrVal[i] = 0; // kill small noisy values
          }
        }

        println(arrVal.length);
      }
      // else{print("twasnull");}
    } catch (Exception e) {
      println("exception");
    }

    // println(sensorVal); // read it and store it in vals!
  }

  background(0);

  // Scale the mouseX value from 0 to 640 to a range between 0 and 175
  float s1 = map(int(arrVal[0]), -255, 255, 0, 255);
  float s2 = map(int(arrVal[1]), -255, 255, 0, 255);
  float s3 = map(int(arrVal[2]), -255, 255, 0, 255);

```

```
float s4 = map(int(arrVal[3]), -255, 255, 0, 255);
float s5 = map(int(arrVal[4]), -255, 255, 0, 255);
float s6 = map(int(arrVal[5]), -255, 255, 0, 255);
float s7 = map(int(arrVal[6]), -255, 255, 0, 255);
float s8 = map(int(arrVal[7]), -255, 255, 0, 255);
float s9 = map(int(arrVal[8]), -255, 255, 0, 255);
float s10 = map(int(arrVal[9]), -255, 255, 0, 255);
float s11 = map(int(arrVal[10]), -255, 255, 0, 255);
float s12 = map(int(arrVal[11]), -255, 255, 0, 255);
```

```
fill(255, s1, 0);
ellipse(width/4.2, height/4.2, s1, s4);
fill(s2, 0, 255);
  ellipse(width/2, height/3, s2, s3);
  fill(s11, 0, 255);
  ellipse(width/2, height/1.4, s11, s12);
fill(s6, 255, 0);
  ellipse(width/1.3, height/4.2, s6, s5);
fill(s9, 255, 0);
  ellipse(width/1.3, height/1.2, s9, s10);
fill(255, s7, 0);
  ellipse(width/4.2, height/1.2, s7, s8);

}
```

## Appendix H: Template consent form

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
<b>A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICIPANT TASKS AND VOLUNTARY PARTICIPATION</b>		
1. I have read and understood the study information dated [ /02/2026], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	<input type="checkbox"/>	<input type="checkbox"/>
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	<input type="checkbox"/>	<input type="checkbox"/>
3. I understand that taking part in the study involves: A demonstration where I am asked to interact with a piece of fabric that has technology embedded into it. A short interview will take place afterwards, that is also recorded on camera and using written notes. During the study I will be anonymously filmed on camera with audio, without my face being apparent on screen. All recordings made will be used to transcribe to text and will be destroyed when the research is finished.	<input type="checkbox"/>	<input type="checkbox"/>
4. I consent to the anonymous recording of myself interacting with the product could be used for a presentation in the deliverable video showcase required for this MSc thesis.	<input type="checkbox"/>	<input type="checkbox"/>
5. I understand that the study will end 30/03/2026		
<b>B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)</b>		
6. I understand that taking part in the study involves the following risks: anonymous recordings of me leaking. I understand that these will be mitigated by the researcher only saving these recordings on personal physical media such as SD cards and a personal laptop.	<input type="checkbox"/>	<input type="checkbox"/>
9. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach: - The recordings are anonymous, not showing the participants' face - All recordings are stored in personal physical media, such as SD cards and a personal laptop - Written transcriptions derived from these recordings will not include any personal identifiable information	<input type="checkbox"/>	<input type="checkbox"/>
11. I understand that the (identifiable) personal data I provide will be destroyed on 30/03/2026 by deleting all recorded footage	<input type="checkbox"/>	<input type="checkbox"/>
<b>C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION</b>		
12. I understand that after the research study the de-identified information I provide will be used for transcription in the Appendix of the report. Said report and Appendix will be published in the TU Delft repository.	<input type="checkbox"/>	<input type="checkbox"/>
<b>D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE</b>		
16. I give permission for the de-identified observation and interview transcripts that I provide to be archived in TU Delft repository so it can be used for future research and learning.	<input type="checkbox"/>	<input type="checkbox"/>
17. I understand that access to this repository is open	<input type="checkbox"/>	<input type="checkbox"/>

**Signatures**

\_\_\_\_\_  
Signature Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

\_\_\_\_\_  
Su Hu Hu Signature Date

Study contact details for further information: Maya Hu, +31643904118, maya.hu@outlook.com

# Appendix I: User test results

Introduction script:

*“Thank you for your willingness to participate in this user test. Before you lies a patch of fabric embedded with pressure sensors, you are allowed to interact with it however you like. When interacting you can do no wrong as there is no right or wrong. You are asked to think out loud for the duration of the demonstration.”*

## 9.9.3 User 1

*Observation notes*

- User starts by pressing individual sensors, she is curious whether something will happen depending on how hard they press.
- Then says: “this one does more than the others”
- then later presses whole hand on the patch of fabric.
- User presses repeatedly on the same sensor to see what effect that has on the visualization.
- User folds the fabric to see what happens
- User says that by pressing more sensors at the same time also causes more to happen in the visualization
- It is clear that some sensors have more of an effect on the visualization than others.
- Tries to press two sensors at the same time to see what will happen

*Interview*

1. How clear was it that interacting with the fabric influences what happened on screen?
  - a. It was very clear; the same things happened even if you touched different parts of it
2. How do you think the sensors on the fabric influence the visualization on the screen?
  - i. It seemed as though the spheres distorted in response to your movements, but when you creased the fabric...
  - ii. ii. But it wasn't entirely clear that this always happened in the same way
3. In what kind of context do they imagine this type of fabric to be used?
  - i. In a shoe whilst running
  - ii. If you made a carpet out of it, you could see how your feet walk on it
  - iii. Where there is more or less deformation
  - iv. A mattress or chair – you could use this for anything slightly ergonomic
  - v. In areas where you need more support

## 9.9.4 User 2

*Observation notes*

- Participant starts by dragging a finger along each sensor row carefully
- Asks “how much pressure am I supposed to apply?”
- Then starts tapping on each sensor and observe what happens on the screen
- Continues pressing each individual sensor going row by row
- Asks what the circles on the screen are
- Continues pressing each sensor individually

- When releasing hands from the fabric asks why the circles are still wobbling

#### *Interview*

1. How clear was it that interacting with the fabric influences what happened on screen?
  - i. There was part where there was less pressure where something happened and other parts where what happened not much
2. How do you think the sensors on the fabric influence the visualization on the screen?
  - i. I don't get it exactly
  - ii. More pressure will put more disturbances on the circle I guess
3. In what kind of context do they imagine this type of fabric to be used?
  - i. In environments where we have difference in pressure such as underwater, lower orbit.
  - ii. Places where pressure is different than compared to the surface.

### 9.9.5 User 3

#### *Observation notes*

- Starts by pressing each sensor individually then then drags finger along the row
- They are curious what would happen if they glide their hand along the fabric but says they have not found a logic within the circles on the screen
- Then they pick up the fabric from the sides
- After which they pick up the whole fabric
- Starts pressing individual sensors again
- Presses the sensor in random order
- When repeatedly pressing one particular sensor she says this one reacts more sensitive.
- "This one reacts more consistent"
- "When I press other sensors I do not see much result"
- Tries more individual sensors
- They try tapping one sensor repeatedly but softer and notices that it seems to work better
- Starts dragging finger along
- Taps two at the same time
- Switches between tapping and dragging on one sensor
- Says that some sensors react more intensely than others

#### *Interview*

1. How clear was it that interacting with the fabric influences what happened on screen?
  - i. I think in general it was clear, I think that in some moments it was less clear, especially when I was pressing the middle button.
  - ii. Even when I wasn't pressing it things happened
  - iii. I think tapping it more lightly helped, light taps did the trick
2. How do you think the sensors on the fabric influence the visualization on the screen?

- i. The dots change colour and the dots also change shape so they become ovals but I did not necessarily figure out a pattern. It still seems quite random to me
3. In what kind of context do they imagine this type of fabric to be used?
  - i. The ski sock example is nice, to measure the gait of someones movement
  - ii. It could be for fun, or for entertainment. You can use it to make musci
  - iii. Use it to make some sort of sensory experience, or create a wearable that has some sensory elements
  - iv. A wearable that would become warm based on where you press a button for comfort
  - v. Or a massage wearable that is influenced by the sensors

#### 9.9.6 User 4

##### *Observation notes*

- User immediately picks up the fabric in their hands
- Presses individual sensors with their thumbs
- Assumes the red parts indicate where the sensors are
- The harder they press the more happens on the screen
- "I feel like I have a little bit figured out which one does what"
- Lays the fabric down, "If I leave it it returns to a more calm state" referring to the visualization on the screen
- Remarks that the fabric feels nice
- "I expected the thread to be stiffer, but it is not so it feels nice"

##### *Interview*

1. How clear was it that interacting with the fabric influences what happened on screen?
  - i. When i grabbed the fabric I could already see changes in the forms on the screen and when I started pressing on the red pieces of the fabric I could see quick changes in the form
  - ii. It did not take long for me to see changes, even when you grab a small piece.
2. How do you think the sensors on the fabric influence the visualization on the screen?
  - i. I think with quite an intensity, when I pressed one I could see that some blobs were very wide or became thin
  - ii. I did not have to press hard to change the blobs shape
  - iii. And if I pressed two I could see multiple blobs change form
  - iv. Also with how hard I was pressing it
  - v. Ligh touch was already changing a lot
3. In what kind of context do they imagine this type of fabric to be used?
  - i. Maybe in a museum, where you can interact with art works  
Musea with digital interfaces or digital artwork  
I can imagine it also in care environments, not necessarily, a hospital but zorghotel.  
People can squeeze something like a pillow or a teddy bear to either let someone know I need something or that caretakers see something happening.

Maybe also interacting with a light, squeeze something and that lights come up.

Either a specific light or environmental.

It is really clear where the sensors are placed en it feels nice.

### 9.9.7 User 5



#### *Observation notes*

- Starts by dragging their finger along the rows
- Notices the colours of the ellipses change
- "It kind of feels like I am playing a piano"
- Continues dragging fingers across the fabric
- Starts wringing the fabric in their hands
- Ellipses on the screen react strongly "It kind of feels like an alarm, like an emergency"
- Flips the fabric and drags a finger along the lines to see if something will happen
- Then lays the fabric down again and tries to roll it up tightly
- Then starts pressing on the rolled up fabric
- "wow this is fun." Rolls the fabric back out "it kinda feels like a children's toy"

#### *Interview*

1. How clear was it that interacting with the fabric influences what happened on screen?
  - i. Very clear, it was very obvious it was directly related
2. How do you think the sensors on the fabric influence the visualization on the screen?
  - i. I think it agitates them, change colour and size,
  - ii. Not really relation between individual sensors and
  - iii. I do feel like the last line was the most effect on the dots
3. In what kind of context do they imagine this type of fabric to be used?
  - i. I think it would be interesting to see it used as a emotional monitoring
  - ii. Children
  - iii. Non verbal people
  - iv. People with autism
  - v. Where they can communicate without using words
  - vi. But still communicate through emotion
  - vii. Play for kids, I think the direct relation of tactile play and some sort of outcome from it
  - viii. Anything involving sports or maybe health or limited mobility
  - ix. Include these sensors in some way of clothing or emergency situations
  - x. Someone falling

# Appendix H: Project brief

## IDE Master Graduation Project

### Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

### STUDENT DATA & MASTER PROGRAMME

Complete all fields and indicate which master(s) you are in

Family name	<input type="text" value="Hu"/>	IDE master(s)	IPD <input checked="" type="checkbox"/>	Dfi <input type="checkbox"/>	SPD <input type="checkbox"/>
Initials	<input type="text" value="S.H."/>	2 <sup>nd</sup> non-IDE master	<input type="text"/>		
Given name	<input type="text" value="Maya"/>	Individual programme (date of approval)	<input type="text"/>		
Student number	<input type="text" value="4660412"/>	Medisign	<input type="text"/>		
		HPM	<input type="text"/>		

### SUPERVISORY TEAM

Fill in the required information of supervisory team members. If applicable, company mentor is added as 2<sup>nd</sup> mentor

Chair	<input type="text" value="Kaspar Jansen"/>	dept./section	<input type="text" value="SDE/MF"/>	<p>! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.</p> <p>! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.</p> <p>! 2<sup>nd</sup> mentor only applies when a client is involved.</p>
mentor	<input type="text" value="Holly McQuillan"/>	dept./section	<input type="text" value="SDE/MF"/>	
2 <sup>nd</sup> mentor	<input type="text"/>			
client:	<input type="text"/>			
city:	<input type="text"/>	country:	<input type="text"/>	
optional comments	<input type="text"/>			

### APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in by the Chair of the supervisory team

Sign for approval (Chair)



Name <input style="width: 150px;" type="text"/>	Date <input style="width: 100px;" type="text"/>	Signature <input style="width: 150px;" type="text"/>
---	---	--

### CHECK ON STUDY PROGRESS

To be filled in by SSC E&SA (Shared Service Centre, Education & Student Affairs), after approval of the project brief by the chair.  
The study progress will be checked for a 2<sup>nd</sup> time just before the green light meeting.

Master electives no. of EC accumulated in total  EC  
Of which, taking conditional requirements into account, can be part of the exam programme  EC

<input type="checkbox"/>	YES	all 1 <sup>st</sup> year master courses passed
<input type="checkbox"/>	NO	missing 1 <sup>st</sup> year courses

Comments:

Sign for approval (SSC E&SA)

Name

Date

Signature

### APPROVAL OF BOARD OF EXAMINERS IDE on SUPERVISORY TEAM -> to be checked and filled in by IDE's Board of Examiners

Does the composition of the Supervisory Team comply with regulations?

YES	<input type="checkbox"/>	Supervisory Team approved
NO	<input type="checkbox"/>	Supervisory Team not approved

Comments:

Based on study progress, students is ...

<input type="checkbox"/>	ALLOWED to start the graduation project
<input type="checkbox"/>	NOT allowed to start the graduation project

Comments:

Sign for approval (BoEx)

Name

Date

Signature



## Personal Project Brief – IDE Master Graduation Project

Name student

Student number

### PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title

*Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.*

#### Introduction

*Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)*

Textile-based sensors can be constructed by combining conductive yarns with conventional cotton, polyester and elastic type of yarns. The advantage over the traditional rigid type of sensors is that textile-based sensors are soft, washable, breathable and have a textile-like feeling. The sensor and the textile are one and the same - a feature that can eventually lead to many novel applications from medical and sports textile-products, to transportation and interaction design cases where soft, seamless and unobtrusive sensors may be desired. Before the sensor can be used in design however, it is necessary to understand how to make them, and explore their properties and behaviour.

In a previous study on woven pressure sensors, a series of functional pressure sensors was designed and it was discovered that the sensor properties were largely affected by small-scale changes in the weave structure design. Depending on the size and position of the elastic yarns, for example, the resistance over the sensor either increased or decreased when compressed. This graduation project will be a continuation of the previous study, using the prototype designs and findings to create new versions of woven sensors. The main purpose of this project will be to obtain knowledge on the properties and behaviour of woven sensors, so that academics may further develop this technology for implementations in design. The intended audience consists of PhD candidates, design researchers, faculty funding officers and other research groups.

→ space available for images / figures on next page

## Personal Project Brief – IDE Master Graduation Project

### Problem Definition

*What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.  
(max 200 words)*

The aim of this project is to perform explorative research to discover how different weaving patterns and utilizing the combination of different yarns will affect the sensitivity and accuracy of a pressure sensor created from woven fabric. The problem that would need solving is that currently there are not enough prototypes to substantially determine the relation between the weave structure and the sensor properties. Through an iterative process of design, prototyping and testing, we will gain a better understanding of the concept of woven sensors and how to further develop them for use. The goal will be to deliver a series of working prototypes at the end of this project and a report that entails the findings from the failed attempts of creating a working sensor.

The results from this explorative research and the developed prototypes will be useful for future researchers. The possibilities of using this technique to develop effective pressure sensors are many. Since fabric as a material and weaving techniques are very versatile components, they can be utilized for different purposes (for example, using a pressure sensor as a button, or measure distributed pressure in an area).

### Assignment

*This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:*

*Create and investigate a series of woven textile systems to understand the relation between the weave structure and the sensor performance for showcasing the potential of woven sensors in design.*

*Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)*

For my master thesis I will use the Research through design method by Stappers and Giaccardi. An approach that uses design as a tool to create iterative material development. It starts by analyzing the forgoing thesis report Woven sensors (Hoogstraten, 2025) and recreating those samples to observe how certain structures and materials behave in a woven sensor. Based on this research, I will design my own weave structures using variants of compound weaving structures to create an yet to be intended function for the sensor.

To map out the relation between the woven structure and the sensor sensitivity each week will be an design and testing iteration. Starting with a hypothesis, design and program, a series of weave structures is fabricated. These weave structures are then each tested on pressure response. Based on these results and conclusions, a redesign is made with a new hypothesis.

### Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a kick-off meeting, mid-term evaluation meeting, green light meeting and graduation ceremony. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).

Make sure to attach the full plan to this project brief.  
The four key moment dates must be filled in below

Kick off meeting	5 juni 2025
Mid-term evaluation	11 aug 2025
Green light meeting	15 okt 2025
Graduation ceremony	12 nov 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	<input type="checkbox"/>
For how many project weeks	<input type="text"/>
Number of project days per week	<input type="text"/>

Comments:

### Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.

(200 words max)

My motivation for this project stemmed from experiences in projects working with textile products and materials. The technique of creating fabrics and utilizing textile materials for products is something I enjoyed working with and aim to do more often. I believe textiles are a very versatile material and therefore offer a lot of freedom, when creating prototypes and products. The creative freedom of this project challenges my imaginative skills as a designers as well as critical thinking, when evaluating the textile designs and the performance of the sensors.

This project allows me to challenge my embodiment design skills within an explorative research, which's success will depend on how often I am able to iterate through the design process. Fast paced ideation and prototyping is one of the competencies I have developed during the MSc programme, which will be useful in this type of research. As well as my comprehension skills, by learning a new prototyping methods, such as weaving. I must analyze and understand weaving well enough to start making my own designs. This I will do by studying others' work and utilize the technique to my understanding and workflow.