# WOVEN PRESSURE SENSORS

MASTER THESIS - CHRISTIAAN HOOGSTRATEN

DEVELOPMENT OF A FULLY WOVEN, READY-MADE PRESSURE SENSOR FOR SMART TEXTILE APPLICATIONS

TU Delft

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***Abstract*—Fabricating woven pressure sensors traditionally comes with considerable constraints, including extensive post-processing steps and manual labor. This is because most existing designs rely on layering multiple fabrics and inserting a high-resistance layer afterward. In this thesis, we present a novel, fully woven, ready-made pressure sensor that overcomes these limitations. Our sensor uses an interlaced double-layer structure, where each layer is a two-faced compound fabric. This design only uses off-the-shelf yarns, significantly enhancing the feasibility of mass production. The resulting sensor is thin, with a sensitivity of 0.5917 kPa$^{-1}$ and a detection range of 10 – 100 kPa. Furthermore, we introduce Press Zoom, a computer mouse button that maps pressure differences to zoom levels in desktop applications, demonstrating a practical use case for our sensor. Finally, we conclude with key findings that provide deeper insights into the working principles of our pressure sensor.**

## I. Introduction

There is a growing interest in developing human-machine interfaces that are unobtrusive, invisible, and comfortable to wear. Smart textiles are among the key technologies emerging in this field, as they promise innovative forms of input and unique data collection by embedding sensors directly into garments and textiles. Potential applications span various domains, including fabric-based controllers [1], [2], [3], [4], [5], [6], [7], sports performance monitoring [8], [9], [10], [11], [12], healthcare [13], [14], [15], [16], [17], [18], [19], home interiors [20], [21], [7], automotive design [21], [22], [6], and robotic interaction [1], [4].

Over the past 30 years, research has led to significant insights into different types of sensors—such as touch, pressure, strain, thermal, optical and more. Most prominently, Google's Project Jacquard [23] demonstrated how touch sensors could be integrated into garments like denim jackets [24] and accessories like backpacks [25]. However, Project Jacquard faced limited market success due to constraints in its functionality and durability: while it could play and pause music, it lacked controls to skip songs, and its washability was limited to only ten machine washes over its lifetime.

Despite the accumulation of literature and companies, there is a surprising absence of research that focuses on woven pressure sensors which don't require manual postprocessing steps. Traditional approaches of pressure sensors are usually realized as an separate surface insert of conductive yarn which can be relatively large and distinct. These inserts often require either stacking, aligning, or fusing of multiple layers. Furthermore, they lack appeal and significantly limit visual and haptic textile design.

Therefore, this thesis presents a research exploration focused on a fully ready-made woven pressure sensor. Our woven pressure sensor is constructed from a two layer compound structure, only making use of off-the-shelf yarns. Due to there only being two layers the woven structure is rather thin and is unobtrusive and flexible enough to be integrated into human-garments. This thesis, present the results of our exploration into physical sensor construction and concludes with Press Zoom. A demonstrator showcasing the potential use cases for this specific pressure sensor. Finally, we conclude with key findings that provide deeper insights into the working principles of our pressure sensor.

## II. Technical context

Significant progress has been made in the pressure sensor domain over the last 30 years. In 2005, the first model was created and validated to understand the working principles of force-sensitive resistors (FSR) [26]. These pressure sensitive sensors operate by measuring changes in electrical resistance between two electrode layers sandwiching a high resistance layer. This method relies on the interface effect, where external pressure increases surface contact, thereby decreasing resistivity, see figure 1. Therefore, pressure can be correlated with resistance. This foundational theory paved the way for various methods to construct pressure sensors. Although FSRs remain the most widely used, other methods—such as capacitance, triboelectric, and optical sensors—have also emerged.

To create an overview of existing literature, we categorize pressure sensors based on their production method, such as knitting, weaving, embroidery, or sewing. Since each production technique requires vastly different sensor structures, it is important to determine the most suitable method early in the design process. This ensures a focused development approach when designing a pressure sensor.

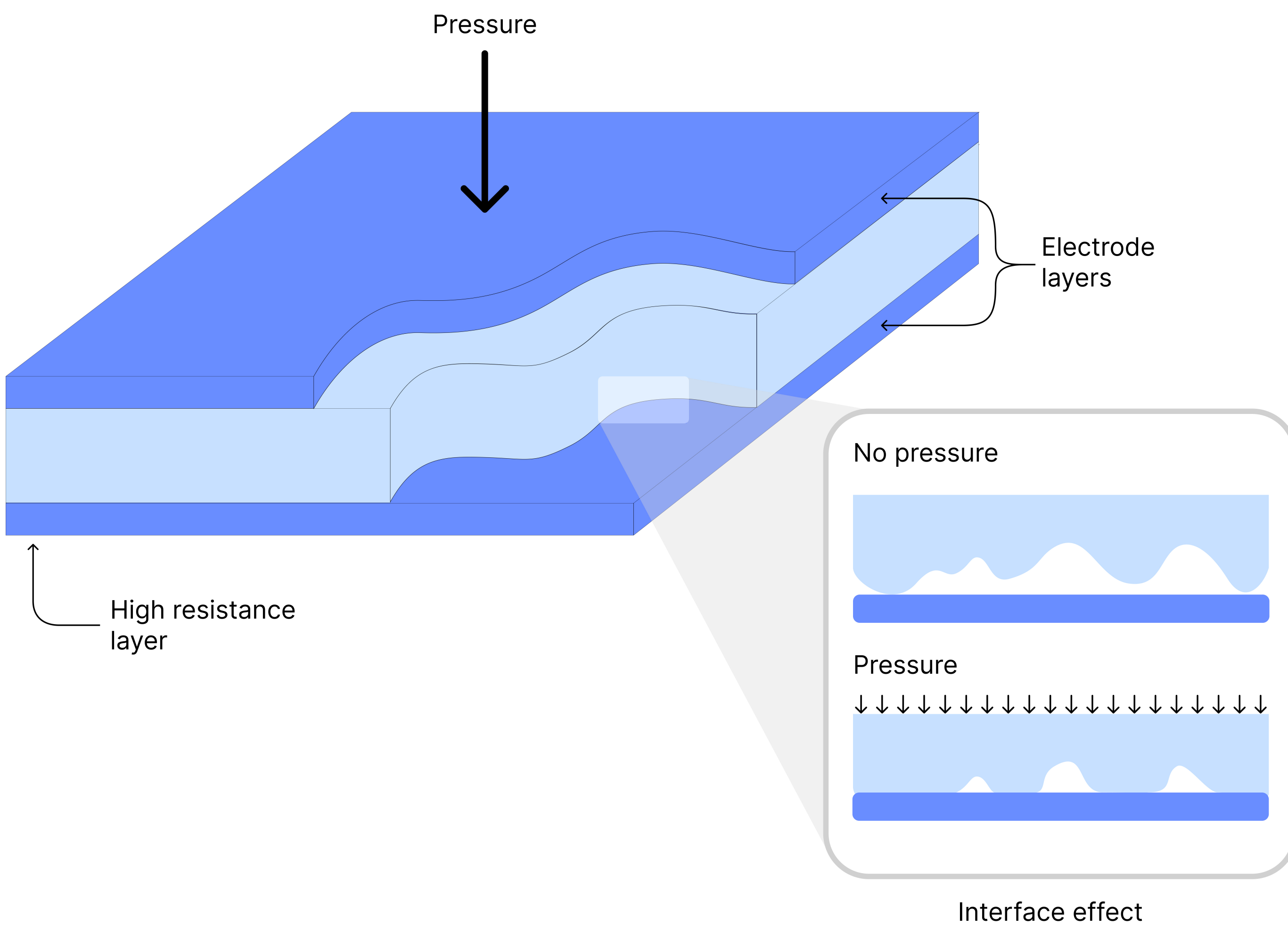



Fig. 1. FSR

*Knitting*

Knitting is a fabric construction technique in which yarn is looped together to create a textile. It uses one or more continuous yarns to form loops of yarn that interlock row by row, with each new row supported by the loops below it, see figure 2. For more information look at The Principles of Knitting by June Hemmons Hiatt [27].

A key advantage of knitting over other fabric construction methods is its natural stretchability. The looped structure tightens when force is applied, making knitted sensors particularly suitable for the clothing industry. This has led to extensive research on integrating knitted textiles into smart pressure sensors.

Textile pressure sensors are typically based on the force-sensitive resistor (FSR) principle, where two fabric layers sandwich a pressure-sensitive material, often a highly resistive fabric. Conductive yarns knitted into these layers function as electrodes. When pressure is applied, the contact surface area increases, altering the measured resistance, which enables pressure detection.

Recent designs have experimented with different approaches at both the structure and yarn level. First structure level: For instance, in 2019, Mingwei Tian [20] utilized a pillow-shaped structure where an encapsulated polypropylene (PP) fiber assembly served as an elastic medium, and a silver-coated fabric acted as the sensitive component. While this design achieved high sensitivity, its thick shape limited its design freedom. Another approach by KnitUI [4] employed short rows in their knits to enhance conductive pathways. Also, Tapis Magique [28] introduced an innovative use case by creating a pressure-sensing mat that allowed a dance performer to interact with music through the mat. The latest work from Roland Aigner [2] utilized multifunctional spacer fabrics by Lea Albaugh [29] to create a pressure sensor with excellent sensitivity, used to control a rocker-button.

At yarn level, studies have investigated various sensing methods besides resistance. Claire Guignier [30] explored the potential of optical fibers inserted in a knitted fabric to measure pressure and friction during walking. Although promising, the brittleness of optical fibers limited them to inlay yarns. In 2020, Wenjing Fan [15] introduced a triboelectric pressure sensor using conductive and nylon yarns in a full cardigan stitch.

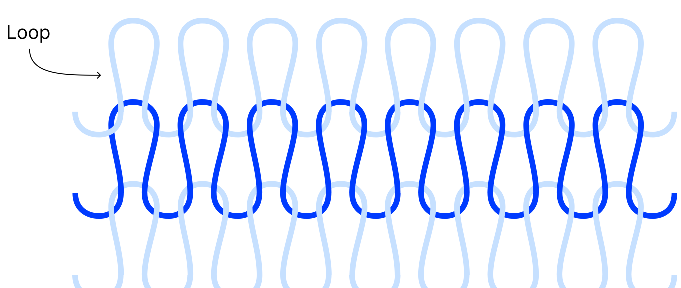



Fig. 2. Knitting

Experimentation with self-produced conductive yarns has also been prominent. In 2020, Andreas Pointner [31] demonstrated a pressure sensor with highly conductive yarn [7], allowing single yarn crossings to function as sensors. Recent research trends indicate a focus on yarn structures, as they embed pressure sensitivity in the yarn, which allows for thinner and invisible integration of sensors. Roland Aigner's Loopsense project [1] exemplifies this direction, showcasing a pressure sensor with Patrick Parzer's highly conductive yarn [7]. This design features FSR cells at each yarn junction, enabling multiple input detections for pressure and strain, which can be discreetly hidden in double jerseys.

*Weaving*

Weaving is a fabric construction technique in which two sets of yarns—warp (vertical) and weft (horizontal)—are interlaced at right angles to form a structured textile, see figure 3. This method produces strong, durable, and stable fabrics and is the most widely used fabric production method worldwide. For more information look at The Key to Weaving by Mary E. Black [32].

While weaving is commonly used in clothing, its rigid structure also makes it suitable for furniture applications. In woven pressure sensors, the structure is often layered, with sensing functionality based on resistance, capacitance, or optical principles.

In 2009, Long-Fei Li [33] utilized contact points between warp and weft yarns in a plain weave to create a pressure sensor. In 2011, Ruquan Zhang [34] experimented with both plain and double weaves, finding that the capacitance of plain weave fabric is greater than that of double-layer fabric under no pressure, but the increasing rate of capacitance of double-layer fabric is larger than that of plain weave fabric under the same pressure. Variations in this approach have since emerged, using different types of yarns and coatings. For instance, die-coated nylon fibers [35], Kevlar fibers coated with dielectric rubber material (SBS) [36], and other specialized materials have been explored. Emmi Pouta [37] introduced a woven pressure-sensing hand puppet in 2019.

Recent experiments have utilized a range of yarns, including triboelectric combinations with nylon, PTFE filaments, and stainless steel cores [38]. In 2020, Ruojia Sun [39] developed an FSR sensor with a piezoresistive layer (Velostat) between two conductive layers, while Yulong Ma in 2021 [10] used Ecoflex as an alternative in a capacitive layering approach. Weibing Zhong in 2021 [11] employed a plain weave with silver-plated nylon yarns coated for a microporous structure.

Almost all of these sensors make use of a special yarn which is either not available of the shelf or lack the desired texture. However this year, Emmi Pouta presented a study [40] on multilayer weave structures for pressure sensors, highlighting new research opportunities in ready-made pressure sensors. In her research she presents a pressure sensor which is based on a linked three-layer structure. This marks a divergence from the double-weave method proposed in prior work and also avoids using self-made yarns.

*Sewing and Embroidery*

Sewing is a fabric joining technique that uses thread and a needle to stitch materials together. Unlike knitting and weaving, which create fabric structures, sewing requires a pre-existing fabric to work on. The process involves a needle pushing thread through fabric layers to form stitches. For more information look at Reader's Digest Complete Guide to Sewing [41].

Embroidery works the same as sewing, only is it typically used for surface decoration, while sewing is employed to join fabrics securely. Both techniques, however, use stitches, with the lockstitch being particularly relevant for pressure sensors due to its ability to thread both upper and bobbin threads, see figure 4.

In 2006, Jan Meyer [9] fabricated a capacitive pressure sensor using an array of embroidered electrodes around a non-conductive dielectric layer. Jose Francisco Saenz-Cogollo [16] introduced a lockstitched grid with conductive polymer intersections in 2016, while Talha Agcayazi [42] achieved similar functionality without conductive polymers, opting instead for capacitive sensing instead of resistance, which is more sensitive. Roland Aigner's 2020 project [6] showcased an FSR sensor using proximity, minimizing interference by avoiding thread intersections. Qi Zhang [43] used a custom yarn with a conductive core and insulating cotton layer to create a pressure sensor within a lockstitch structure, while Roland Aigner's latest research [1] explored a capacitive pressure sensor, in which pressure-driven reduction in fabric thickness allows charge exchange between bobbin threads via human fingers.

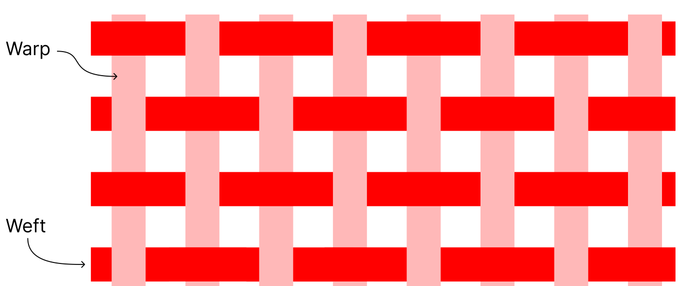



Fig. 3. Weaving

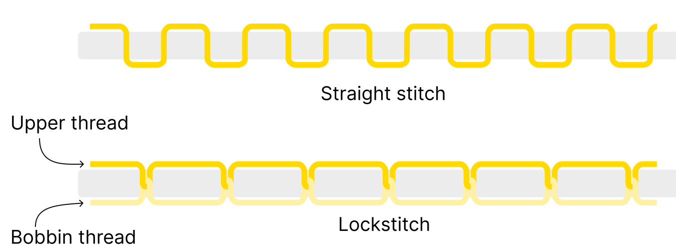
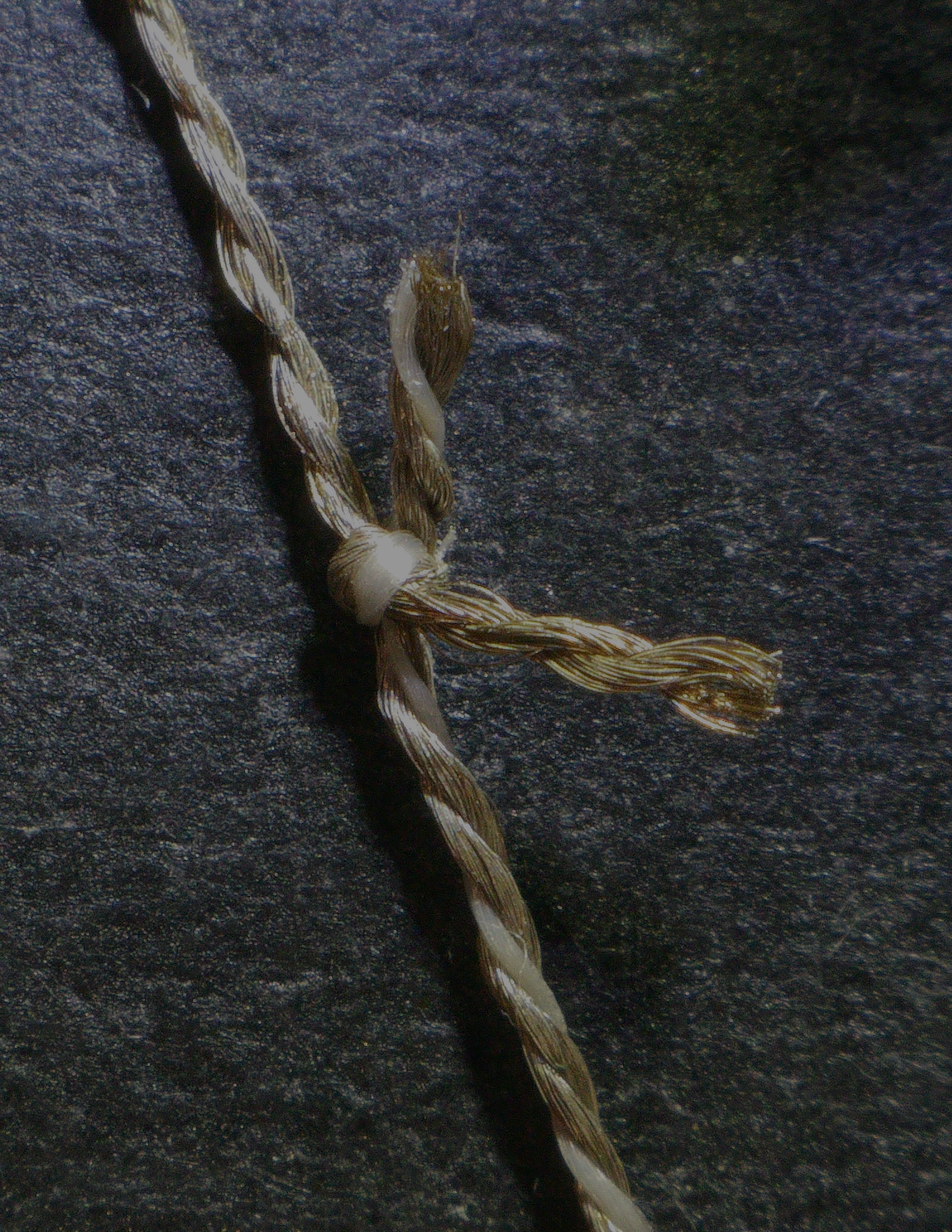



Fig. 4. Sewing



# III. Literature Research

Having explored various methods for creating textile pressure sensors, the next step is to identify opportunities within this context. We are looking for opportunities who allow us to either knit, weave or sew a pressure sensor ready-made without any post-production steps. These opportunities may arise from research gaps, where new sensor structures can be developed, or from existing studies that show promise but could be enhanced by applying a structural design perspective to the pressure sensor.

To choose between knitted, woven or sewn pressure sensors, we employ a systematic categorization process in which sensors are filtered based on specific criteria. For instance, if our target detection range is 0–100 kPa, we exclude any sensors that operate outside this range and retain only those within it. This approach narrows the selection, allowing for further refinement based on additional criteria. The chosen criteria are:

- Production method
- Sensing technique
- Sensitivity
- Detection range
- Response and recovery time
- Hysteresis
- Applications
- Conductive yarn

Each of these criteria will be explained in detail in the upcoming sections. To facilitate this quantitative comparison, a database was created to compile all relevant information on different pressure sensors. This database, available in Appendix A, allows for a structured evaluation of sensor performance and consist of 40 different sensors.

However, it is important to note that not all papers provide data for every relevant criterion mentioned above. As a result, some papers could not be ranked equally. To address these gaps, a qualitative assessment was also conducted by analyzing the structure and methodology of each sensor. This gives insight into what structures are used and which of those are ready-made or need to insert an extra layer.

*Production*

There are three main production method when looking at textile pressure sensors which are knitting, weaving, and sewing. Figure 5 shows how distributed our range of sensors is. It is clear that the majority of literature focuses on knitting, although some studies on weaving and sewing were also identified. In particular, only four weave-based sensors provided usable data on sensitivity and detection ranges, suggesting that weaving is less explored for pressure sensor applications compared to knitting and sewing.

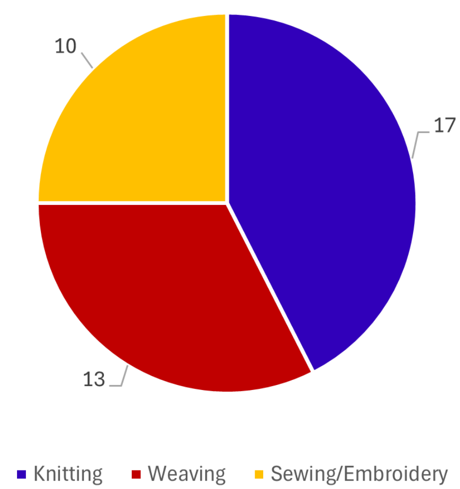



Fig. 5. Production type

*Sensing*

The most common sensor types found in the literature are resistive or capacitive, as shown in figure 6. As explained earlier, resistive sensors, often referred to as force-sensitive resistors (FSRs) [26] operate according to the interface effect, where external pressure changes the surface contact area, thus altering conductivity. Capacitive sensors, on the other hand, offer certain advantages, such as more sensitive to pressure changes which gives a higher sensitivity. However they present a more challenges in signal processing due to a lower output frequency, which complicates control-level handling compared to resistive sensors.

Some sensors used triboelectric sensors, which leverage friction at the yarn level [15], [44], [38]. This approach seems counterintuitive for pressure sensing, as perpendicular force applied to the surface—resulting in pressure—does not create shear forces that would cause friction. Given this and our limited experience with triboelectric sensing, we decided not to pursue this method further.

Lastly, optical sensors offer another way to measure pressure using light. One study inlayed an optical fiber within knitted fabric to achieve pressure sensing [30]. While effective, the optical fiber emitted visible light and proved to be brittle, limiting its practicality.

This thesis will focus on force sensitive resistors (FSR). These sensors offer the benefits of requiring simpler circuitry for signal conditioning. Often a basic voltage-divider or current-measurement setup is enough to capture the changing resistance. Due time constraints this seems like the most optimal solution.

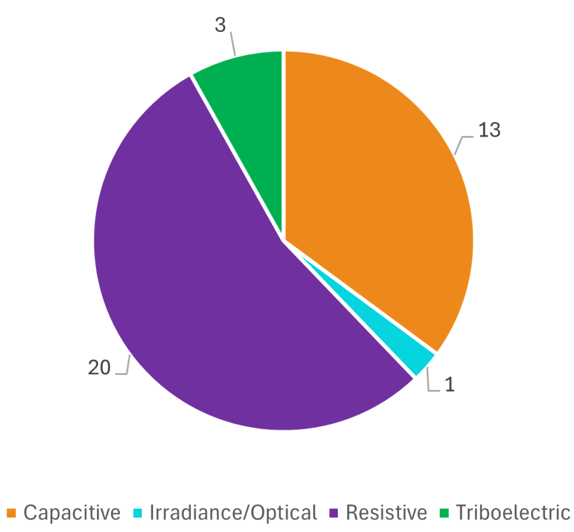



Fig. 6. Sensing type

*Sensitivity*

Sensitivity measures how responsive a sensor is to an externally applied pressure. This criterion provides a quantitative value that allows for the comparison of sensor performance, helping to determine how effectively different sensors detect pressure changes.

The standard notation for sensitivity is expressed as:

$$\frac{\frac{\Delta R}{R_0}}{\Delta p} or \frac{\frac{\Delta C}{C_0}}{\Delta p}$$

where:

- $\frac{\Delta R}{R_0}$ represents the relative resistance change,
- $\frac{\Delta C}{C_0}$ represents the relative capacitance change,
- $\Delta p$ is the applied pressure.

A typical sensitivity plot is shown in figure 7, illustrating the sensitivity of Qi Zhang's sensor [43]. The graph shows that the relative capacitance change increases with applied pressure. Additionally, it highlights two linear regions, indicating different sensitivities at different pressure ranges.

- The sensor exhibits higher sensitivity in the 0–10 kPa range (steeper slope).
- Beyond 20–120 kPa, the sensor becomes less sensitive (flatter slope).

Out of the 38 papers reviewed, 18 reported sensitivity values, but they were often presented in a wide variety of units. Among these, 11 papers provided sensitivity values specifically in $\frac{\frac{\Delta R}{R}}{\Delta p}$ or $\frac{\frac{\Delta C}{C}}{\Delta p}$, which is the preferred unit.

Sensitivity measures how effectively sensors detect small pressure changes and can be viewed as a stand-in for their accuracy. Because our exact accuracy requirements are not yet defined, we will assume that higher sensitivity is better. However, as the thesis develops, it may become clear that only a certain level of accuracy is actually needed.

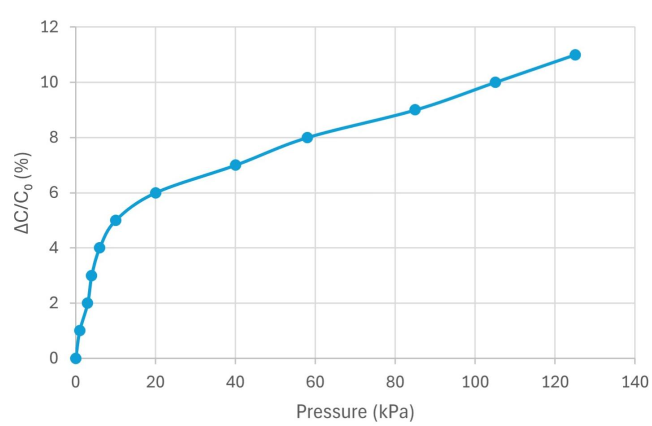



Fig. 7. Sensitivity plot

*Detection range*

The detection range provides insight into suitable applications of a pressure sensor. Since this research focuses on pressure sensors for human interaction, it is essential to consider the average pressures humans exert on sensors and the means by which pressure is applied.

The most common forms of input are finger, foot, and seating pressure:

- Finger input typically ranges from 20 kPa to 100 kPa [45].
- Foot pressure varies significantly depending on the activity:
  - Static load (standing): 32 kPa [46].
  - Dynamic load (walking/running): up to 810 kPa [47].

Since designing a pressure sensor for impulse inputs (e.g., dynamic forces) is more complex than for continuous inputs, the study focuses on a sensor operating within the range of 0–100 kPa.

Using the previously analyzed data, we constructed figures 8 and 9, which visualize the relationship between sensitivity and detection range within this scope. These two graphs show the sensors which would be interesting to further investigate as they fall within the desired detection range and have a known/high sensitivity.

Figure 8 clearly shows that sewn and knitted sensors are more prevalent, while woven sensors are less represented. This suggests a stronger research focus on knitted and sewn pressure sensors, where as woven sensors remain relatively unexplored. As a result, a research gap exists in woven pressure sensors, presenting a valuable opportunity to be among the first to advance this field.

In figure 9 we see that capacitive sensors are the most common sensors followed by resistive sensors. Capacitive sensors seem to have a larger detection range than resistive sensors. However, it should be noted that almost all capacitive sensors were also sewn sensors, suggesting that the larger detection range can also be due to the production method.

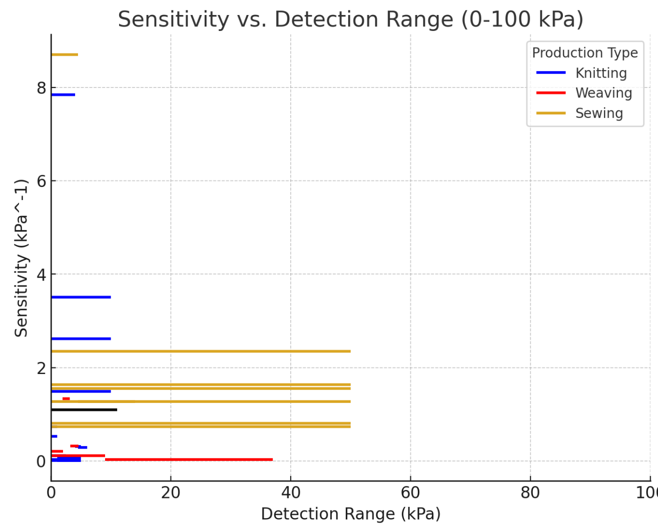



Fig. 8. Sensitivity vs detection range (0-100kPa)

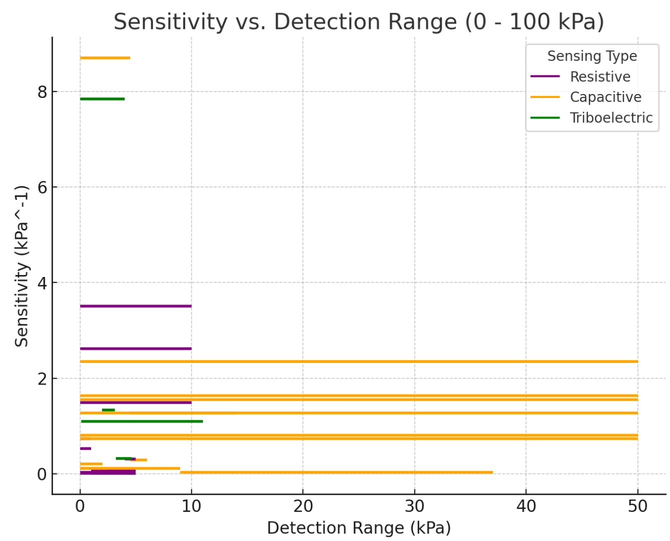



Fig. 9. Sensitivity vs detection range (Sensing technique)(0-100kPa)

*Response and recovery time*

Response and recovery time are important for pressure sensors, as they determine how quickly and frequently a user can input a signal. If a user gives an input but the sensor reacts too slowly, it may appear laggy or unresponsive. Similarly, if a user inputs a signal too frequently, the sensor may fail to reset properly, leading to incorrect pressure readings and a frustrating user experience.

Humans have an average response time of approximately 213 ms, according to [48]. Therefore, a response time of 213 ms or lower is desirable to ensure sensor responsiveness and reliability in high-frequency applications.

The response and recovery times for all sensors are summarized in table I. Notably, only 14 out of 38 papers provided data on response or recovery time. Interestingly, these times tend to cluster into two distinct ranges: a longer range exceeding 100 ms and a faster range around 10 ms. Five of the fourteen sensors have a response time beneath 213 ms. These will be useful to investigate, while the rest can be filtered out.

TABLE I
RESPONSE & RECOVERY TIME

| Response (ms) | Recovery (ms) | Reference |
|---|---|---|
| 2.1 | 2.4 | [11] |
| 13 | 10 | [42] |
| 20 | - | [15] |
| 'ms range' | 10 | [36] |
| 200 | 200 | [20] |
| 340 | 275 | [10] |
| 400 | - | [49] |
| 500 | - | [35] |
| 'Good response' | - | [43] |
| 'Quick response' | - | [8] |
| 'Quick response' | - | [2] |
| 'Quick response' | - | [3] |
| 'real-time response' | - | [38] |

*Hysteresis*

Hysteresis in pressure sensors is the difference in output sensitivity during loading and unloading of the pressure sensor. This occurs because the material in the sensor does not immediately return to its original state after the pressure is removed. An example of this phenomenon can be seen in figure 10.

Hysteresis is a problem in pressure sensors because it introduces inconsistencies in measurements, leading to reduced accuracy, slower response and recovery times, and unreliable data. Although these problems can sometimes be solved by applying a software filter, it is favourable to solve these issues on a hardware level.

Only fifteen papers discussed hysteresis, and of those, only six provided specific values, as shown in table II. The sensor with the lowest hysteresis, 3.4%, achieved this low value by incorporating Ecoflex elastomer as a spacer material, which offers exceptional elasticity. Another notable example is Meyer [17], which improved hysteresis from 25% to 5% by applying a Preisach model. The Preisach model allowed them to capture the hysteretic behaviours of the nonlinear system.

Although a low hysteresis value is desirable, determining an acceptable threshold is challenging. Therefore, hysteresis will be considered as a sub-criterion when selecting the most suitable sensor design.

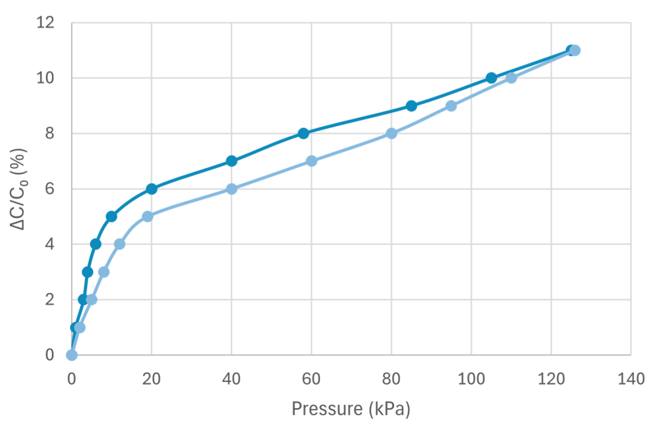



Fig. 10. Hysteresis graph

TABLE II
HYSTERESIS

| Hysteresis (%) | Reference |
|---|---|
| 3.4 | [10] |
| 12 | [42] |
| 16 | [4] |
| 24 | [17] |
| 27 | [12] |
| 30 | [9] |
| No hysteresis | [13] |
| Negligible | [15] |
| Negligible | [36] |
| Negligible | [43] |
| Negligible | [6] |
| Low | [16] |
| Little hysteresis | [2] |
| Little hysteresis | [3] |
| Large | [1] |

*Applications*

Smart textile pressure sensors are used across various domains, including fabric-based controllers, sports performance monitoring, healthcare, home interiors, automotive design, and robotic interaction. Their inherently soft and flexible nature makes them particularly suitable for applications involving close human interaction. To determine whether knitted, sewn, or woven pressure sensors are more prevalent in specific domains, an overview was created (see figure 11).

All applications were mapped and categorized, showing a clear distinction between sensors used as input devices and those used for data collection from users, and if they are either knitted, sewn or woven. Research appears to slightly favor input devices, as they are widely integrated into controllers, clothing, furniture, and other interactive objects. This preference may stem from their visual appeal and “fun factor,” often showcased through engaging demonstrators and props.

Data collection applications, meanwhile, are most prevalent in health and sports sectors. It is evident that personal data on pressure ulcers, muscle activity, and other metrics can greatly benefit patients and athletes by enhancing health and performance. Additionally, robotic sensors are an essential application area, showing promise in VR motion-tracking gloves and pressure-sensitive ”skin” for humanoid robots that replicate human tactile response.

There is no clear correlation between the textile technique used and the intended application. Knitting, sewing, and weaving are utilized across various use cases, although knitting appears more frequently in demonstration examples. This indicates that application-based criteria cannot serve as an effective filter in our research, since it appears all textile fabrication methods can be adapted to produce any type of application.

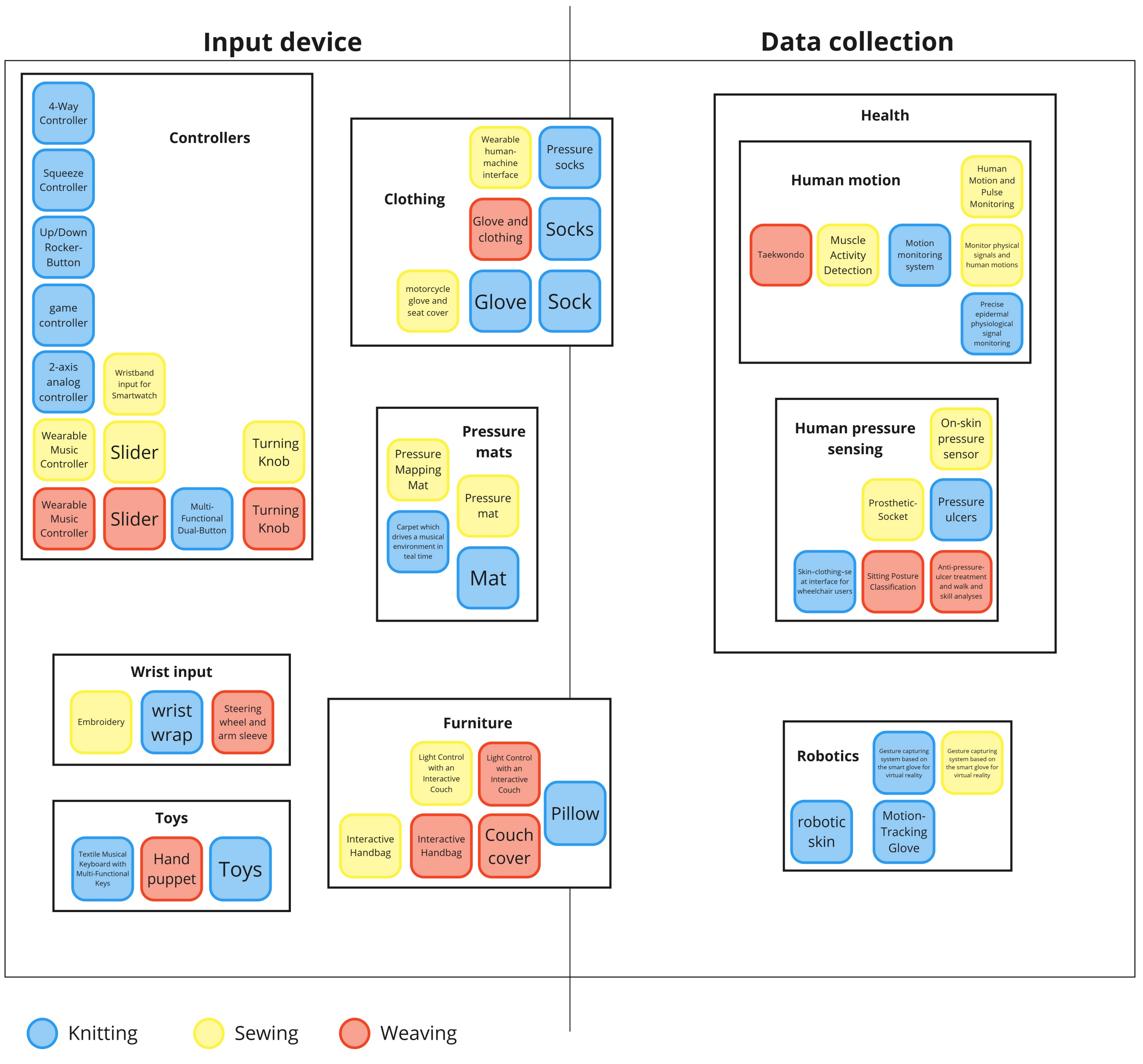



Fig. 11. Applications

*Conductive yarn*

A yarn is a continuous strand of fibers spun or twisted together for weaving, knitting, sewing, or embroidery. In smart textiles, these yarns are combined with conductive materials—commonly silver-coated, stainless steel, or carbon-based fibers—to create conductive yarns.

Conductive yarns are crucial in two main areas: performance and availability. In reviewing our database of conductive yarns, it is difficult to determine whether one outperforms another because many variables influence a pressure sensor's performance. However, we can distinguish conductive yarns by whether they are self-produced or off-the-shelf.

In appendix B, all researched yarns are listed and ranked as off-the-shelf or self-produced yarns. Preferably a off-the-shelf yarn would be desirable as getting access to these self-made yarns is highly unlikely and out of the scope of this project. Because we know which yarns are off-the-shelf a comparison can be made between those yarns which have the desired sensitivity and detection range. Figure 12 shows all sensors from previous analyses in the detection range chapter.

If we now remove all self-produced yarns and indicate the sensing method, but exclude triboelectric sensors, we get figure 13. With this selection of sensors we have come to our final set of sensors which we can choose from. All these sensors are either resistive or capacitive, have a known sensitivity value, a desired detection range between 0 - 100 kPa and makes use of an off-the-shelf yarn.

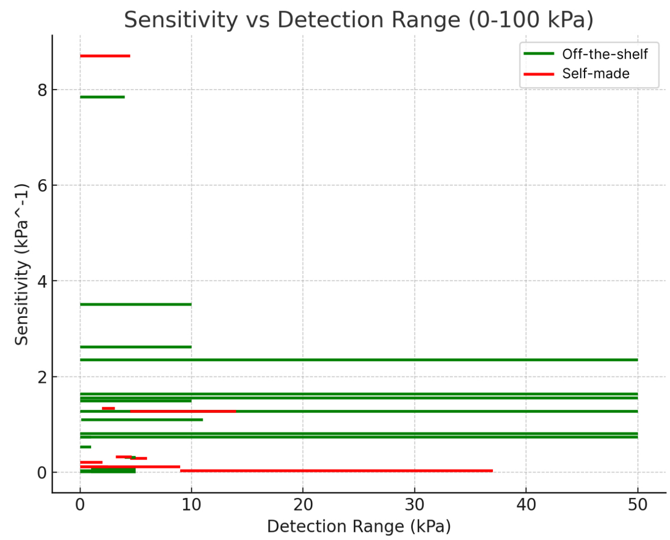



Fig. 12. Sensitivity vs detection range (Yarn type)(0-100kPa)

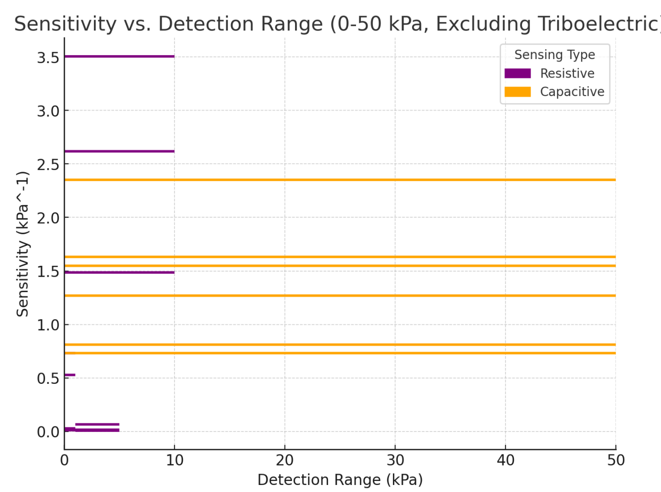



Fig. 13. Sensitivity vs detection range (Yarn type and sensing technique)(0-100kPa)

*Conclusion*

The focus of this literature research was to find potential research gaps or opportunities who allow us to either knit, weave or sew a pressure sensor ready-made without any post-production steps. We did this gathering a collection of different sensor designs who we have evaluated quantitatively and qualitatively. Our quantitative research focused on filtering sensors based in their criteria. We found that the criteria sensing technique, sensitivity, detection range, response and recovery time and conductive yarn gave us a clear filtering value while hysteresis turned out to be hard to define and applications didn't filter any production technique.

The final quantitative selection of sensors are shown in figure 14. These are: 'A Pillow-Shaped 3D Hierarchical Piezoresistive Pressure Sensor' [20] from Tian, 'Fully-Textile Seam-Line Sensor' [42] from Agcayazi and two from 'High sensitivity knitted fabric bi-directional pressure sensor' [49] from Xie.

From our qualitative selection seven papers were chosen. These papers didn't contain any data about the sensitvity of their sensor but were considered because of their structure. They either had rather thin structures or their structure didn't include any post-proccesing steps. These are: 'spaceR' [2] from Aigner, 'KnitUI' [4] from Luo, 'Loopsense' [1] from Aigner, 'Embroidered Resistive Pressure Sensor' [6] from Aigner, 'Opportunities with Multi-Layer Weave Structures' [40] from Pouta, 'TexYZ' [5] from Aigner and finally Footfalls patent from McMasters [50].

A clear observation from figure 14 is visible, most ready-made pressure sensor are knitted, second is sewing and last is weaving. As far as this research can conclude their are no ready-made woven pressure sensors developed, so far. This shows a clear opportunity to be one of the first to develop such a sensor.

There is one sensor which comes close though, the multilayer weaving design from Emmi Pouta [40]. Her paper explores multi-layer weaving structures and concludes with a woven pressure sensor. She diverges from the double-weave approach that simply inserts a piezoresistive sheet into a pocket. Instead, Pouta wove a middle layer using piezoresistive EeonTex stripes. However, EeonTex stripes are not yarns and are unsuitable for large industrial weaving machines. Therefor we can come in and try to develop a fully woven, ready-made pressure sensor based on her work.

Besides the weaving opportunity a smaller exploration was made for knitting ready-made pressure sensors. These two sensors were the 'High sensitivity knitted fabric bi-directional pressure sensor' [49] from Xie and Footfalls patent from McMasters [50]. These didn't turn out to be fruitful and can therefor be found in Appendix C.

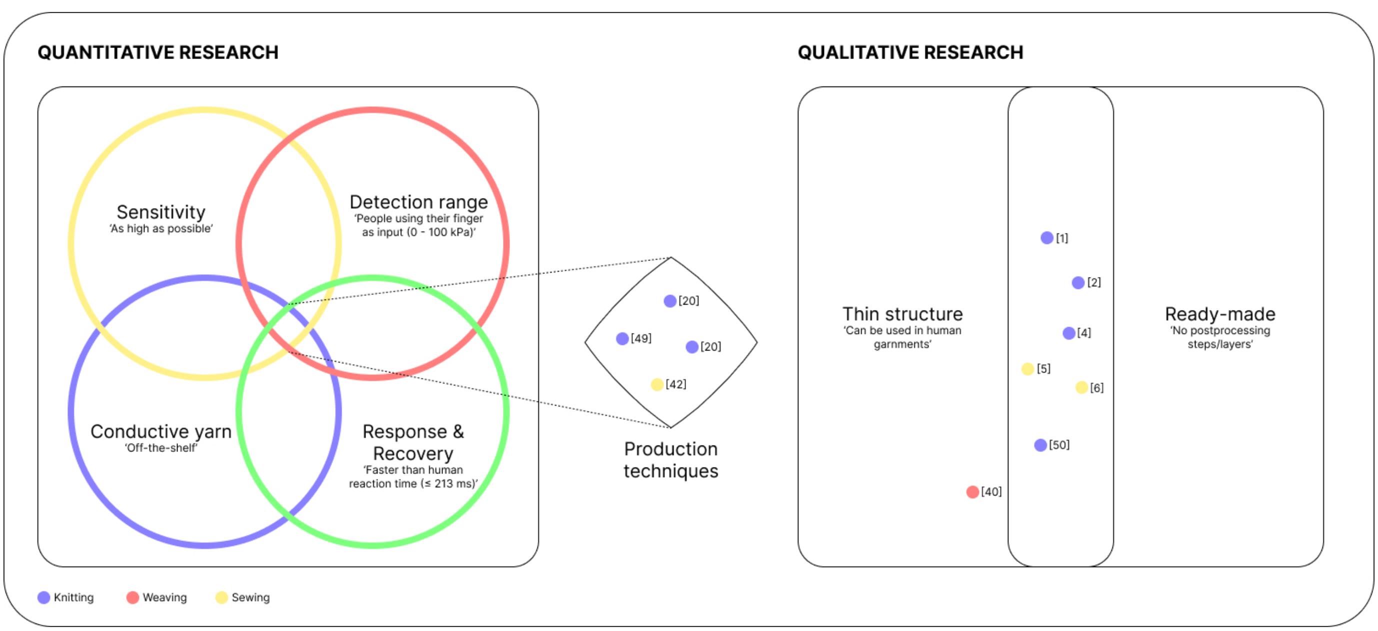



Fig. 14. Conclusion literature research

## IV. METHODOLOGY

This thesis research is conducted on an iterating process, see figure 15. Based on the literature research a promising research gap was identified that their are no fully woven ready-made pressure sensors. Pouta's sensor seems to be close but falls short due to using EeonTex stripes.

Our iterative process consists of 11 explorations, beginning with the investigation of eight different sensor structures. These structures are compared to identify key working principles. In each subsequent exploration, we modify a single variable in the structure to assess its impact. These comparisons help determine whether a specific change improves or negatively affects the sensor's performance.

Five iterations are conducted for the initial eight structures, leading to the development of four new structures based on newly gained insights. After four additional iterations, a final structure is selected. This structure undergoes three further iterations, ultimately resulting in the final sensor design. The sensor is then integrated into an application called Press Zoom, demonstrating potential an usecase. Our methodology ends with extracting the key insides found in our explorations.

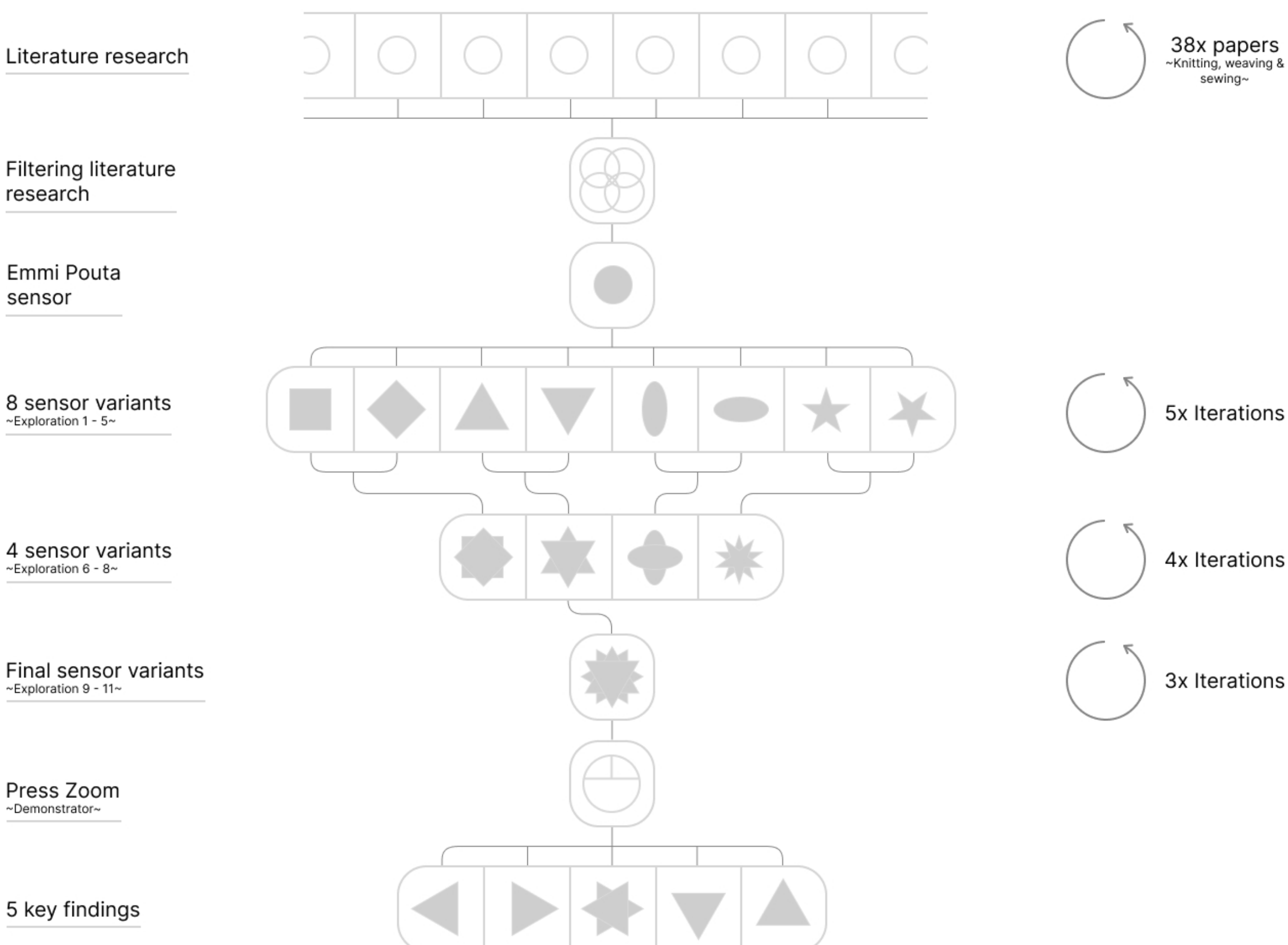



Fig. 15. Experimentation

## V. Design variables weaving

From the literature research, we identified multiple criteria for evaluating pressure sensors. The next step is to establish design variables that allow us to control and optimize these criteria.

For example:

- To design a sensor with low hysteresis (and therefore high response and recovery time), the sensor materials should be more elastic.
- To increase sensitivity, the sensor structure can be adjusted to deform more easily under lower force.
- Selecting conductive yarns with higher conductive fiber/particle content can enhance the interface effect, increasing sensitivity.

In woven pressure sensors there are a limited amount of design variables which can be tuned to control the behaviour of our sensor. These design variables are critical, as the allow us to compare and adjust parameters for sensor performance. In this research we define three main variables, yarns, structure and dimensions which all have multiple parameters, as illustrated in figure 16.

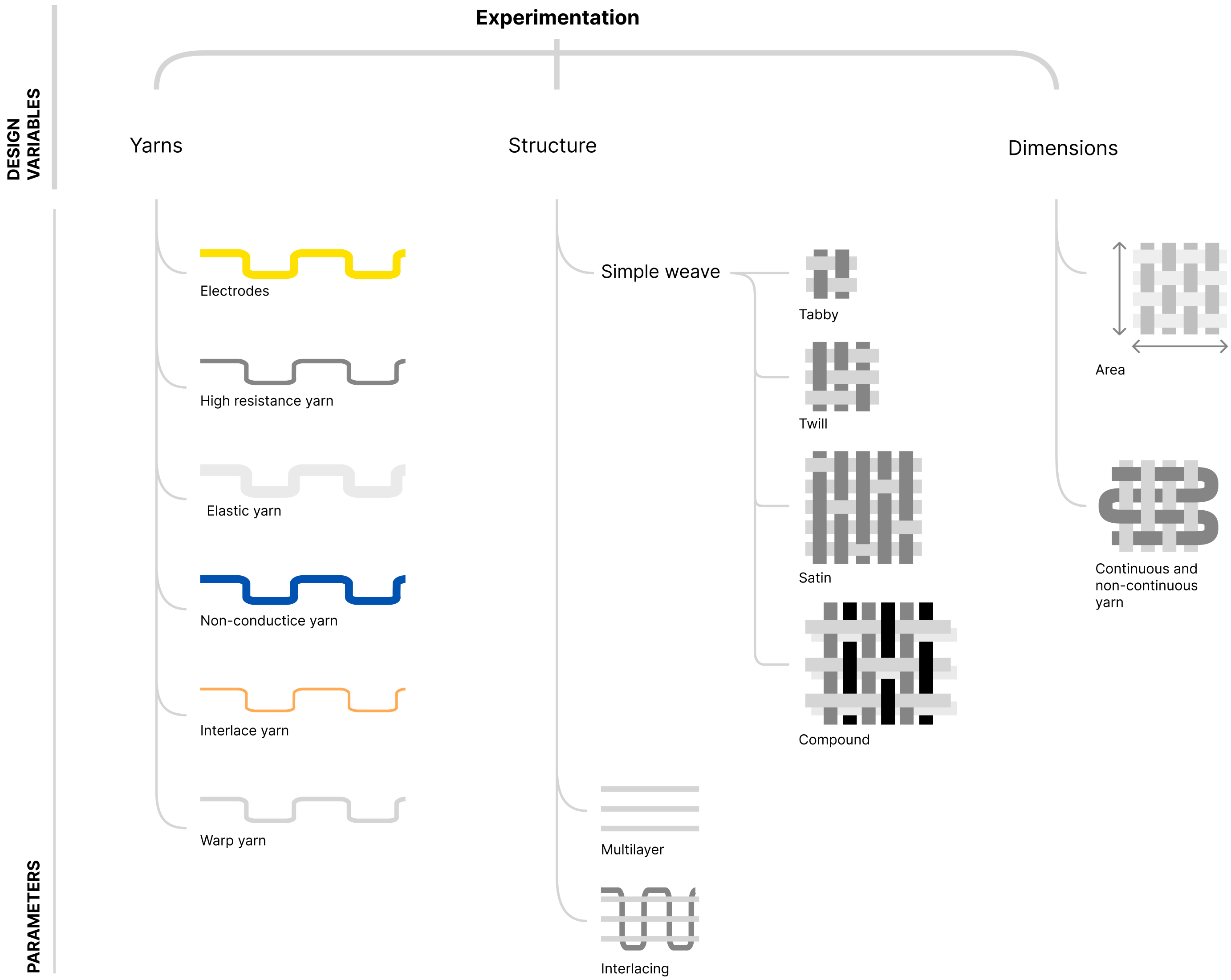



Fig. 16. Experimentation

*Yarns*

The choice of yarn is critical in sensor design because it affects both resistivity and elasticity. In our research, we consider five distinct yarn roles:

- Electrodes
- High resistance yarns
- Elastic yarns
- Non-conductive yarns
- Warp yarns

*Electrodes:* Electrodes measure changes in resistance. In a standard pressure sensor, two electrodes are placed on the top and bottom sides of a piezoresistive material.

Key parameters for electrode yarns include:

- Material: Typically silver-coated or stainless steel, though materials such as graphene or carbon may also be used.
- Electrical Resistivity: This quantifies the resistance per meter; lower resistivity is preferred for electrodes relative to high resistance yarns.
- dtex: This measures the linear density of the yarn (mass per 10,000 meters) and indicates its thickness or fineness.

Among these, resistivity is the most critical parameter, ensuring that the electrode yarn has a significantly lower resistivity than the high resistance yarn.

*High Resistance Yarns:* High resistance yarns are arguably the most crucial component in a pressure sensor. They enable the interface effect—as pressure deforms the sensor, more contact points form between the high resistance yarn and the electrodes, which leads to a decrease in resistance. Like electrodes, their key parameters include material, resistivity, and dtex; however, the high resistance yarn must exhibit a relatively higher resistivity than the electrode yarn.

*Elastic Yarns:* Elastic yarns are an area of focus in this research, as they may help mitigate hysteresis—a phenomenon where the relative resistance change differs between applying and releasing pressure.

Elastic yarns could carry the load applied by pressure, and when released deform back to its original state. The interface effect would still occur while the compressive strength is handled by the elastic component instead of the high resistance yarns. This approach eliminates the need for a single ”ideal” yarn that combines both properties.

Here, factors such as the diameter and elasticity of the yarn are particularly important.

*Non-conductive yarn:* Due to certain sensor structures it may be needed to introduce a non-conductive yarn to allow for structure stability. In these cases its important, that these yarns don’t conduct electricity. Parameters like material and dtex are leading here. Materials can vary widely but most common are polyester, cotton and nylon.

*Warp yarn:* The warp yarns are held under tension on a loom, while weft yarns pass between warp yarns that are raised in specific sequences to create structures and patterns. In this research it wasn’t feasible to test with different kind of warp yarns, as replacing warp yarns on the TC2 is a cumbersome and labourite process. Therefor the mercerised cotton 44/2 is used pre-installed on the loom.

*Structure*

The structure of a pressure sensor allows for control of how the yarns interact with each other. There are an infinite amount of ways to structure a weave but for this research the focus was put on the parameters simple weaves, multilayer and interlacing.

*Simple weaves:* Simple weaves like tabby, twill and satin are the most common structures you will find in woven fabrics. A visual representation can be seen in figure 16. These structures differentiate themself due to their interlacing frequency and therefor have different properties as well, see table III.

TABLE III
SIMPLE WEAVES

| Weave | Interlacing pattern | Appearance | Flexibility | Strength |
|---|---|---|---|---|
| Tabby | 1/1 (over-under) | Uniform | Low | High |
| Twill | Over 2+ | Diagonal lines | Medium | High |
| Satin | Over 4+, under 1 | Smooth | High | Low-Medium |

Twill and satins tend to be less stiff thus making them more breathable and yarns within them can move around more freely. Tabbies on the other hand are more stiff which allows yarn to be more snug and move less around. The breathability would maybe allow for a better recoverability while the snug fit would maybe allow for better control over the movement of the yarns.

Lastly compounds are also an interesting approach as these allow for double-layered fabrics, with for example one conductive yarn on the top and one high resistance yarn on the bottom.

*Multilayer:* Multilayer structures are fabrics with multiple layers, as the name implies. These could be incredibly useful for pressure sensors. For example, with a three layer structure the bottom and top layers could use electrode yarns, and the middle layer could use the high resistance yarns. There is even possibility to allow for more layers like four or five.

*Interlacing:* Interlacing refers to where the weft passes over or under a warp the yarn. This seems obvious for simple tabbies and twills but becomes more interesting when looking at multiple layers. For example when you have a three layer weave, you can let a weft yarn from the top layer interlace all the way down to the bottom layer. This causes the two layers to get stuck together at this point and would for example allow for control over how far the layers are able to separate from each other, before getting tensioned by the interlacing yarn.

*Dimensions*

Would we find a proper structure that shows desired behaviour, the next step would be to look at making the pressure sensor area larger, according to its specific use case. This does have certain implications as making the conductive area larger also has implications for the resistance for example.

*Area:* There are multiple factors which would influence the pressure sensor behaviour ones the area is increased. The first factor is that the total resistance would decrease as there are more contact points. A larger sensor means more high resistance yarns are in contact with electrodes, reducing the total resistance. If the resistance would drop too low than measurement errors would become a bigger problem, as these are not affected by the pressure sensor area and would probably stay the same.

Second, its possible that the fluctuations in measurements will decrease due to a larger area. Fluctuations in smaller sensors can be because of misaligned yarns which can cause weird peaks in initial measurements. It could be that these peaks will average out when a larger sensing area is used which would result in more stable behaviour.

*Continuous or non-continuous yarns:* When increasing the dimensions of a pressure sensor in the warp direction you are faced with the following problem. The electrodes and high resistance yarns conduct electricity from the top to the bottom layer, but they also conduct electricity from the beginning till end point of the yarn. This yarn is therefore running left to right in the weft direction as illustrated in figure 16. This is what we call a continuous woven yarn, as their is no point where the yarn is cut in two pieces.

However the problem comes when the sensor is cut through the middle in the warp direction. Most industrial weaving machines make use of a rapier which cuts the yarns at the end of the fabric. This would only allow for a non-continuous yarn structure to form.

Electricity would thus most likely have a higher resistance flowing from one yarn segment to the next.

## VI. Experiments weaving

For the weaving sensor tests, Emmi Pouta's design was chosen as a baseline. Her paper explores multi-layer weaving structures and concludes with a woven pressure sensor. She created a linked three-layer structure within a single-layered double-faced satin weave base fabric, diverging from the double-weave approach that simply inserts a piezoresistive sheet into a pocket. Instead, Pouta wove a middle layer using piezoresistive EeonTex stripes.

However, EeonTex stripes are not yarns and are unsuitable for large industrial weaving machines. This study aims to take a step closer to industrially viable woven pressure sensors.

### *Materials*

To ensure comparability, all woven pressure sensors follow standardized variables, including yarns, weave structure, and machine settings. In each experiment, only one variable is altered to assess its impact on sensor performance.

The following yarns were used:

TABLE IV
Yarn specifications weaving

| Yarn | Notation | Linear density | Resistivity |
|---|---|---|---|
| Electrode | Shieldex 235f36 | 235/36 dtex | 600 Ω/m |
| High resistance | Bekaert Bekinox/VN35 | 350 dtex | 35 Ω/m |
| High resistance | Silver-Tech HY7LX | 96 dtex | 85 Ω/m |
| Elastics | Elastomeric | - | - |
| Interlace | Mercerised cotton | 44/2 dtex | - |
| Non-conductive | PES W009262-W11111 | 110/32 dtex | - |
| Warp yarn | Mercerised cotton | 44/2 dtex | - |

The pressure sensors were woven on a TC2 hand-weaving machine with a tension between 250 and 350. Every sensor has a weft length of 40 mm while the warp length can vary based on the woven structure.

### *Measurements techniques*

The electromechanical performance of the woven pressure sensors was evaluated using a Rheometer, applying 80 kPa of pressure in four test cycles. Each cycle applied pressure for 10 seconds before release. To ensure even pressure distribution, the sensor was placed between two rubber pads. Resistance changes were recorded using a two-probe multimeter, which also captured resistance variation over time. A schematic of the setup is shown in figure 17.

For these initial tests, only the relative resistance change was measured, comparing the initial state to the state after 10 seconds. Once a specific pressure sensor structure is selected for further development, more detailed measurements will be assessed such as sensitivity and detection range.

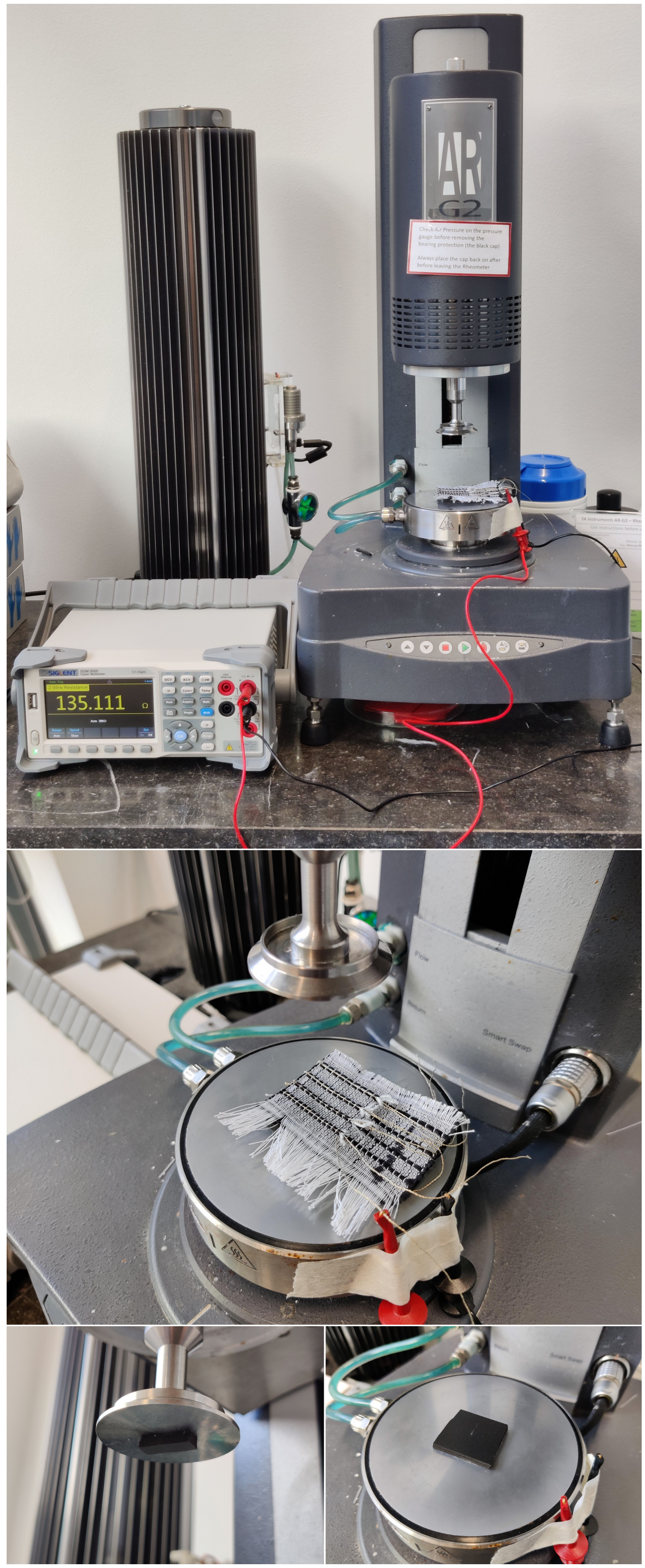



Fig. 17. Measurement setup

*Exploration 1: Three-layer weave*

To replicate Emmi Pouta's sensor, Shieldex S235 is used as the electrode yarn, while Bekinox Bekaert serves as the high-resistance yarn. The sensor is constructed as a three-layer structure (see figure 18), with a plain weave applied to all layers. To prevent short-circuiting between the electrodes, two Bekinox yarns are woven for every one Shieldex yarn. Since Bekinox yarns have approximately half the diameter of Shieldex yarns, this configuration ensures an even and balanced structure.

To explore variations within this design, additional structures were tested with two key modifications (see figure 18):

- Threading Shieldex yarns either single- or double-sided.
- Increasing the number of Bekinox yarns in the warp direction.

These variations are inspired by the FSR model from Karsten Weib and Heinz Wörn [26], who investigated the effects of single- and double-sided sensor contacts. Their study suggests that placing both electrodes on the bottom prevents the upper electrode from experiencing bending stress. In our design, this is less problematic since our electrodes are inherently flexible; however, it remains an interesting aspect to explore.

Additionally, increasing the number of high-resistance yarns creates a higher resistance path, as the current must traverse multiple yarns before reaching the opposite electrode. By extending this length, we can determine the effective limit of this approach. All bitmaps and map of bindings can be found in Appendix D.

*Results:* The complete results are presented in table V. This table shows the most promising graph from the four tests conducted, all graphs can be seen in Appendix E. The analysis focuses on two key factors:

- The presence of a U-shaped or inverse U-shaped profile, indicating the expected resistance change during pressure application and release.
- Repeatability across four test cycles. The first two tests often show irregularities due to initial yarn positioning, making the last two tests more representative.

TABLE V
RESULTS EXPLORATION 1

| Sensor | U-shape | Repeatable | Relative resistance change $\frac{\delta R}{R}$ |
|---|---|---|---|
| 1 | Yes | No | -0.82 |
| 2 | Inverse | No | 5.25 |
| 3 | No | No | - |
| 4 | No | No | - |
| 5 | Yes | No | -0.80 |
| 6 | No | No | - |

If a sensor exhibits a well-defined U or inverse U profile, the relative resistance change can be estimated, providing insight into its potential accuracy.

*Discussion:* This initial exploration suggests that the sensors exhibit largely random behavior with no repeatability, indicating minimal yarn recovery. Additionally, the Bekinox yarns, composed of a stainless steel core with loosely twisted fibers, may cause sticking effects that hinder recoverability.

A slight trend emerged: as the number of high-resistance yarns in the current path increased, the U-shaped profile deteriorated. This is expected, as only the Shieldex yarns make firm contact with the Bekinox yarns beneath them due to pressure, while intermediate yarns remain less engaged. In contrast, Weib and Wörn's design used an EVA foam probe, which conducts current within its material unaffected by applied pressure. However, this exploration relies on an interface effect between the Bekinox yarns perpendicular to the applied pressure, which explains the malfunctioning of sensors with more high-resistance yarns.

Due to the lack of clear advantages for either single-sided or double-sided electrode weaving, we have decided to exclusively use double-sided electrode sensors moving forward. These sensors offer a more compact structure, as demonstrated by sensors 1 and 2, which do not have a single-sided variant.

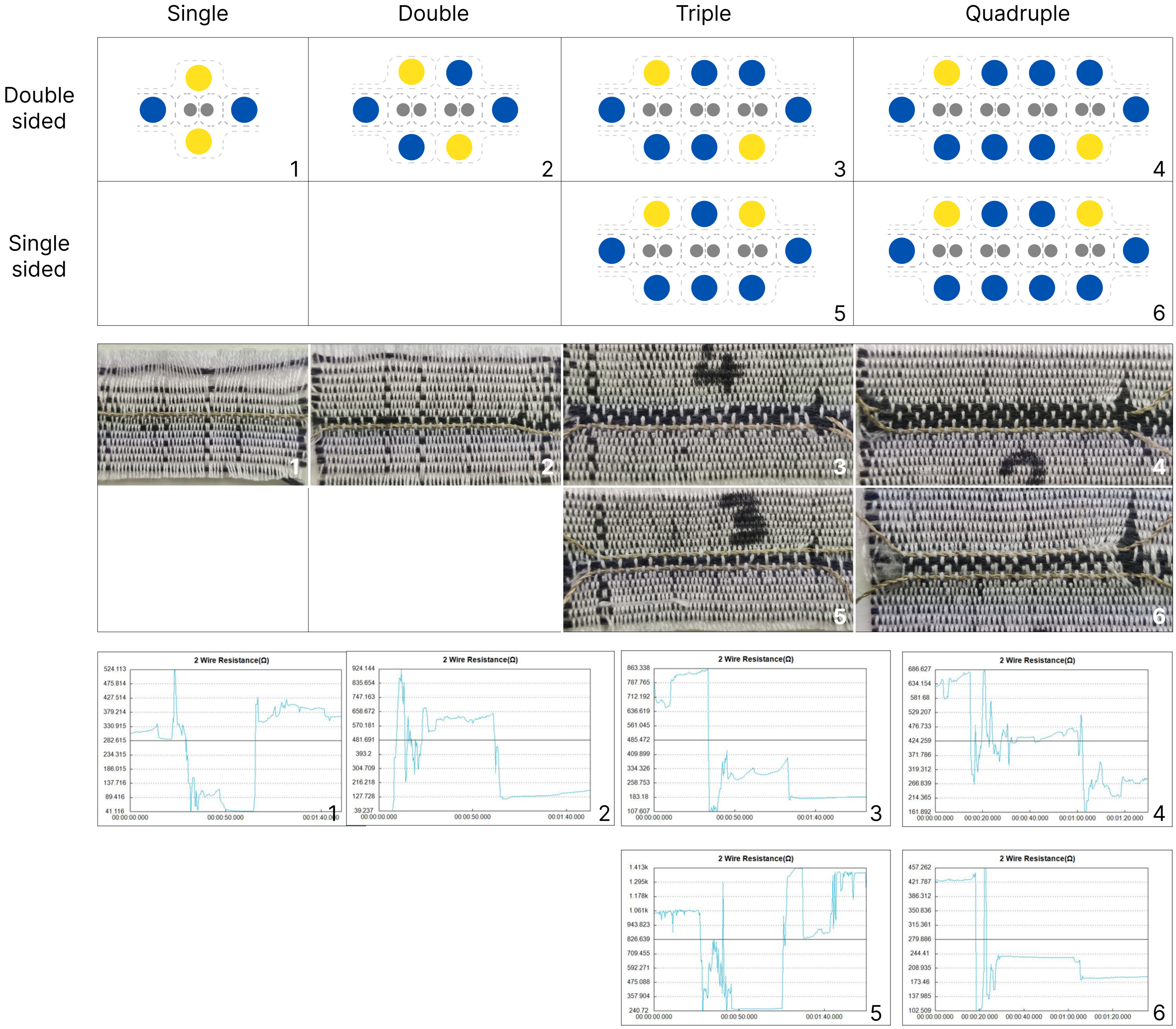



Fig. 18. Exploration 1

*Exploration 2: Adding elastic yarns*

To investigate sensor recoverability, a modified structure incorporating elastic yarns in the middle layer was used (see figure 19). These elastic yarns help separate the Shieldex and Bekinox layers when decompressing, while their larger diameter increases spacing between layers.

To explore variations within this concept, different structures were tested (figure 19). Two key factors were adjusted:

- *Stacking of Bekinox and elastic yarns* – This affects the relative distance change between the electrode yarns. For example, sensor 2 has a short travel distance due to a single elastic layer and a double Bekinox layer, whereas sensor 7 has the opposite configuration, with a double elastic layer, a single Bekinox yarn, and offset Shieldex electrodes.
- *Electrode alignment (parallel vs. offset)* – This tests whether individual layers shift relative to each other, as the three layers are not interlaced. Interlacing could be a potential avenue for further exploration.

*Results:* The full results are presented in table VI. Three out of eight sensors exhibited repeatable behaviour, a promising indication. Additionally, half of the sensors displayed either a U-shaped or inverse U-shaped response.

TABLE VI
RESULTS EXPLORATION 2

| Sensor | U-shape | Repeatable | Relative resistance change $\frac{\delta R}{R}$ |
|---|---|---|---|
| 1 | Inverse | Yes | 1.54 |
| 2 | Inverse | No | 0.61 |
| 3 | No | No | - |
| 4 | Yes | Yes | -0.73 |
| 5 | No | No | - |
| 6 | Yes | Yes | -0.70 |
| 7 | No | No | - |
| 8 | No | No | - |

*Discussion:* The inclusion of elastic yarns appears beneficial, as three sensors demonstrated both repeatability and a clear U-shaped response.

Sensors 1, 2, 4, and 6 all exhibit U-shaped behavior, and notably, three of these sensors employ a double high-resistance structure. This observation may suggest that the interface effect between high-resistance yarns is more effective than the interface between the electrodes and the high-resistance yarns.

Among the parallel electrode structures, three produced U-shaped profiles. Sensor 3, which did not, had the largest relative electrode distance, as seen in graph 3 where no connection was made. A similar issue was observed in sensor 7, which shared the same structure but with offset electrodes, suggesting that double elastics with single high resistance structures are ineffective.

Most offset electrode structures failed to yield meaningful results, except for sensor 6. Its success may be because it has the smallest relative distance between the electrodes.

Another noteworthy observation was that the large diameter of the elastic yarns caused adjacent yarns to slide over them, necessitating adjustments prior to testing. This could pose challenges for obtaining accurate measurements.

Overall, offset electrode placement significantly influenced sensor performance, with shifting layers contributing to unpredictable behaviour. However, elastic yarns improved recoverability, particularly in parallel electrode structures.

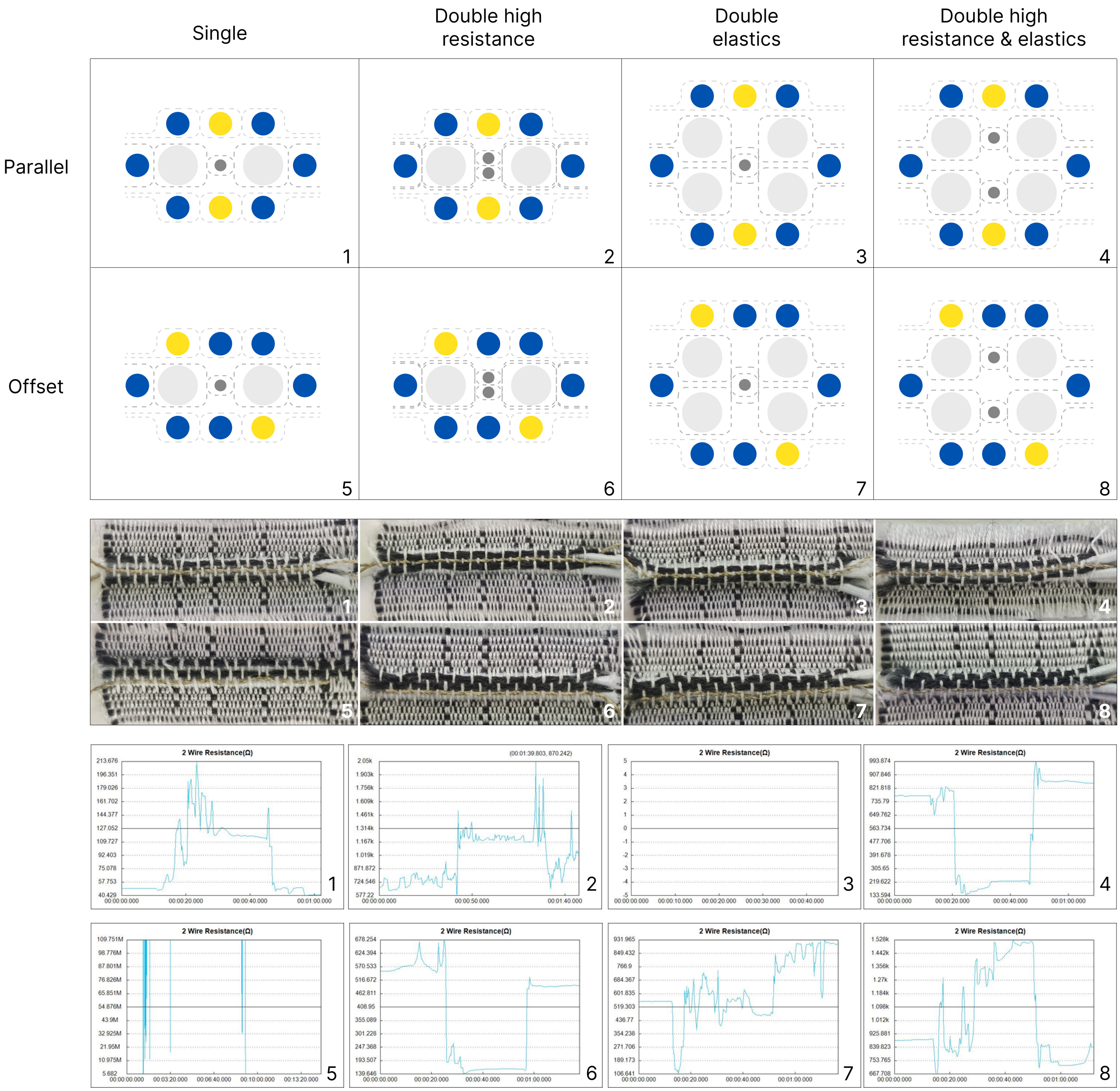



Fig. 19. Exploration 2

*Exploration 3: Adding smaller elastic yarns*

To address the issue of yarns gliding over the elastic yarns in the previous exploration, this iteration used elastic yarns with a smaller diameter while keeping the overall structure unchanged (see figure 20).

*Results:* Four out of eight sensors exhibited repeatable behavior, similar to the previous exploration. Five sensors displayed a U-shaped or inverse U-shaped profile, again matching prior results, see table VII.

A noticeable improvement was the elimination of yarn slippage over the elastic yarns, leading to more consistent test.

TABLE VII
RESULTS EXPLORATION 3

| Sensor | U-shape | Repeatable | Relative resistance change $\frac{\delta R}{R}$ |
|---|---|---|---|
| 1 | No | No | - |
| 2 | Inverse | Yes | 1.50 |
| 3 | Inverse | Yes | 0.99 |
| 4 | Inverse | Yes | 1.84 |
| 5 | Yes | Yes | -0.43 |
| 6 | No | No | - |
| 7 | Inverse | No | 2.29 |
| 8 | No | No | - |

*Discussion:* The hypothesis from Exploration 2—that a greater relative distance between electrodes negatively impacts performance—does not hold for these samples. Among the parallel electrode sensors, only sensor 1 failed to exhibit a U-shaped profile or repeatable behaviour. If excessive electrode spacing were the primary issue, sensor 3 should have performed the worst, yet it performed reasonably well.

An alternative explanation is that electrode spacing not only has a maximum but also a minimum threshold. The elastic yarns may create sufficient separation between the Bekinox and Shieldex yarns, but too small a gap could also impair function, by creating permanent contact between electrodes and high resistive yarns. If this were true, sensors 1 and 2 should perform worse than sensors 3 and 4 due to insufficient spacing. However, since sensor 2 performed well while sensor 1 did not, this theory does not fully hold.

For the offset electrode sensors, sensors 5 and 7 performed well, while sensors 6 and 8 did not. If electrode spacing were the determining factor, this would suggest that sensors 5 and 7 fall within an optimal range, while sensor 8 exceeds the maximum threshold and sensor 6 is below the minimum.

Overall, although this exploration resulted in more successful sensors, a clear pattern explaining their behavior remains unclear—it raises more questions than answers. One consistent observation, however, is that the parallel sensors continue to outperform the offset sensors.

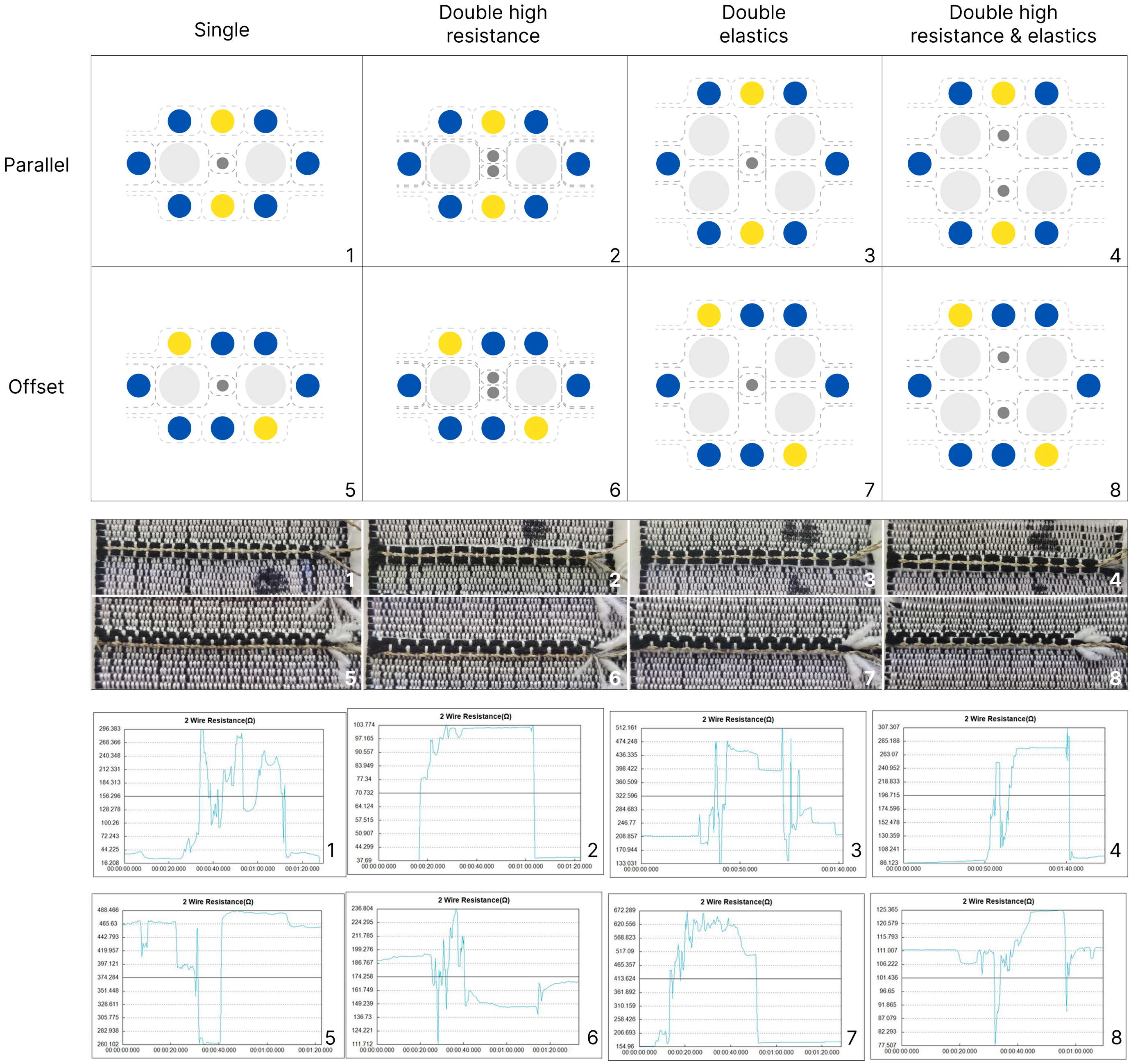



Fig. 20. Exploration 3

*Exploration 4: Wider elastic yarn area*

One hypothesis from the previous exploration was that the elastic yarns might not recover fully because they are too densely compressed by the surrounding plain weave (see figure 22). This experiment builds directly on Exploration 3, aiming to improve sensor stability.

*Results:* A key observation is that the double-stacked elastic yarns did not function as expected. Sensors 3, 4, 6, 7 and 8 failed to exhibit a proper U-shaped response, suggesting that combining a double elastic yarn layer with a wider elastic yarn area leads to instability, see table VIII.

TABLE VIII
RESULTS EXPLORATION 4

| Sensor | U-shape | Repeatable | Relative resistance change $\frac{\delta R}{R}$ |
|---|---|---|---|
| 1 | Inverse | Yes | 0.93 |
| 2 | Inverse | No | 0.43 |
| 3 | No | No | - |
| 4 | No | No | - |
| 5 | Yes | Yes | -0.22 |
| 6 | No | No | - |
| 7 | No | Yes | - |
| 8 | No | No | - |

*Discussion:* One possible explanation for the failure of sensors 3, 4, 6, 7 and 8 is layer shifting, as previously discussed. This phenomenon, illustrated in figure 21, occurs because the layers lack interlacing yarns, causing them to shift into a hexagonal configuration. This likely increases or varies the relative electrode distance between tests, reducing sensor consistency.

Despite these challenges, sensors 1 and 5 exhibited repeatable behavior, and sensors 1 and 2 showed an inverse U-shaped response. The reasons behind these improved performances remain unclear. Overall, sensors with a wider elastic yarn area performed worse than those in Explorations 2 and 3, and have therefore been discarded going forward.

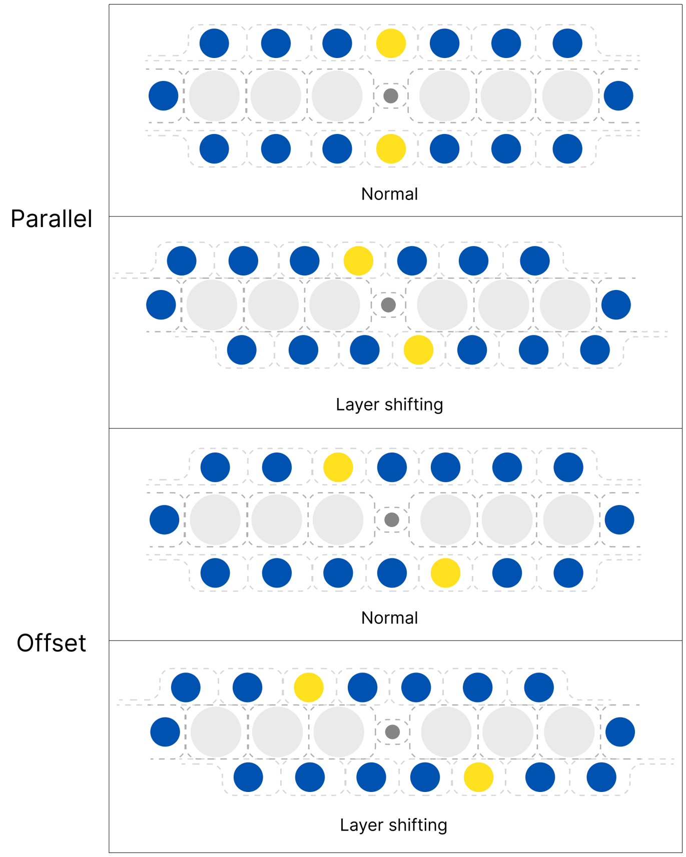



Fig. 21. Layer shifting

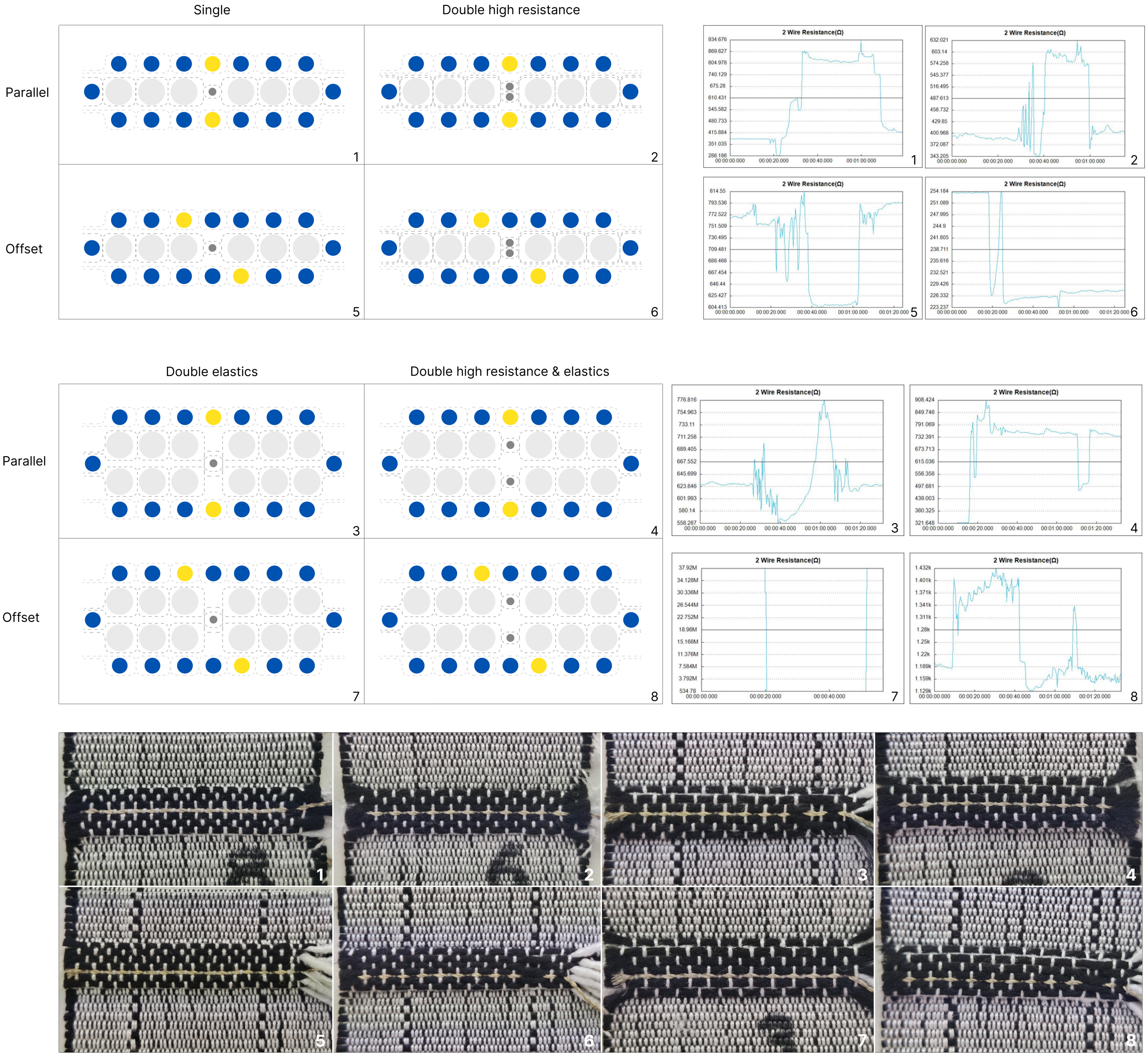



Fig. 22. Exploration 4

*Exploration 5: Different high resistance yarn*

Until now, the role of the Bekinox yarn in sensor performance has remained unclear. The use of double Bekinox yarns was theorized to have a better interface effect in Exploration 2. To investigate further, Bekinox was replaced with an alternative high-resistance yarn, see figure 23.

A selection was made from the available conductive yarns, see table X, ultimately choosing Silver-Tech HY7LX. This yarn was selected because its resistance falls within the same range as Bekinox, but it has a larger diameter. The increased diameter gives the yarn a bigger contact area which would theoretically allow for a higher interface effect.

TABLE IX
RESULTS EXPLORATION 5

| Sensor | U-shape | Repeatable | Relative resistance change $\frac{\delta R}{R}$ |
|---|---|---|---|
| 1 | Yes | Yes | 0.11 |
| 2 | No | No | - |
| 3 | Yes | Yes | 0.16 |
| 4 | No | No | - |
| 5 | No | No | - |
| 6 | No | No | - |
| 7 | No | No | - |
| 8 | No | Yes | - |

*Results:* An interesting trend emerged from the data: there appears to be a correlation between yarn resistance and stability. Higher-resistance yarns tend to be more unstable. Here, instability refers to a simple test where a 1-meter yarn is tensioned and plucked like a guitar string to observe its resistance fluctuations. A stable resistance is desired as it would probably decrease noise coming from the sensor output.

TABLE X
HIGH RESISTANCE YARNS

| Yarn | Resistivity Ω/m | Stability |
|---|---|---|
| Elektrisola 30004021L | 2.404 | Stable |
| Bekaert 9006089 | 10.677 | Stable |
| Bekaert 9006088 | 15.826 | Stable |
| Bekaert 9048821 | 29.727 | Stable |
| Shieldex 235f36 | 53 | Stable |
| Silver-Tech HY7LX | 295 | +/- 15 Ω/m |
| Silver-Tech RXR9K | 433 | +/- 3 Ω/m |
| Silver-Tech RNNT7 | 599 | +/- 4 Ω/m |
| Bekaert Bekinox | 789 | +/- 30 Ω/m |
| Shieldex 117f17 | 8000 | Unstable |
| Shieldex 78f20 | 10000 | Unstable |
| Bekaert BK 50/2KS | 180000 | Unstable |
| Bekaert BKSol1 | 200000 | Unstable |
| Elektrisola 3190409100002 | Overload | - |
| Elektrisola 3190409300 | Overload | - |

*Discussion:* Overall, the Silver-Tech yarn performed worse than the Bekinox yarn. Only two of the eight sensors exhibited a U-shaped response, and just three showed repeatable behaviour. Additionally, the two sensors with a U-shaped profile had relatively low resistance changes (0.11–0.16).

One clear finding is that offset electrodes do not contribute meaningfully to sensor function. Sensors 5, 6, and 7 showed no response, while sensor 8 functioned but at a high resistance of 34 $M\Omega$. Despite this, sensor 8 shows potential for use as a touch sensor or button.

One advantage of the Silver-Tech yarn is its stability. It provides a more consistent reading and fluctuates less than Bekinox. This is likely due to the structural differences: Bekinox consists of a stainless steel core with loosely twisted conductive fibers, both of which contribute to its conductivity but also to its variability in performance.

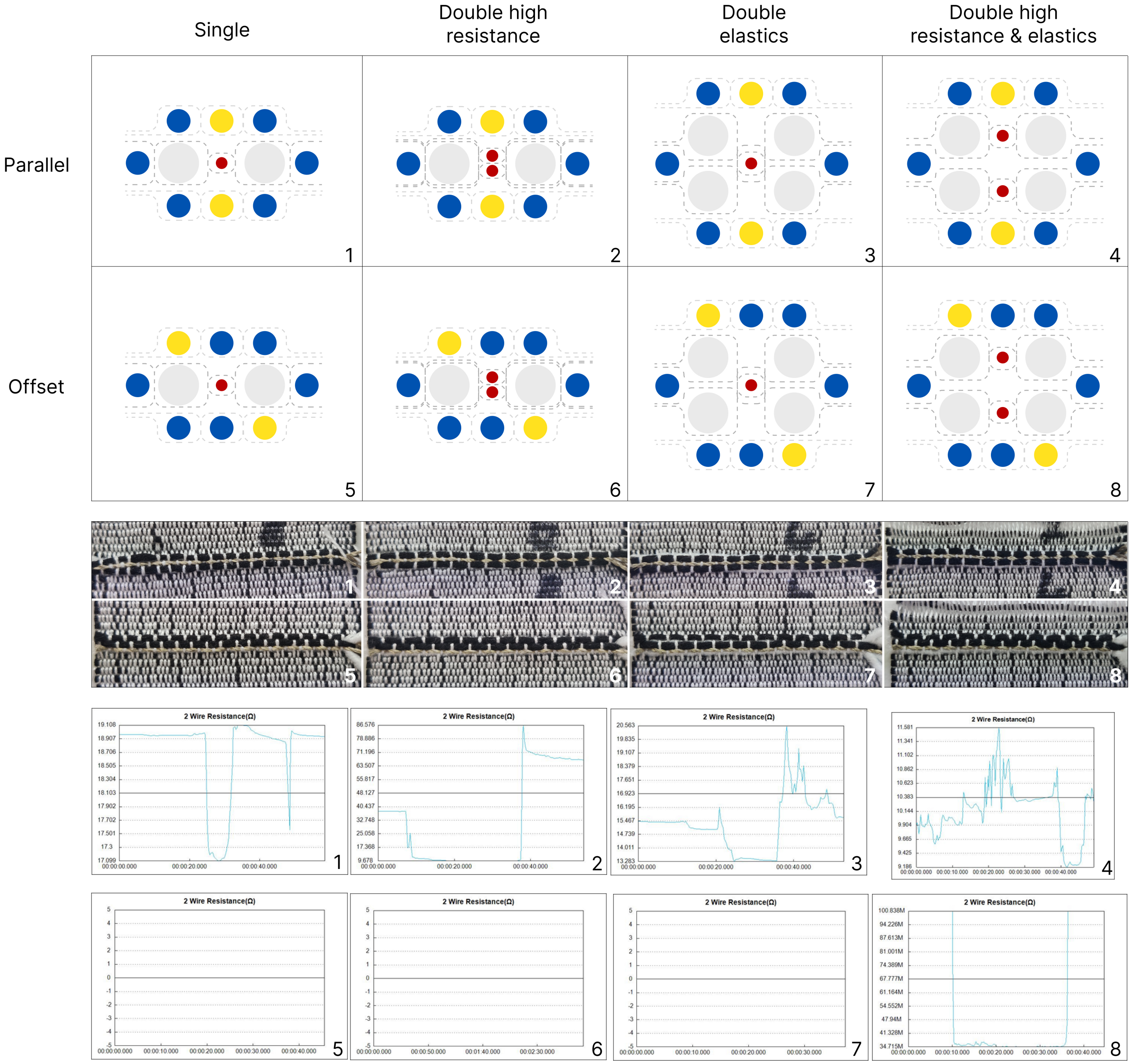



Fig. 23. Exploration 5

*Exploration 6: Larger conductive area*

This exploration investigates the effect of making the entire top and bottom layers conductive, rather than limiting conductivity to a single stripe, see figure 24. This approach aims to mitigate the issue of layer shifting, as any movement would still involve conductive yarns. Consequently, no distinction is made between parallel and offset electrodes, since Explorations 2 and 5 have shown that offset electrodes do not provide any performance benefits in sensor design.

For this test, conductive yarns were introduced in a discontinuous manner—each weft insertion included a new conductive yarn rather than using a single continuous yarn that snakes through the layers. This method was chosen for its ease of fabrication.

*Results:* Three of the four sensors showed an inverse U-shape relationship and of these three one showed repeatable behaviour, see table XI.

TABLE XI
RESULTS EXPLORATION 6

| Sensor | U-shape | Repeatable | Relative resistance change $\frac{\delta R}{R}$ |
|---|---|---|---|
| 1 | Inverse | No | 2.44 |
| 2 | No | No | - |
| 3 | Inverse | Yes | 1.46 |
| 4 | Inverse | No | 0.84 |

*Discussion:* Three out of four sensors exhibited a desirable inverse U-shape response, accounting for 75% of the samples—the highest success rate observed in any exploration so far. This suggests that increasing the electrode area has a positive impact on sensor performance.

When analyzing the results through the relative distance theory, sensor 2 likely falls below the minimum effective distance. This is expected, as its Bekinox yarns are positioned too close to the electrodes.

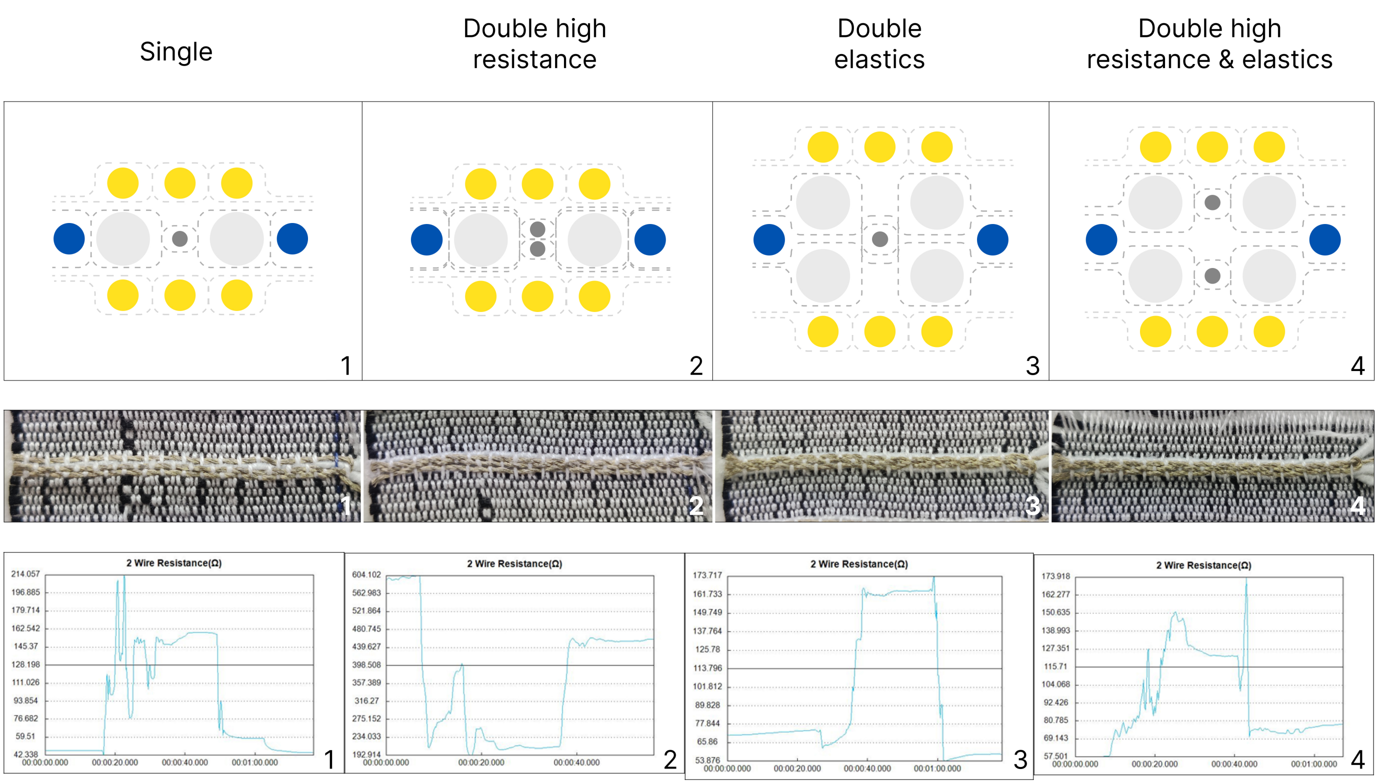



Fig. 24. Exploration 6

*Exploration 7: Combining different high resistance yarn and larger conductive area*

In this exploration, Explorations 5 and 6 were combined to evaluate whether the parallel and offset sensor configurations had any meaningful effect when using Silver-Tech resistive yarn see figure 25.

*Results:* None of the four sensors exhibited a U-shape response, but all produced repeatable results—just not in the desired manner, see table XII.

- Sensors 1 and 3 maintained a constant resistance of 7 Ω during both pressing and release, indicating that the high-resistance yarn was continuously in contact with both electrodes.
- Sensors 2 and 4 exhibited a resistance drop to 150 Ω and 290 Ω under pressure, suggesting intermittent electrode contact.

TABLE XII
RESULTS EXPLORATION 7

| Sensor | U-shape | Repeatable | Relative resistance change $\frac{\delta R}{R}$ |
|---|---|---|---|
| 1 | No | Yes | - |
| 2 | No | Yes | - |
| 3 | No | Yes | - |
| 4 | No | Yes | - |

*Discussion:* The results suggest that using two Silver-Tech yarns produces a more desirable response, as it creates a clear resistance change under pressure, whereas a single Silver-Tech yarn shows no variation at all. This is in line with Exploration 2 where it was theorized that the interface effect between high-resistance yarns is more effective than the interface between the electrodes and the high-resistance yarns.

Additionally, the behavior of Sensors 1 and 3 raises an interesting question: since no resistance change is observed, the resistive yarn may not be perfectly centered between the elastic yarns, potentially affecting performance.

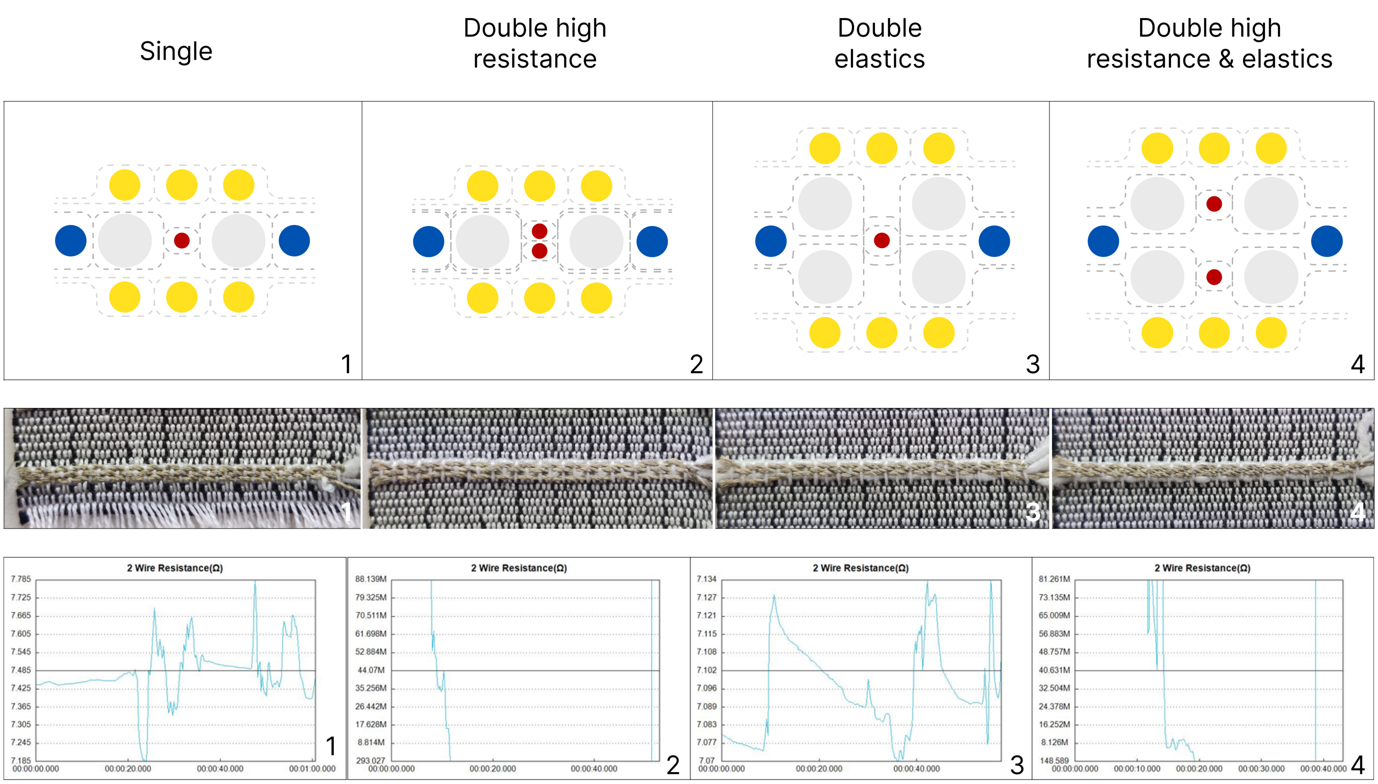



Fig. 25. Exploration 7

*Exploration 8: Interlacing*

A closer inspection of the woven sensors from Exploration 7 revealed why sensors 1 and 3 maintained continuous contact. A visualization of the sensor structure is shown in figure 26.

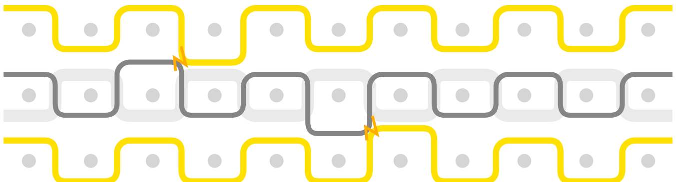


Fig. 26. Intermittently protrudes

It became clear that due to the plain weave, the high-resistance yarn intermittently protrudes through the weave structure. Initially, this was overlooked because previous analyses only considered a cross-section of the structure, where this effect was not immediately visible.

To address this, interlacing was introduced to ensure that the high-resistance yarn remains in firm contact with the electrodes (see figure 27). This design change allows the high-resistance yarn to recover above the elastic yarns when pressure is released.

This exploration tested two sensor types:

- Sensors from Exploration 6 (with a larger conductive area)
- Parallel sensors from Exploration 3 (as offset electrodes were found undesirable in Exploration 5)

*Results:* Of all eight sensors four show desired U-shape responses, of these four three show repeatable behaviour, see table XIII.

TABLE XIII
RESULTS EXPLORATION 8

| Sensor | U-shape | Repeatable | Relative resistance change $\frac{\delta R}{R}$ |
|---|---|---|---|
| 1 | No | Yes | - |
| 2 | Inverse | No | 0.77 |
| 3 | No | No | - |
| 4 | Yes | Yes | -0.23 |
| 1a | No | No | - |
| 2a | Inverse | Yes | 1.46 |
| 3a | No | No | - |
| 4a | Yes | No | -0.40 |

*Discussion:* One key takeaway is that sensors with only one resistive yarn did not produce the desired characteristics:

- Sensors 3 and 3a either showed no response or behaved more like a binary button, likely due to an excessive relative distance caused by the double-stacked elastic yarns.
- Sensors 1 and 1a also failed to show significant resistance changes, probably for the same reason.

Comparing Sensors 2 and 4 with Sensors 2a and 4a, the latter group exhibited a higher relative resistance change. This suggests that a larger conductive area improves overall sensor performance in terms of resistance variation.

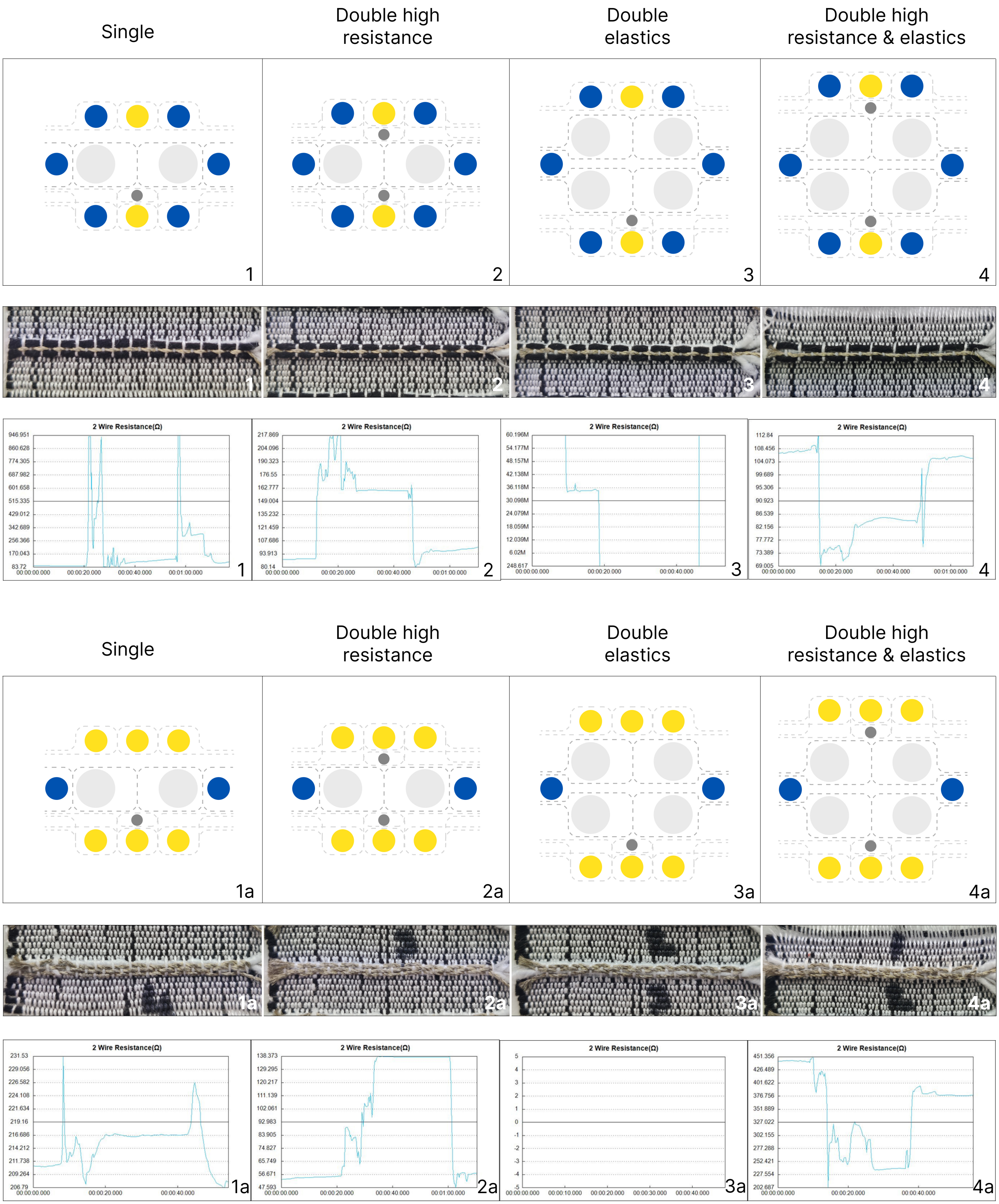



Fig. 27. Exploration 8

*Exploration 9: Larger Sensor*

Sensor 2a from Exploration 8 showed the most promising performance and was therefore chosen as the basis for experimenting with a larger sensor (see figure 28). Until now, our explorations have focused on testing single-line structures that are not repeated—an approach that improved production time and increased the number of tests in this project. However, larger sensors are likely required for most applications since the applied pressure is significantly influenced by surface area.

In this exploration, the sensor structure was slightly altered compared to previous exploration. Instead of interlacing a single high-resistance yarn below the middle electrode (refer to figure 27), the new structure employs a compound configuration that covers the entire inner faces of the electrode layers. This design change prevents layer shifting from adversely affecting performance because any shifted layers will still include high-resistance yarns. The middle elastic layer continues to use a plain weave.

*Results:* The results, shown in table XIV, indicate that the sensor did not perform as expected—no U-shaped profile was observed.

TABLE XIV
RESULTS EXPLORATION 9

| Sensor | U-shape | Repeatable | Relative resistance change $\frac{\delta R}{R}$ |
|---|---|---|---|
| 1 | No | No | - |

*Discussion:* Because the sensor structure has a larger area and the three layers aren't interlaced, it allows us to see in between the different layers, something that wasn't possible in previous explorations. This helps explain the absence of a U-shaped response. As shown in figure 29, the densely woven plain weave of the elastic layer forms a wall between the two electrode layers. In contrast, the earlier structures, with only a single row of sensors, likely provided more space for the elastic yarns to "breathe."

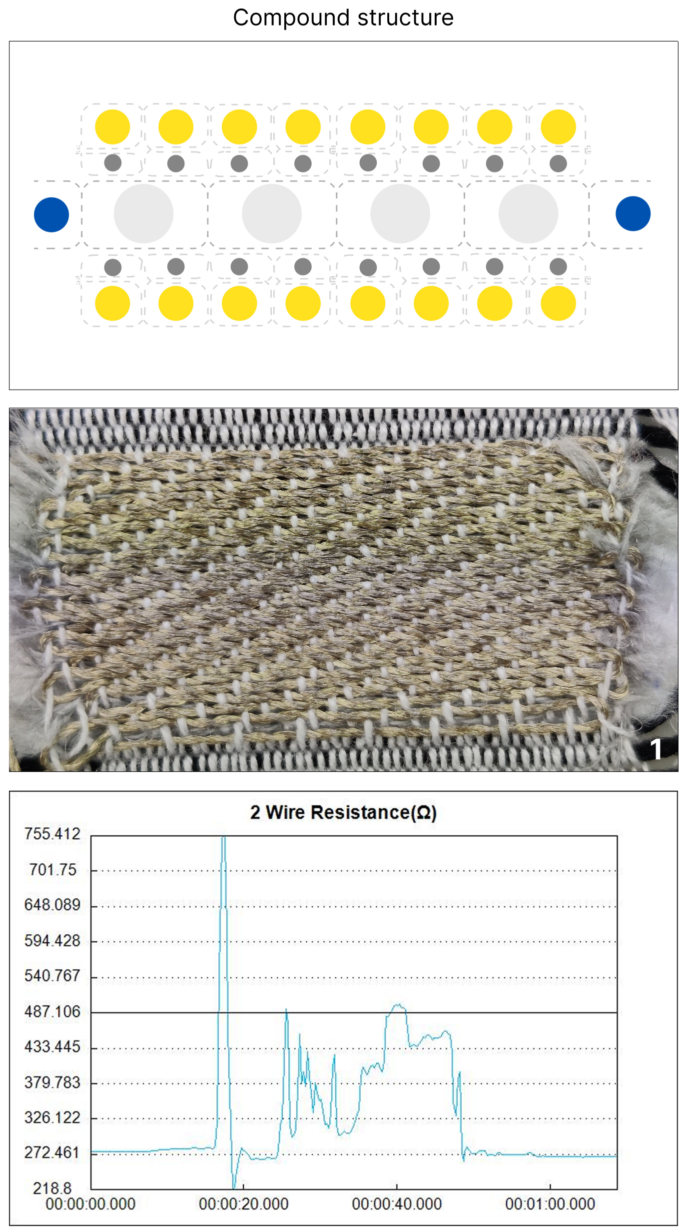



Fig. 28. Exploration 9

Fig. 29. Elastic wall

*Exploration 10: Interlacing multiple layers*

Due to the elastic layer being woven too tightly in Exploration 9, it may be possible to provide the elastics with more space by interlacing yarns through all three layers (see figure 30). By interlacing thinner yarns (indicated by the orange yarns) from the bottom to the top of the structure, the elastics are effectively prevented from moving toward each other. This creates a gap between the elastic yarns, allowing the high-resistance yarns to pass through and make contact.

*Results:* The results, shown in Table XV, indicate that the sensor performs as expected—a clear U-shaped profile is observed, and the response is repeatable.

TABLE XV
RESULTS EXPLORATION 10

| Sensor | U-shape | Repeatable | Relative resistance change $\frac{\delta R}{R}$ |
|---|---|---|---|
| 1 | Yes | Yes | -0.8 |

*Discussion:* This sensor demonstrates excellent performance: it exhibits a proper U-shaped behaviour, is repeatable, and consistently produces the same results, with a relative resistance change of -0.8. Notably, the sensor does not fluctuate in the high resistance ranges. In previous explorations, sensors showed repeatable behaviour in low resistance ranges (20–300 Ω) but behaved erratically in the high resistance ranges (500 Ω and above).

However, examining the physical sensor shows that the intended weaving structure did not form exactly as expected. The orange interlacing caused the sensor structure to tighten in the area where a gap was intended to form. This suggests that the elastic yarns may not be able to recover the relative distance needed to separate the high-resistance yarns from each other. Nonetheless, this sensor outperforms all previous designs, raising the question of whether the elastic yarns are necessary at all.

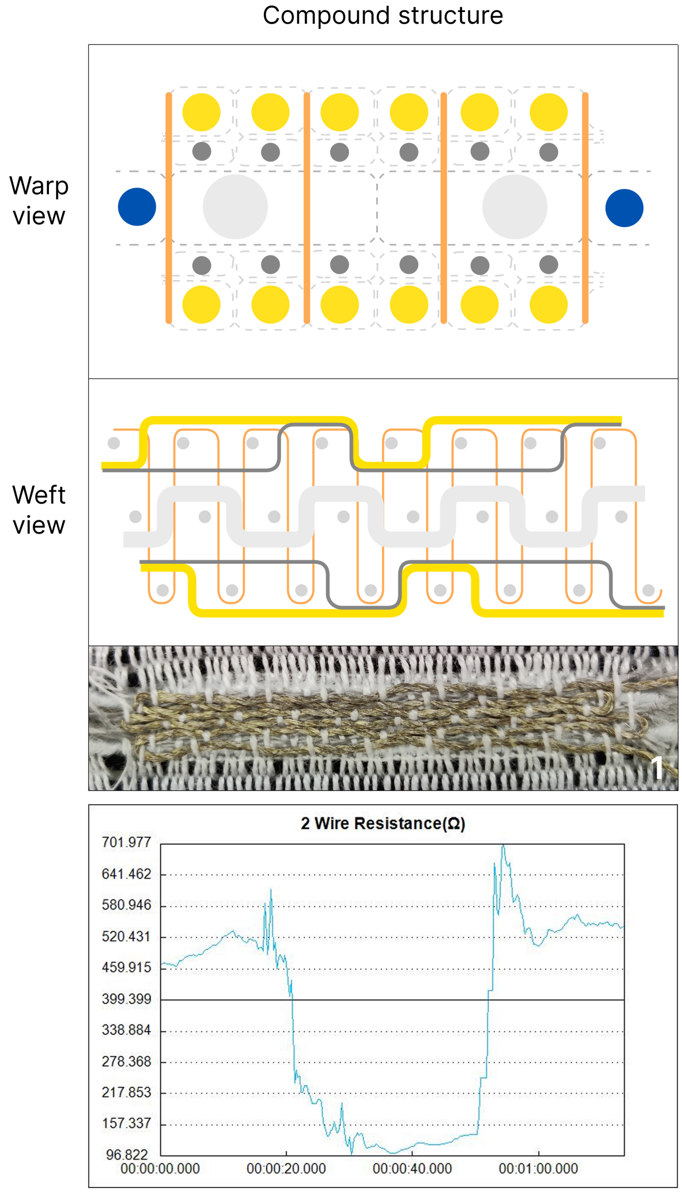



Fig. 30. Exploration 10

*Exploration 11: Removing elastics*

This last exploration focuses on removing the elastic yarns from Exploration 10 to find out if elastics yarns contribute or withhold the performance of the pressure sensor structure. Both sensors with 6 and 14 weft wide arrays are evaluated to see the difference in performance, see figure 31.

*Results:* The results, shown in Table XVI, indicate that the sensor performs as expected—a clear U-shaped profile is observed, and the response is repeatable. Just like the sensors from Exploration 10 but without the elastic yarns.

TABLE XVI
RESULTS EXPLORATION 11

| Sensor | U-shape | Repeatable | Relative resistance change $\frac{\delta R}{R}$ |
|---|---|---|---|
| 1 | Yes | Yes | -0.85 |
| 2 | Yes | Yes | -0.5 |

*Discussion:* It seems clear that the elastics don't contribute to the performance of the pressure sensors. On the contrary, they even seem to withhold the performance. An possible explanation is as follows:

One of the assumptions made moving from Exploration 1 to 2 was the cause of recoverability, which was assumed to be due to the high resistance yarns not separating properly from the electrode yarns. A solution for this would be to make the sensor structure behave more elastic, therefor elastic yarns were introduced. However the definition of recoverability was too vague when looking back at the problem.

It was assumed that the recoverability of the sensor was needed when being pressed and released. The layers would not separate enough distance from each other, which was named the relative distance. However it now seems like the layers were separated too far from each other, as the high relative distance would cause fluctuations in the resistance. By interlacing the three layers the fluctuations are prevented as a low enough resistance of 500 Ω is kept.

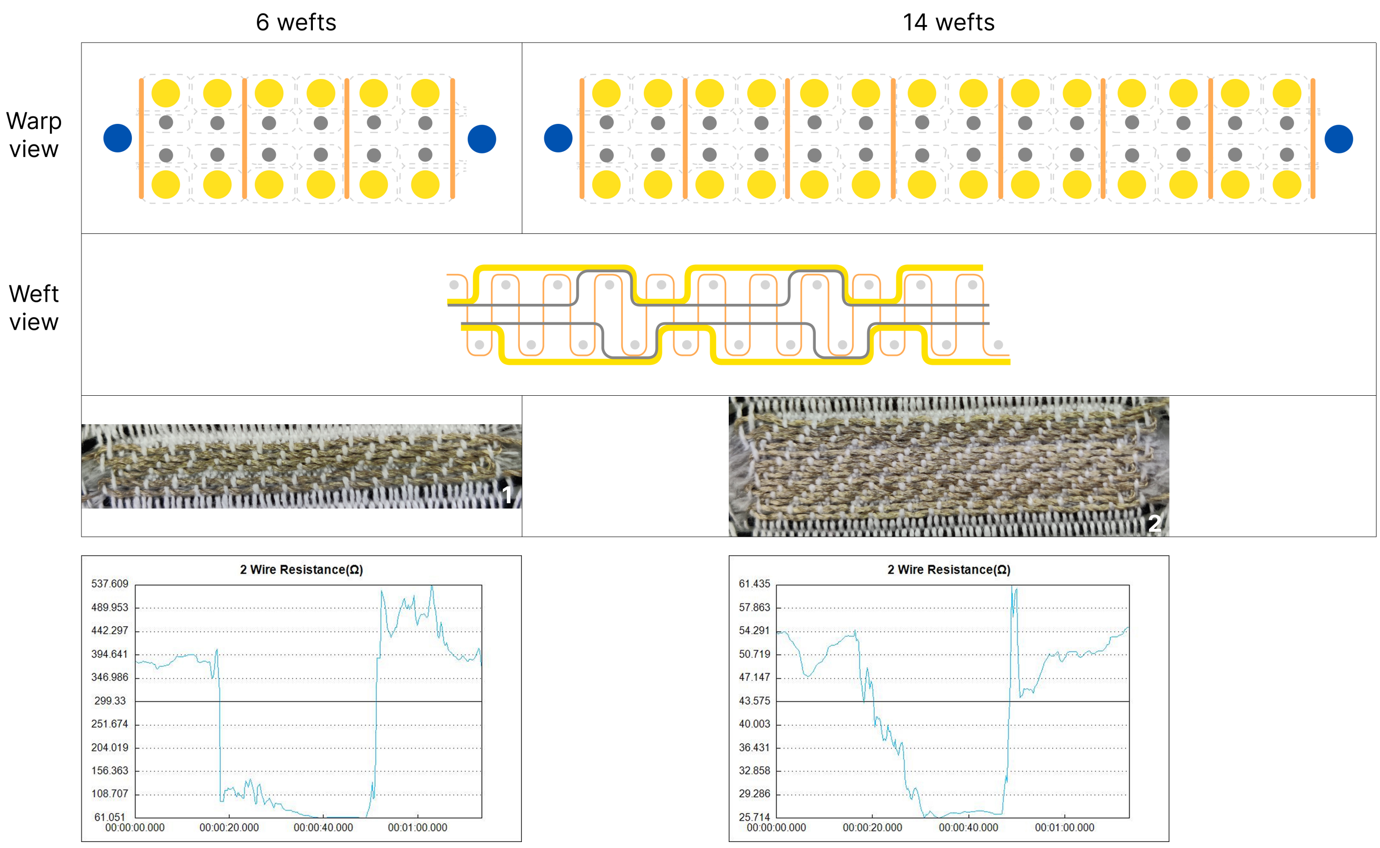



Fig. 31. Exploration 11

*Sensitivity and Repeatability*

To compare our new pressure sensor to existing sensors discussed in the literature research we require the sensitivity of this sensor, which is plotted in figure 32. From a range of 0 - 100 kPa the sensor has a sensitivity of 0.5917 $kPa^{-1}$. The sensitivity could be higher in the lower pressure ranges from 0 - 5 kPa but this will have to be tested in a future research.

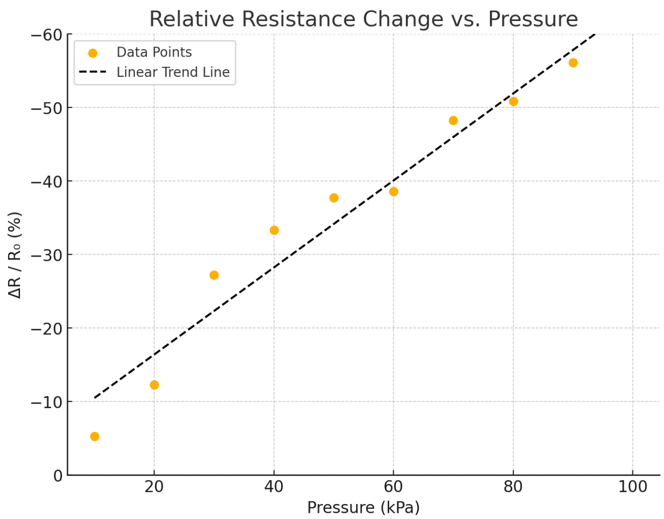



Fig. 32. Sensitivity of 14 weft sensor

The sensor still fluctuates a little as can be seen in figure 33. The released state of the sensor fluctuates between 520 Ω and 420 Ω while the pressed state between 200 Ω and 120 Ω.

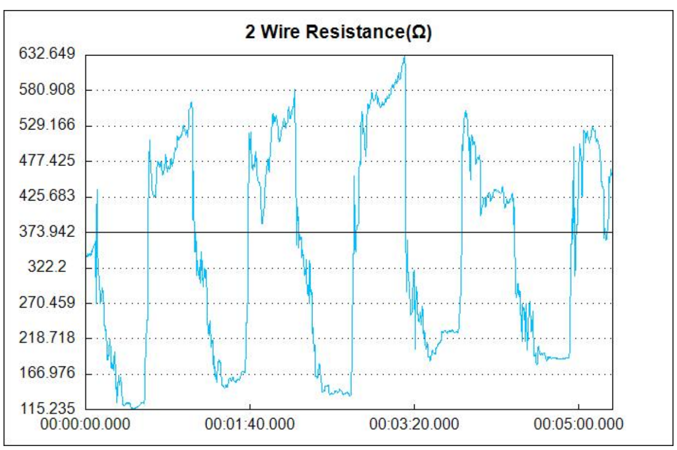
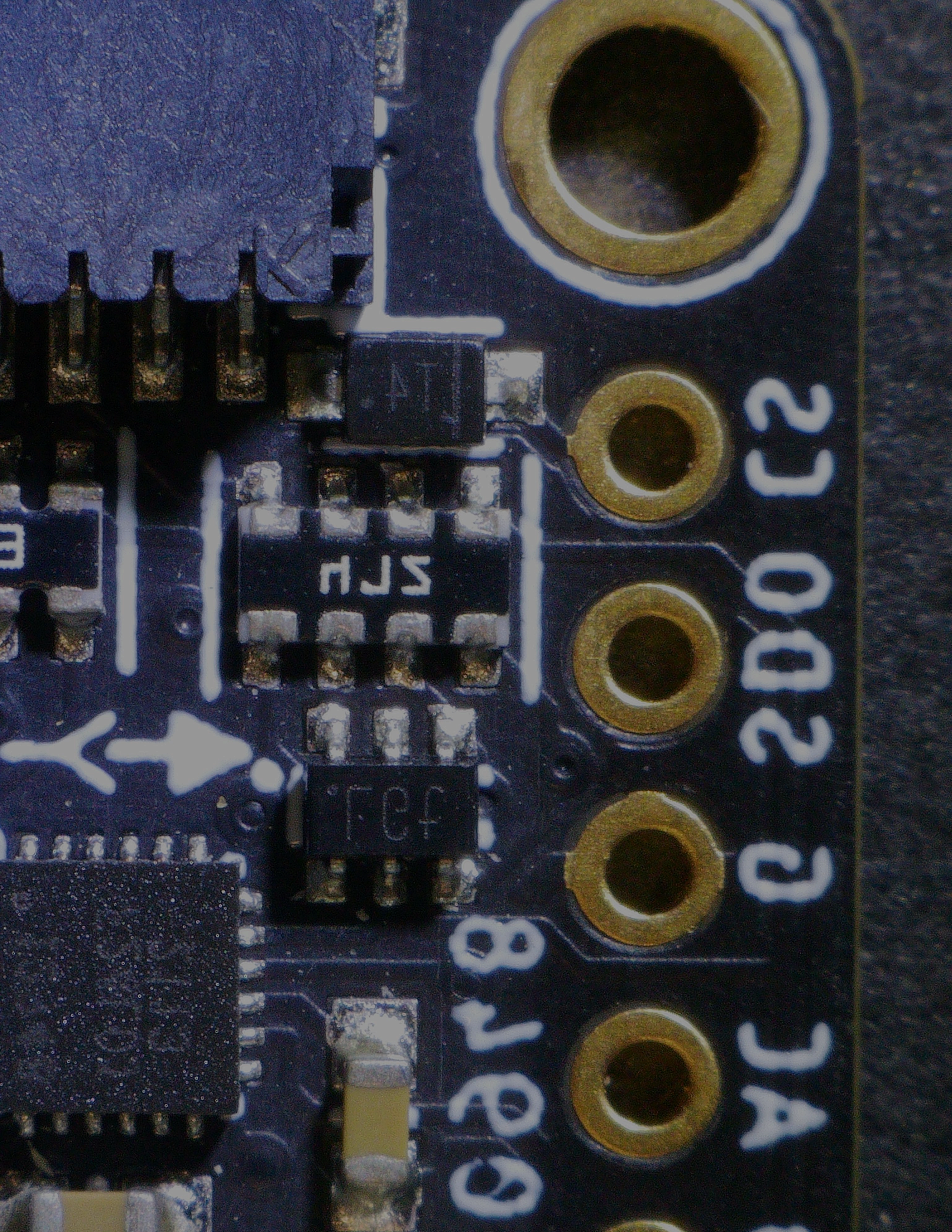



Fig. 33. Repeatability of 14 weft sensor



## VII. Application: Press Zoom

The application demonstrator is a computer mouse featuring an additional woven pressure button on the side, designed to control the zoom level on the screen. Press Zoom detects the intensity of pressure, adjusting the zoom level accordingly while the user is pressing the woven button with his thumb. Once the user releases their thumb, the view zooms back out to its original state. Press Zoom allows for fine zoom control in areas such Miro, Figma, Adobe programs, Google Maps and many more. It is an extra layer of control which allows users to zoom and peak. Press Zoom is inspired by Suzuki [51] who made Bounce back, a similar pressure sensitive zooming feature which is made for mobile interactions. In their paper they made use of a pressure sensitive display.

The common alternative for zooming is Ctrl-scrolling or Ctrl plus and minus, which requires the user to use two hands and a keyboard. This can slow down workflow and may require users to look at their keyboard. One handed use on the other hand brings several advantages. Users can increase productivity and efficiency by only pointing and pressing with their mouse. People with limited mobility or dexterity in one hand experience more comfortable and ergonomic control. And one of the biggest advantages is the intuitiveness. We use our fingers all the time to sense texture and depth in the world. While pressing the keys on our keyboard we feel the depth of the keys moving down and when pressing the left mouse button we want to no more about this link we just pressed. Using pressure to signal an action inherently feels like we want to know more of what we are seeing on the screen.

### *Implementation*

Press Zoom makes use of the sensor tested in Exploration 11. This sensor was determent to be most stable out of all explorations and added the benefit of being rather thin. The other components of the application are:

- Woven pressure sensor from Exploration 11
- Dell Optical Mouse-MS116: A simple mouse which has lots of empty space inside for the other components.
- Arduino Micro: Runs the C++ program which controls the Press Zoom logic
- Voltage divider: Allows the Arduino to measure the resistance
- Arduino program: runs a loop which checks the resistance every 200 ms and adjust the zoom action accordingly

*Woven pressure sensor:* The pressure sensor, measuring 30 mm × 15 mm, is positioned on the left side of the mouse for right-handed users but can easily be adapted for left-handed use. This placement aligns naturally with the thumb's resting position, allowing it to apply sufficient force to the sensor. For both comfort and aesthetics, the entire bottom surrounding surface of the mouse is covered in a twill weave structure. The woven textile gives the mouse an approachable and

Fig. 34. Electronics

cuddly feeling while still keeping an ordered and professional appearance. The woven fabric is cut to the appropriate size and securely adhered to the mouse exterior.

*Arduino Micro:* The Arduino Micro provides an easy-to-program platform with built-in USB communication, enabling it to function as a mouse or keyboard when connected to a computer. This feature allows for Ctrl-scrolling, which we use to control the zoom function. Additionally, the compact dimensions of the Arduino Micro make it an ideal fit, allowing all components to be housed within the Dell mouse casing.

*Voltage divider:* A voltage divider allows the Adruino Micro to read the resistance based on the change in voltage. Arduino's do not have an in-built resistance reading which makes this an excellent alternative. The resistance is measured based on the difference in voltage measured between two resistors. The first resistor being the woven pressure sensor and the second a fixed resistor. These resistors need to be approximately of the same value.

*Arduino program:* The Arduino program is a loop who constantly checks the resistance from the pressure sensor. This value is compared to the last recorded value and than run through a if-else statement. If the value recorded is lower than the previous measured resistance, than it executes Ctrl-forward command, making the opened program zoom in. Else, if the value recorded is higher than the previous measured resistance, than it executes Ctrl-backward command, making the opened program zoom out. If there is no difference between the resistances, than it does nothing. The full code can be seen in Appendix F.

The detection range for pressure was set between 10 – 75 Ω, as resistance fluctuations became too unstable beyond 75 Ω. It remains unclear whether this instability was caused by the thumb resting on the pressure sensor without actively applying pressure or by inherent fluctuations in the sensor's sensitivity due to its structural design.

A step size of 5 Ω is used to trigger a zooming action, providing the sensor with a resolution of 13 zoom levels. This resolution proved to be more than sufficient for applications such as PDF viewers, Figma, Miro, and similar programs.

### *User study*

After realizing the demonstrator, we invited five participants to use the mouse and execute the following tasks:

- Hold the mouse and move your cursor over Picture 1
- Press the sensor to zoom in on Picture 1 until the picture is fully within the frame
- Repeat the previous steps with Picture 2 and 3

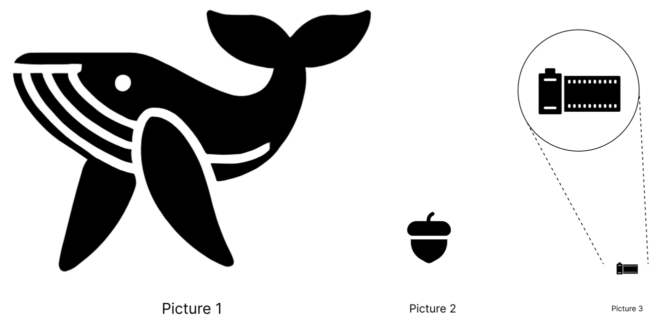



Fig. 35. User study

Figure 35 shows the pictures. Users will have to zoom in further when looking at the smaller pictures, which means pressing the button harder. After executing the tasks, we ask the users how they experienced the function and what they thought about the button being woven.

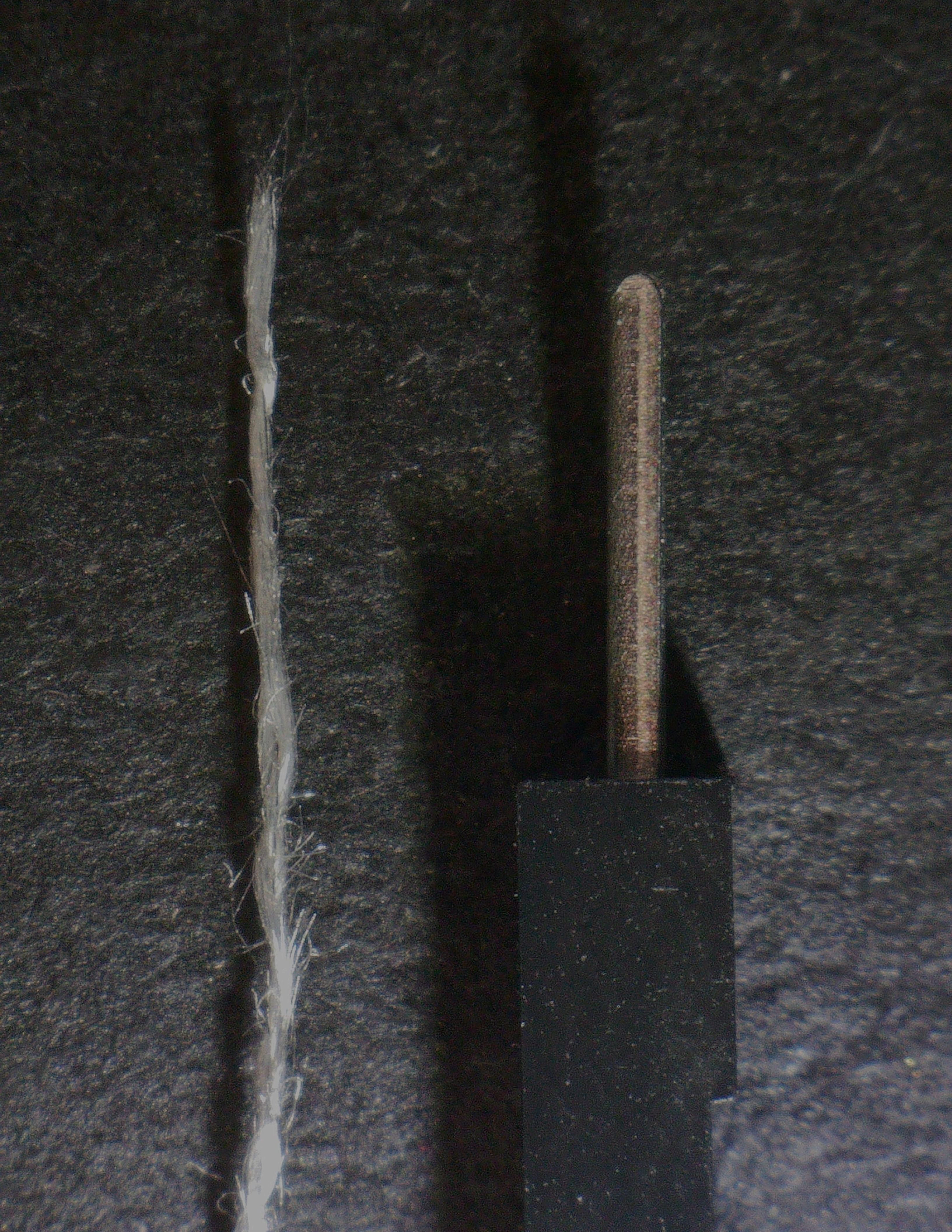
*Benefits:* All users agreed that pressing to zoom made a lot of sense. They also agreed that the sensor being woven made interacting with the mouse inviting and comfortable. Most users understood the zooming feature rather quickly and were able to control the function. Some participants noted that the woven fabric appeared more personal and intimate compared to the rigid plastic housing of a traditional mouse.

*Drawbacks:* Most users agreed that the force to press down on the sensor was rather high. Some users also had a looser grip on their mouse, who needed to adjust their grip to properly apply the desired zooming force.

### *Conclusion*

Overall, Press Zoom feels intuitive to use, and users appreciate the woven appearance of the mouse. The textile covering gives it a comfortable and inviting feel, which is often missing in non-woven mice.

However, the sensor lacks sensitivity—users reported having to press harder than expected, often causing them to squeeze the mouse. A sensor with higher sensitivity would therefore be more desirable for improved user experience.



## VIII. Discussion

Overall, this thesis demonstrates that it is indeed feasible to create a fully woven, ready-made pressure sensor. We will now discuss the key findings from our explorations, after which we reflect on the implications for smart textiles. Then, we will discuss directions for further research.

*Key finding 1: High resistance yarn:* The interface effect results from the interaction between two distinct high-resistance yarns, rather than from the interaction between electrode and high-resistance yarns. In this thesis, Bekaert Bekinox is used as a high resistance yarn. It consists of a stainless steel core with conductive twisted fibers. We hypothesize that the interaction among these fibers forms contact points through which electricity flows, thereby enabling the interface effect.

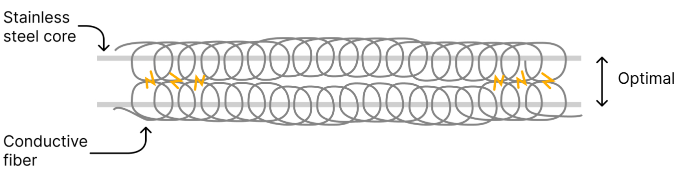



Fig. 37. Interface effect

*Key finding 2: Relative distance:* The relative distance between high resistance yarns has an optimal range. When this distance is larger, there are fewer contact points between the high-resistance yarns, resulting in higher overall resistance. While increased resistance can improve sensitivity, it also reduces the sensor's repeatability and consistency. Because the number of contact points is low and cannot be precisely controlled, random fiber movements have a greater impact on resistance. This leads to significant fluctuations at higher resistance values, ultimately making the pressure sensor inconsistent. This finding indicates that the relative distance between high resistance is crucial when designing a woven pressure sensor.

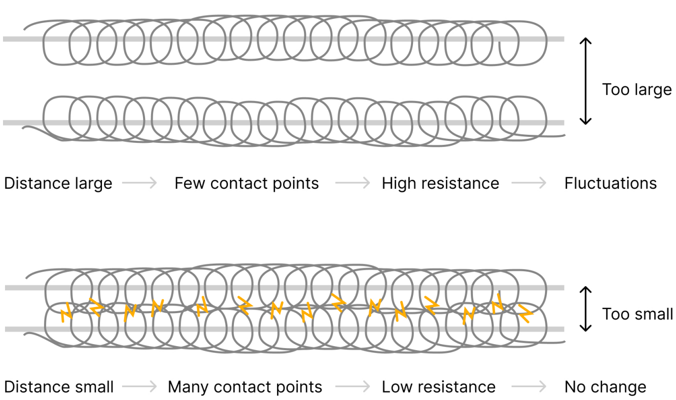



Fig. 38. Relative distance between high resistance yarns

*Key finding 3: Elastic yarn:* The elastic yarns used in this thesis do not improve sensor repeatability or consistency. Their diameter is too large, resulting in fewer contact points between the high resistance fibers and causing the resistance to fluctuate unpredictably. As a recommendation, smaller-diameter elastic yarns should be tested to allow for more contact points in the sensor's unpressed state.

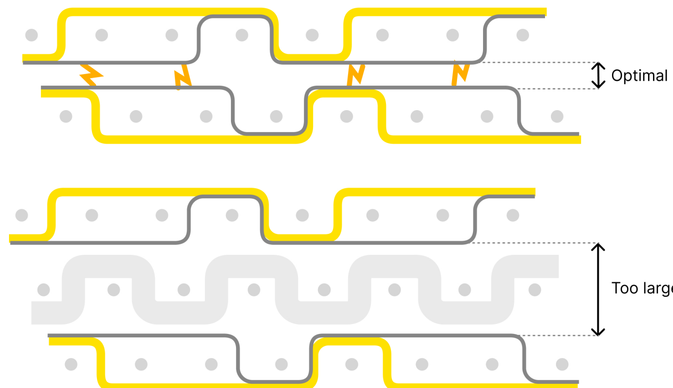



Fig. 39. Elastic yarns

The elastic yarns exhibit unpredictable behavior. In some cases, the sensor's resistance decreases under load, as expected, while in others, it increases under load—phenomena referred to as "U-shape" and "inverse U-shape" behavior, respectively, in this thesis. We hypothesize that the increased resistance occurs because the elastic yarns act as barriers, preventing contact between the high-resistance yarns. However, this behavior appears to happen randomly, and it remains unclear how to control it.

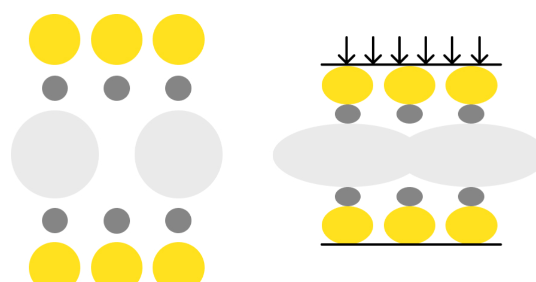


Fig. 40. Elastic barrier

*Key finding 4: Interlacing:* By interlacing multiple layers, the sensor maintains an optimal relative distance that results in a consistent change in resistance. This approach ensures sufficient contact points between the high-resistance yarns, preventing uncontrollable resistance fluctuations. Additionally, the high-resistance yarns can recover enough distance due to their innate springiness.

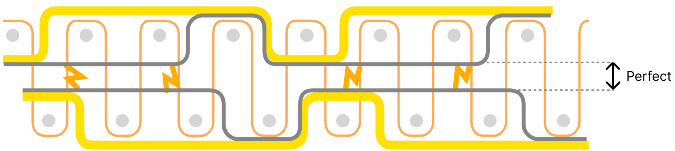



Fig. 41. Interlacing

*Key finding 5: Structure:* A fully woven electrode layer on both the top and bottom ensures consistent contact between the high resistance yarns and the electrodes. By making these layers uniform, there will always be contact points between the high-resistance yarns—unlike designs that rely on single electrode threads.

Using continuous electrode threading, instead of discontinuous threading, reduces the resistance within the electrode layer. As a result, only the resistance changes between the high-resistance yarns are measured, rather than measuring the resistance between separate electrode segments.

A compound structure ensures proper contact between electrodes and high resistance yarns while preventing short circuits. This design involves weaving two layers—one with conductive yarn on top and high resistance yarn on the interior. It keeps the electrode yarn from protruding through the high resistance layer while still enabling adequate contact among the high resistance yarns.

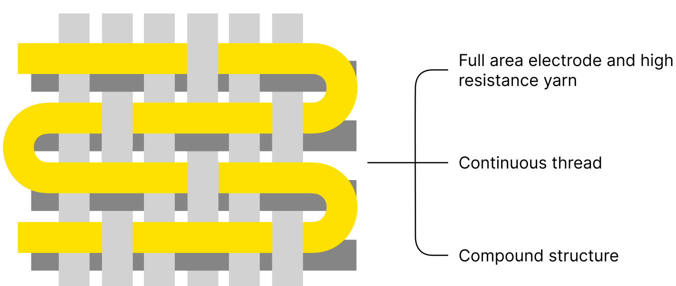



Fig. 42. Structure

*Limitations*

The intention behind this thesis was to develop a fully woven, ready-made pressure sensor. However, there are still several obstacles ahead to make this a reality.

First of all, our sensor uses an electrode thread which is continuously woven to improve conductivity. However, most modern high-speed weaving machines insert the weft thread one pick at a time and cut it after each insertion. So, rather than the weft running continuously back and forth, these machines trim the weft at the fabric's edge. This applies to industrial machines such as air-jet, rapier, and projectile looms. Continuous weaving is therefore impractical for most mass production machines and would have to be woven on a different machine such as shuttle looms.

Second, our pressure sensor performs best when only a perpendicular force is applied to its surface. Its performance declines under multiple forces, such as shear or tension. Consequently, this sensor is less suitable for applications like wearable clothing, where folding and twisting can lead to inaccurate readings. Instead, it is better suited to scenarios with more controlled inputs and minimal external forces—such as HCI interfaces, buttons, rockers, switches, and similar applications.

Overall, our sensor represents an important first step toward enabling mass-producible smart textiles. However, several challenges remain before this technology can be fully realized.

*Future research and applications*

For the next steps, it is recommended to continue research for optimizing the woven pressure sensor. This thesis left of at a working pressure sensor which has a promising sensitivity, small thickness and can be ready-made. However, there are many variables which can still be tweaked, such as:

- Interlacing repeats: How often should the interlaces repeat? Every three wefts, five wefts, six wefts, etc.
- Surface area to sensitivity ratio: The larger the area, the lower the resistance. What is an adequate area for a desired sensitivity? Can we identify a direct relationship between area and sensitivity that would allow us to calculate a suitable range of sizes based on a specific target sensitivity?
- Non-continuous electrode thread: Can we make a sensor which performs as well or even better by using non-continuous threads?

Overall, there remains significant work in two key areas: sensor robustness and mass production. For pressure sensors to be successfully integrated into everyday garments, they must maintain accuracy in unpredictable environments and be easy to manufacture. Achieving these goals will make the sensors both affordable and viable for real-world applications.

Once these remaining challenges are overcome, we may find ourselves on the brink of a new era of possibilities. Consider how the LED revolutionized lighting, becoming an essential component in nearly every consumer electronic product. Similarly, we can envision a future where woven pressure sensors are just as ubiquitous. These sensors could be integrated into robotics, enabling object detection and texture recognition for advanced manipulation. In sportswear, they could dynamically adjust tightness based on pressure, enhancing comfort and performance. In military gear, they could detect injuries, track posture, or monitor armor integrity in real time. They could even be used in adaptive airbags, sensing impact forces and dynamically altering their shape to improve safety. See figure 43 for a visualization of these concepts.As you see, there are endless possibilities in which we can sketch an exciting future.

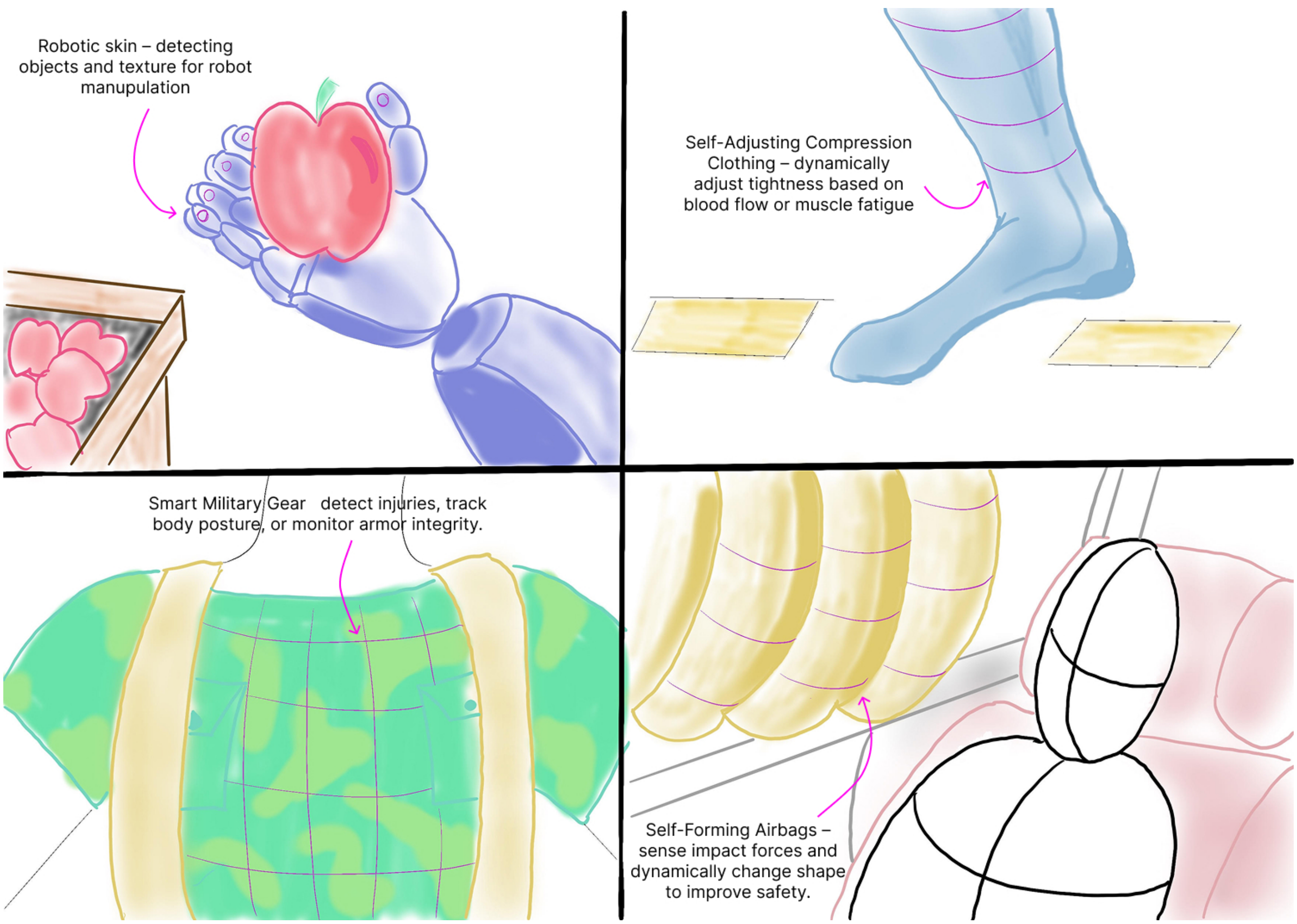



Fig. 43. Future applications

## IX. Conclusion

We showed a novel method for fabricating a fully woven, ready-made pressure sensor. By weaving an interlaced double-layer structure—each layer consisting of a two-faced compound fabric—we can sense pressure across a range of 10 to 100 kPa with a sensitivity of 0.5917 $kPa^{-1}$. This two-faced compound approach leverages off-the-shelf yarns, greatly improving the feasibility of mass-producing woven pressure sensors for real-world applications. Manufactured on a digital jacquard hand loom, our sensor is ready-made without requiring extensive manual postprocessing, finishing, or layering of multiple fabrics. Furthermore, the double-layer design keeps the sensor thin, making it ideal for applications where low-profile fabrics are required.

We also demonstrated an application called Press Zoom, which makes use of our sensor design. Press Zoom maps pressure differences to zoom levels in desktop applications, enabling users to zoom in on topics of interest. User feedback indicated that the woven pressure sensor felt inviting and comfortable, with some participants noting that the woven fabric appeared more personal and intimate compared to the rigid plastic housing of a traditional mouse.

There are still a lot of steps to be taken before our woven pressure sensor becomes a reality in everyday garments. Hopefully, this thesis can serve as an inspiration and starting point for more research where the before mentioned topics such as non-continuous thread, interlacing repeats and surface area to sensitivity ratio.

## Acknowledgment

I would like to thank my mentor Holly McQuillan who has introduced me to weaving which has been a wonderful world to discover. I really appreciated her positive mindset and she was always able to understand what I was trying to achieve and giving valuable feedback.

I would like to think my chair Kaspar Jansen who introduced me to smart textiles with all its complex problems still to uncover. I really appreciated him helping me with my struggles I had at the beginning of the project and he always had a keen eye for the details which comes with doing research.

Lastly, I would like to thank my friends and roommates who have helped me through this project. My thesis came with ups and downs and they were always willing to help me.

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## X. Appendix

### *A. Pressure sensor database*

**View Excel Sheet**
This is hyperlink when viewed in pdf format

### *B. Conductive yarns research papers*

TABLE XVII
CONDUCTIVE YARNS RESEARCH PAPERS

| Conductive yarn | Available | Source |
|---|---|---|
| Shieldex 235/32 dtex–2–ply–HC +B silver yarn | Off-the-shelf | [13] |
| Silver-plated polyamide and stainless steel | Off-the-shelf | [42] |
| Shieldex 235/34dtex 2ply HC. | Off-the-shelf | [17] |
| Silver coated yarn | Off-the-shelf | [9] |
| Conductive fiber | Off-the-shelf | [19] |
| Textile dielectric: Kraton MD 1653, Shieldex 235/364 ply | Off-the-shelf | [18] |
| Stainless steel core yarn and cotton fiber | Off-the-shelf | [34] |
| Geniomer POF | Off-the-shelf | [30] |
| Copper coated acrylic yarns | Off-the-shelf | [52] |
| Shieldex 235/32 dtex–2–ply–HC +B silver yarn, HITEK Electronic Materials GL2016-031 | Off-the-shelf | [14] |
| Encapsulated polypropylene fiber, silver conductive coated fabric | Off-the-shelf | [20] |
| Stainless steel 20 procent, Polyester 80 procent | Off-the-shelf | [4] |
| Resistat P6204 Merge H100i from Shakespeare Conductive Fibers LLC7 Madeira HC408 silver plated Polyamide yarn (dtex 290 ¡300 $/Omega$/m) | Off-the-shelf | [2][3] |
| Madeira HC40 and SEFAR CARBOTEX 03-82 CF weave | Off-the-shelf | [6] |
| Conductive and High-flex Polyester Yarns Matrix (30x60) | Off-the-shelf | [28] |
| Electrical conductive polymer fibers | Off-the-shelf | [33] |
| Two layers of zebra fabric with one layer of EeonTexTM LG-SLPA in-between | Off-the-shelf | [21] |
| Conductive silver/polyamide, and a piece of Velostat in between | Off-the-shelf | [37] |
| Insulated copper wires (38 AWG, Remington Industries Magnet wire, Stainless steel conductive threads (2 ply, 3 W/in) | Off-the-shelf | [39] |
| Silver-polyamide yarn | Off-the-shelf | [40] |
| Conductive and nylon yarns | Off-the-shelf | [15] |
| Stainless steel fiber and polyester fibers integrated in multi-twist process | Off-the-shelf | [44] |
| Conductive yarn SSPP (50 tex, resistivity 18 $/Omega$/cm) produced from 25 wt of stainless steel (SS) staple fibers and 75 wt short polypropylene fibers | Off-the-shelf | [49] |
| Wrapping silver fibers with cotton fibers, and fixed with polyurethane adhesive | Self-produced | [43] |
| Enameled silver-plated copper wire | Self-produced | [5] |
| Conductive metallic core thread with a resistive coating consisting of an organic polymer solution containing conductive carbon-based particles | Self-produced | [1][31][7] |
| Piezoresistive knit textile (LTTSLPA60k, Eeonyx Corporation) | Self-produced | [12] |
| Conductive rGO/CNTs fibre via capillary wicking assisted coating route and thermal reduction treatment | Self-produced | [10] |
| Coating poly(styrene-block-butadienstyrene) (SBS) polymer on the surface of Kevlar fiber, followed by converting silver ions into Ag nanoparticles directly in the SBS polymer | Self-produced | [36] |
| Water-soluble poly(vinyl alcohol) (PVA) template-assisted silver nanofibers (Ag NFs) transferred on the fabrics surface to serve as sensor electrodes | Self-produced | [8] |
| Conductive polymer PEDOT:PSS coated on nylon fiber with the die-coating system, dielectric polymer of ultraviolet (UV)-curable polymer coated on the PEDOT:PSS layer | Self-produced | [35] |
| Silver-coated yarn | Self-produced | [16] |
| Internal silver-plated nylon electrodes and surface microporous structured carbon nanotubes (CNTs)/thermoplastic polyurethane (TPU) sensing layer | Self-produced | [11] |
| Nylon filament and polytetrafluoroethylene filament as positive and negative layers with built-in helical stainless steel yarn serving as inner electrode layer | Self-produced | [38] |

*C. Experiments Knitting*

For the knitted sensor tests, the bi-directional design by Xie and the Footfalls design by McMaster were chosen as baselines. Both studies explore plain knits, which have shown promising results and can be rapidly prototyped.

Xie developed a knitted pressure sensor capable of measuring pressure in both the course and wale directions. When pressure is applied, the yarn-to-yarn interlacing points between loops make contact, reducing resistance due to the interface effect.

McMaster's design utilizes tucks and floats to create a pressure-sensitive structure. The tuck legs have an increased surface area against adjacent loops, which enhances the interface effect, leading to a decrease in resistance when pressure is applied.

*Materials*

To compare the Footfalls and Bi-directional sensors, all variables except for the structure configuration have been standardized. This includes using the same silver conductive yarn, the same course and wale lengths, and the same loop density, as summarized in table XVIII. The properties of Shieldex and polyester used in the samples are outlined in table XIX.

TABLE XVIII
SAMPLE CONFIGURATION

| | Footfalls | Bi-direcional |
|---|---|---|
| Conductive yarn | Shieldex | Shieldex |
| Non-conductive yarn | Polyster | Polyster |
| Courses | 25 | 25 |
| Wales | 25 | 25 |
| Loop density | 0 or 2 | 0 or 2 |

TABLE XIX
YARN SPECIFICATIONS KNITTING

| Yarn | Notation | Linear density | Resistivity |
|---|---|---|---|
| Shieldex | S235 | 235/36 dtex | 600 Ω/m |
| Polyster | - | - | - |

The pressure sensors for these tests were weft-knitted on a Brother KH860 hand knitting machine, using knitting densities of 0 and 2. However, knitting with Shieldex silver conductive yarn proved challenging. As Shieldex is a relatively thick and stiff yarn, increasing the knitting density often caused skipping loops, which would cause the sample to unravel. An overview of all samples is provided in figure 44.

*Measurement techniques*

The electromechanical performance of the knitted pressure sensors was assessed by conducting six test cycles at two different rates: 1.5 kPa/min and 4 kPa/min. A minute was chosen to allow the yarns to move into a static position, measuring right after pressure input has a lot of dynamic fluctuation. Two different pressures are used to see if the relative resistance increase is higher when a greater pressure is applied. To ensure proper fixation and prevent movement, the samples were mounted on a piece of paper using four pins at each corner. The resistance changes were measured using a two-probe multimeter, with probes wired in both the course- and wale-wise directions. A schematic of the setup can be seen in figure 45.

For these initial exploratory tests, only the relative resistance change was measured, comparing the initial state to the state after one minute. Once a decision is made on the pressure sensor structure to be further developed, a more detailed measurement system will be employed, incorporating sensitivity and detection range.

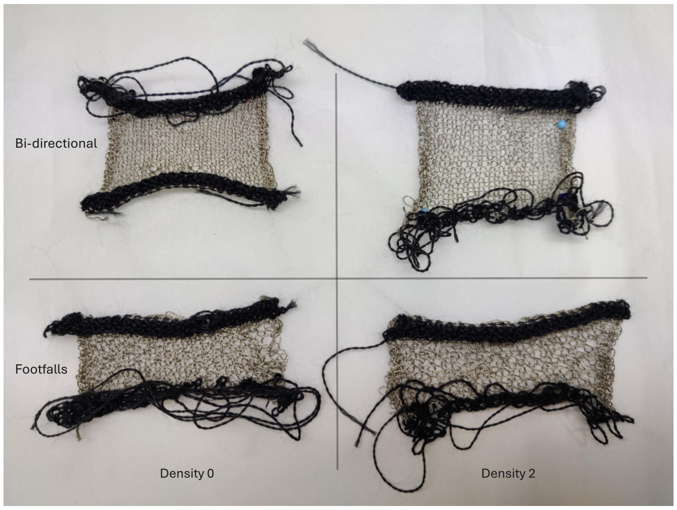


Fig. 44. Overview samples bi-directional

Fig. 45. Setup

*Results Footfalls and bi-directional*

Table XX shows the results of the relative resistance change when 1.5 kPa of pressure was applied, while table XXI shows the corresponding results for 4 kPa.

It turns out that the Footfalls design does not use a uniform structure like the bi-directional sensor. Instead, it incorporates a non-conductive polyester yarn placed between the two conductive yarns. This finding makes the Footfalls results unusable. However, the results for the bi-directional pressure sensor remain valid and appropriate for comparison.

Additionally, due to the large knitted areas, the measured resistance is low (around 1 Ω). This significantly affects measurement accuracy, as the contact error from attaching probes can vary between 0.1 and 1 Ω, which is of the same order of magnitude. Therefore, designing a pressure sensor with a higher resistance (around 100 Ω) would be more desirable for improved accuracy.

*Results Footfalls and plating*

An overview of all samples can be seen in figure 46. This time, the correct Footfalls patent was used, which incorporates two conductive courses with a non-conductive yarn between them. To compare the performance of this sensor, a double-plated sensor was chosen as the comparative design. Plating is theorized to be effective as it increases contact area, potentially enhancing sensor performance.

Additionally, samples with different densities were excluded from this test, as they did not show any significant influence on the pressure sensor performance in the previous tests. As noted earlier, a finer grid might be necessary to observe meaningful results.

Table XXII presents the relative resistance change when 1.5 kPa is applied, while Table XXIII shows the results at 4 kPa. Both samples exhibit a higher resistance compared to previous tests. However, a resistance of 10 Ω remains relatively low, and with a contact error of 1 Ω from probe attachment, this results in a 10% measurement error—which falls within the range of the measured relative resistance change (17.28%). Due to these limitations, knitting experiments will be discontinued, and the remaining project will focus on weaving as the primary fabrication method.

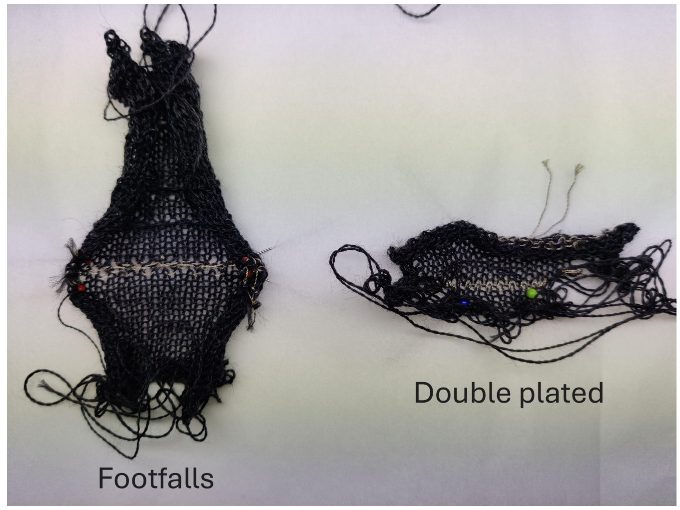



Fig. 46. Overview samples Footfalls

TABLE XXII
RESULTS FOOTFALLS AND PLATING 1.5 KPA

| | Initial state (Ω) | State after 1 min (Ω) | Relative resistance change (%) |
|---|---|---|---|
| Footfalls | 11.0 | 10.4 | 5.46% |
| Double plating | 8.3 | 8.3 | 0% |

TABLE XXIII
RESULTS FOOTFALLS AND PLATING 4 KPA

| | Initial state (Ω) | State after 1 min (Ω) | Relative resistance change (%) |
|---|---|---|---|
| Footfalls | 11.0 | 9.1 | 17.28% |
| Double plating | 8.3 | 8.1 | 2.41% |

TABLE XX
RESULTS FOOTFALLS AND BI-DIRECTIONAL 1.5 KPA

| | Course | | | Wale | | |
|---|---|---|---|---|---|---|
| | Initial state (Ω) | State after 1 min (Ω) | Relative resistance change (%) | Initial state (Ω) | State after 1 min (Ω) | Relative resistance change (%) |
| Footfalls (density 0) | 1.1 | 1.1 | 0% | 1.2 | 1.2 | 0% |
| Footfalls (density 2) | 1.1 | 1.1 | 0% | 1.2 | 1.2 | 0% |
| Bi-directional (density 0) | 1.0 | 1.0 | 0% | 1.5 | 1.4 | 6.66% |
| Bi-directional (density 2) | 1.0 | 1.0 | 0% | 1.5 | 1.4 | 6.66% |

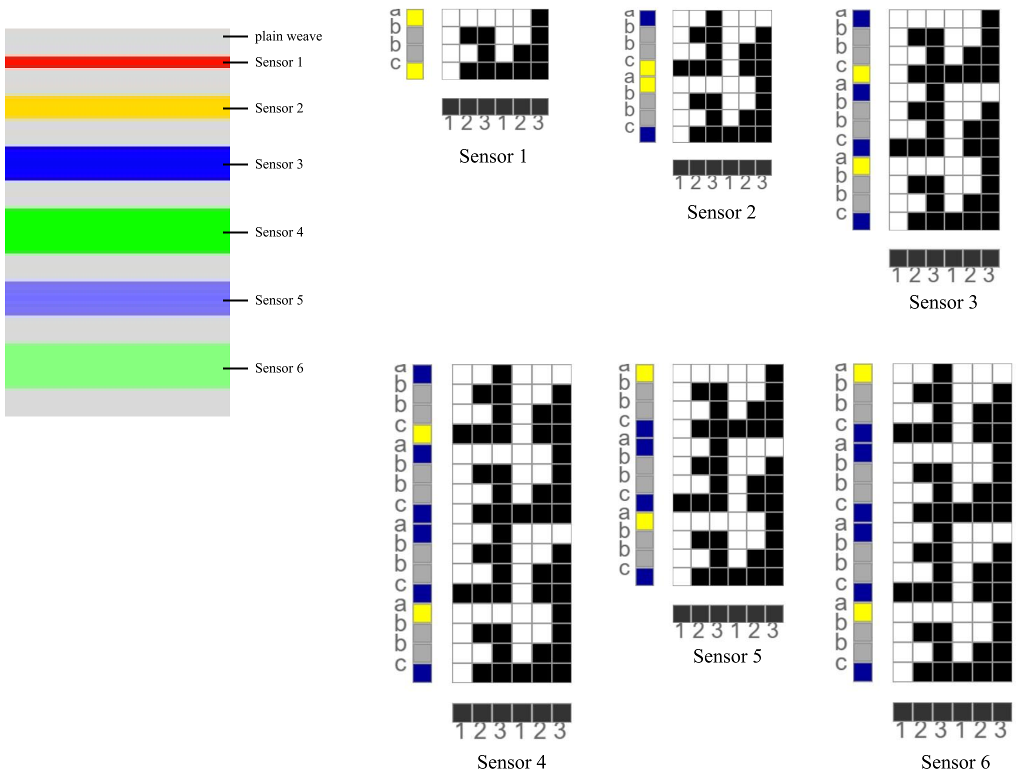
TABLE XXI
RESULTS FOOTFALLS AND BI-DIRECTIONAL 4 KPA

| | Course | | | Wale | | |
|---|---|---|---|---|---|---|
| | Initial state (Ω) | State after 1 min (Ω) | Relative resistance change (%) | Initial state (Ω) | State after 1 min (Ω) | Relative resistance change (%) |
| Footfalls (density 0) | 1.1 | 1.1 | 0% | 1.2 | 1.1 | 8.33% |
| Footfalls (density 2) | 1.1 | 1.1 | 0% | 1.2 | 1.1 | 8.33% |
| Bi-directional (density 0) | 1.0 | 0.9 | 10% | 1.5 | 1.4 | 6.66% |
| Bi-directional (density 2) | 1.0 | 0.9 | 10% | 1.5 | 1.3 | 13.33% |

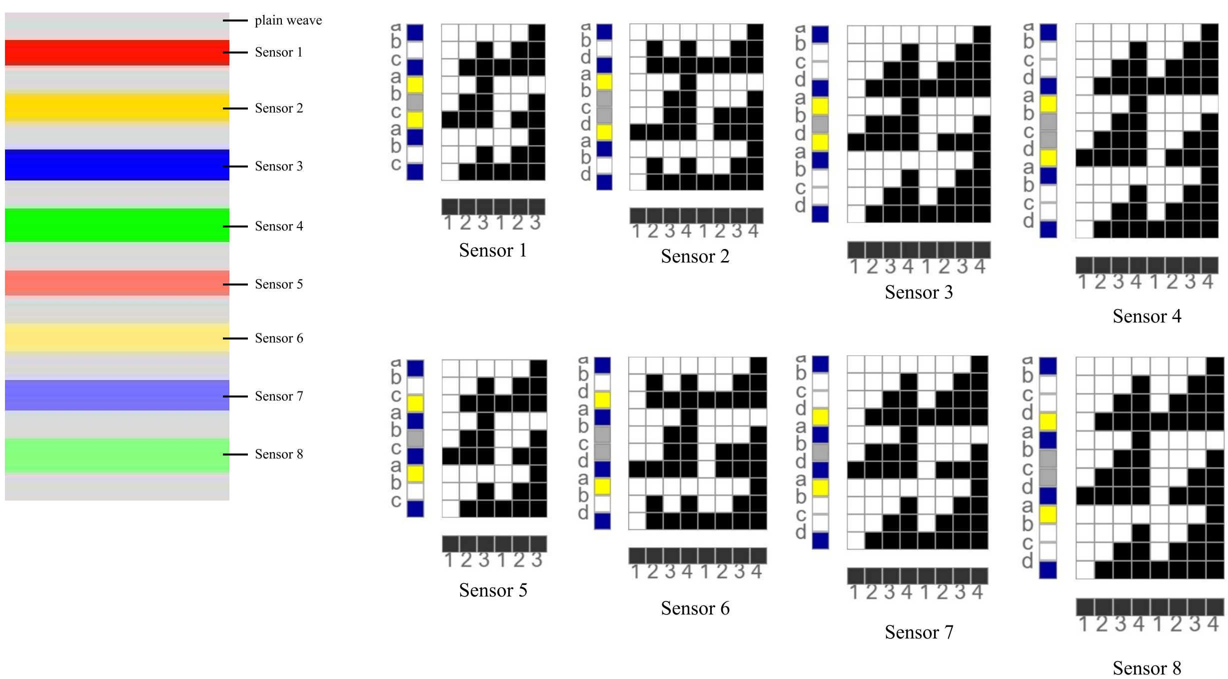
## *D. Bitmap and map of bindings*

### Weave patterns and weft-yarn order

#### Exploration 1

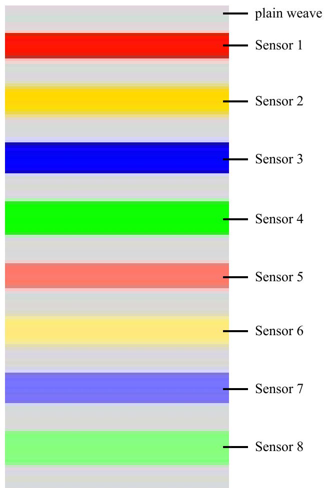


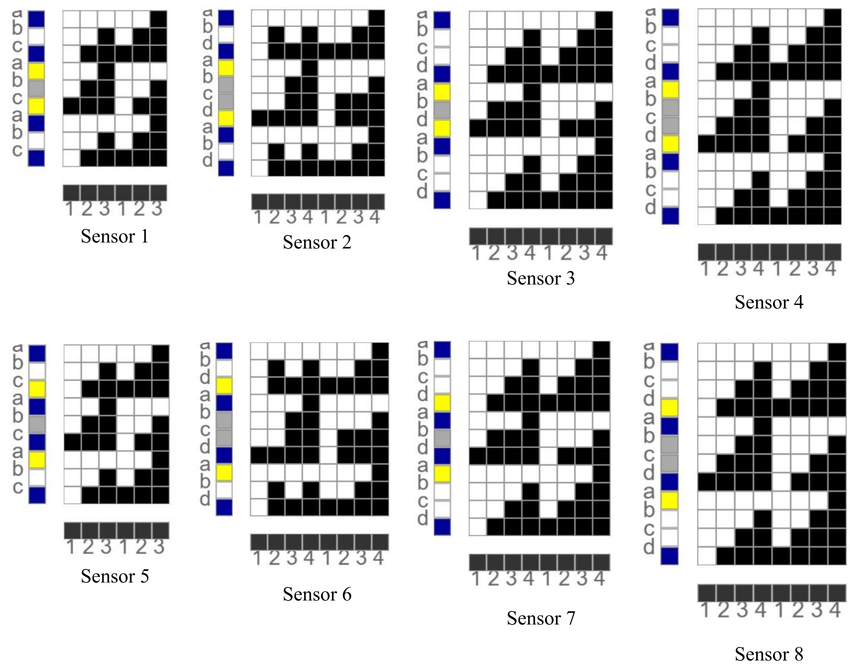

#### Exploration 2



## Weave patterns and weft-yarn order

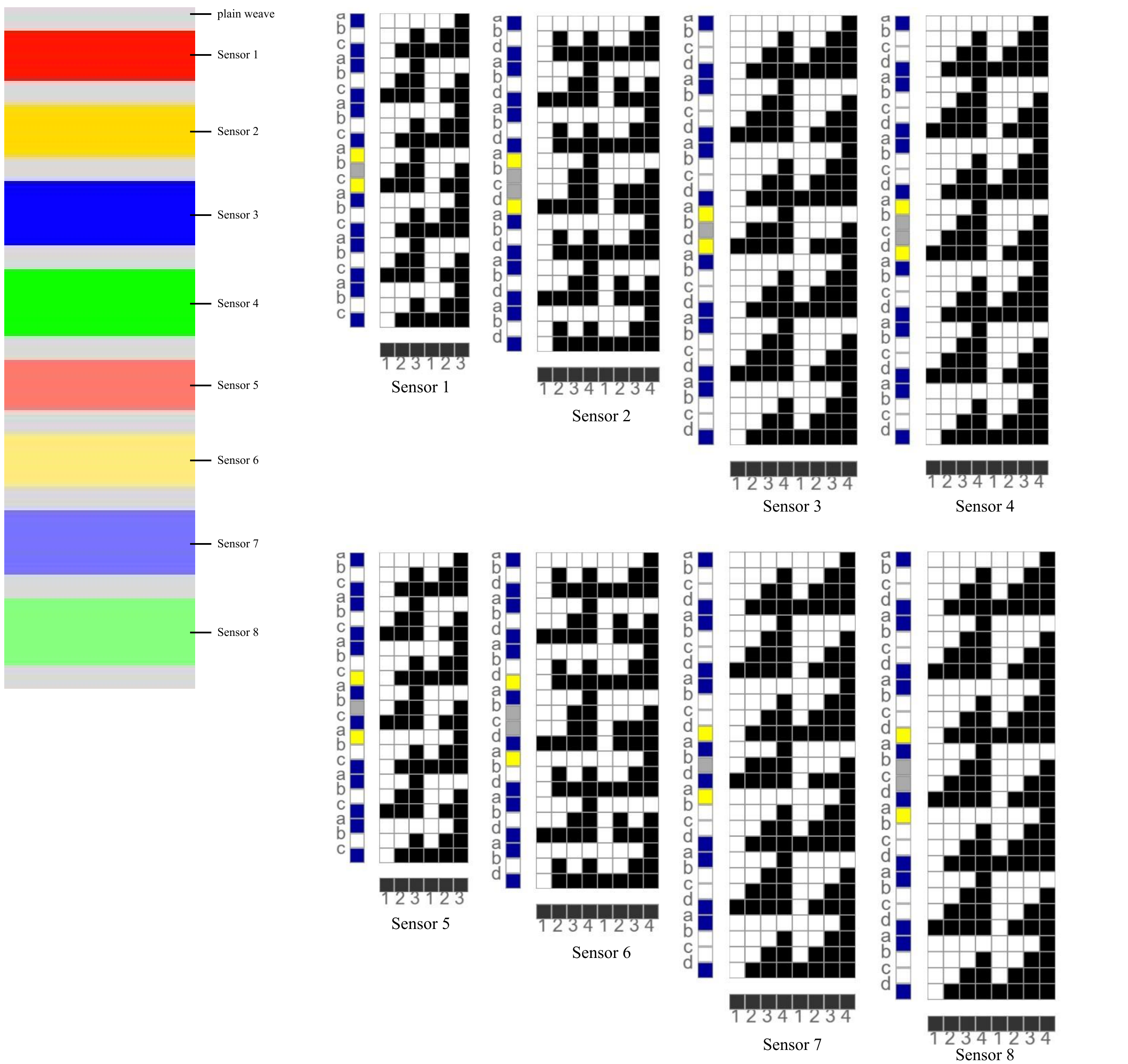
### Exploration 3



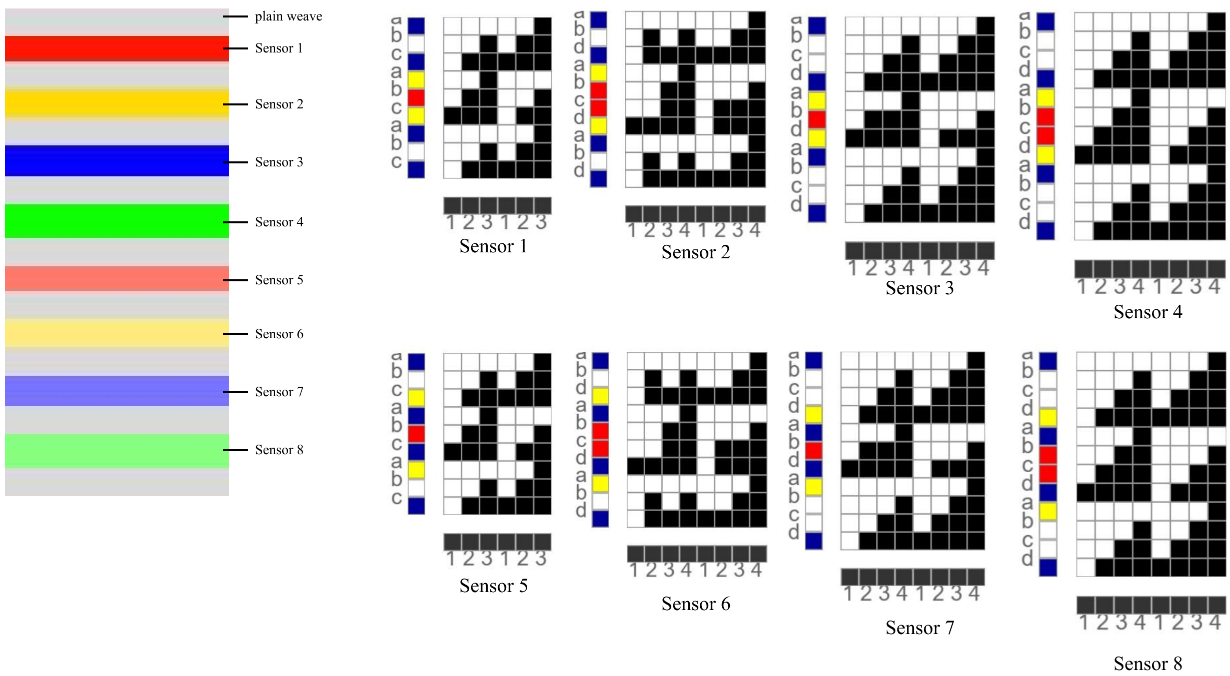
# Weave patterns and weft-yarn order

## Exploration 4

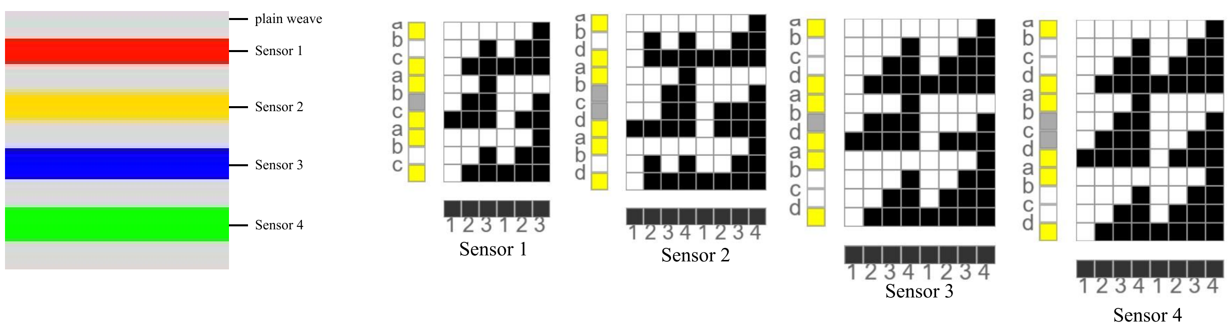


## Weave patterns and weft-yarn order

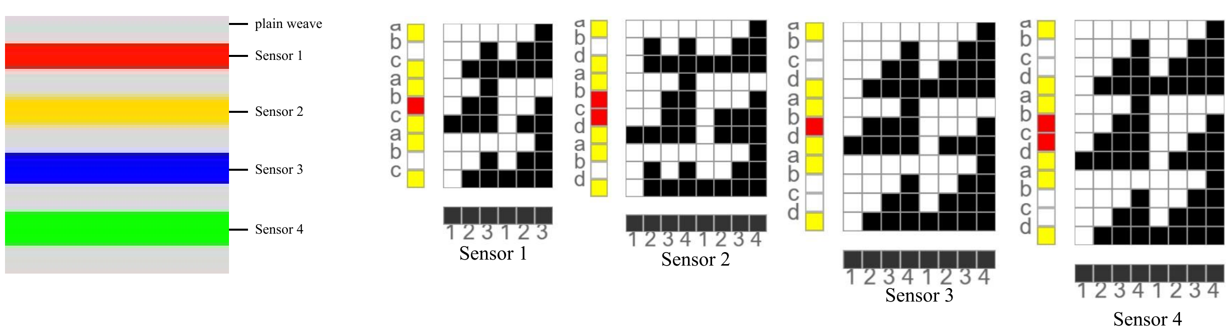
### Exploration 5




### Exploration 6

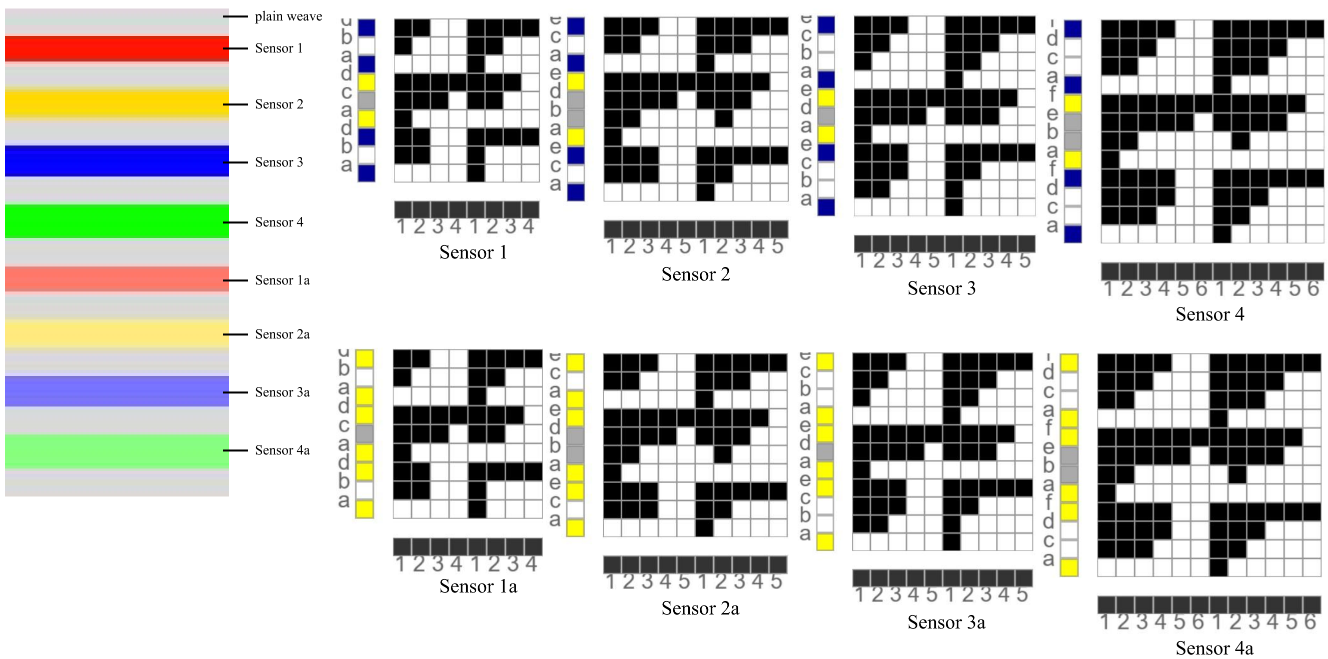



### Exploration 7

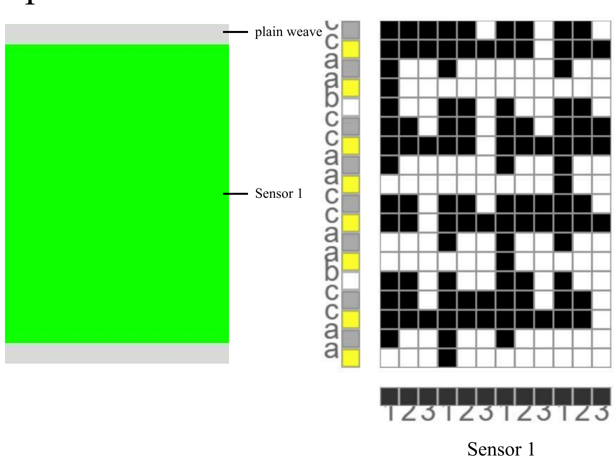


# Weave patterns and weft-yarn order

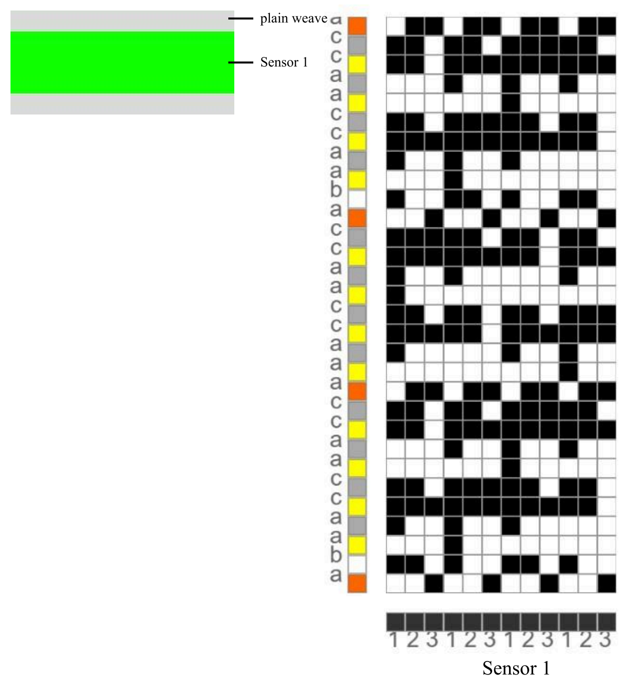
## Exploration 8




## Exploration 9

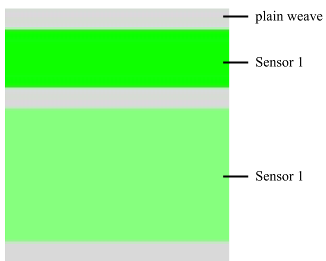


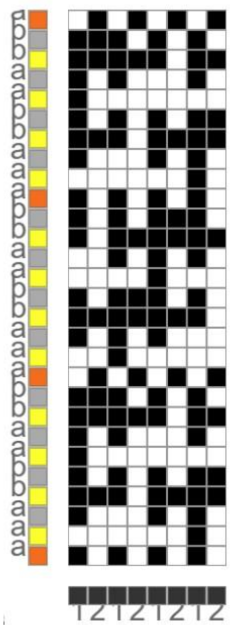

## Exploration 10



# Weave patterns and weft-yarn order

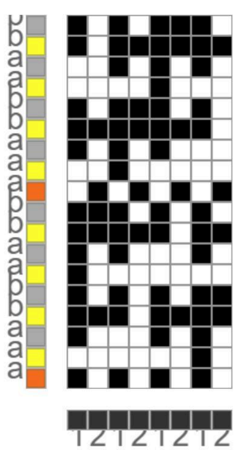
## Exploration 11



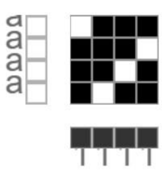




Sensor 1 and 2

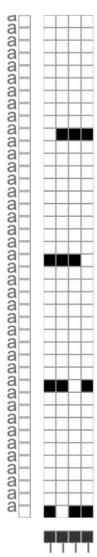
## Demonstrator: Press Zoom


Sensor 1



Inverse twill

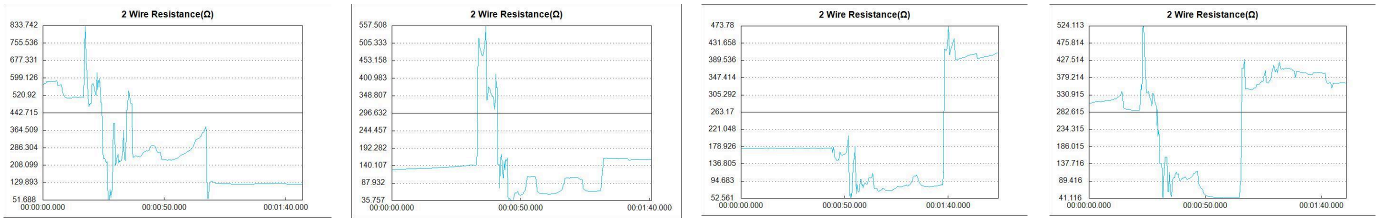


Inverse twill*

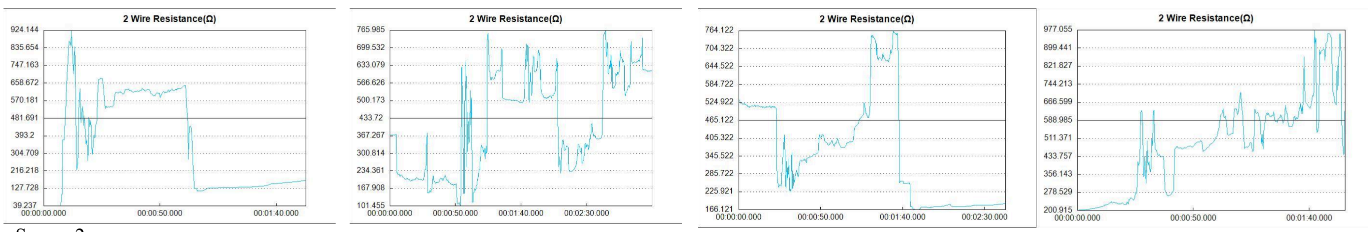
## *E. Resistance graphs*

## Tests: Exploration 1

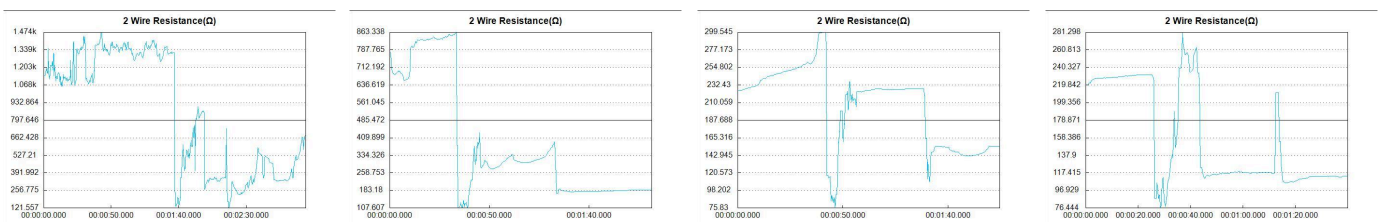
Test 1 | Test 2 | Test 3 | Test 4



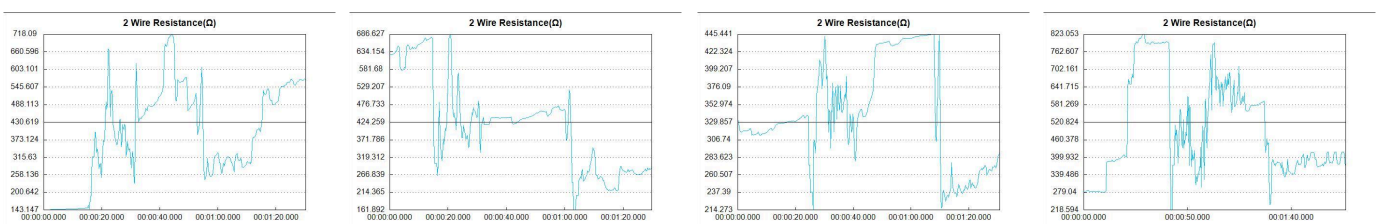

Sensor 1



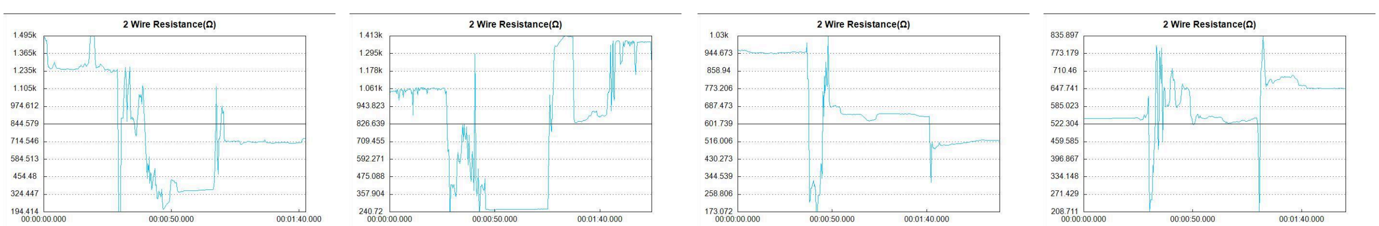

Sensor 2



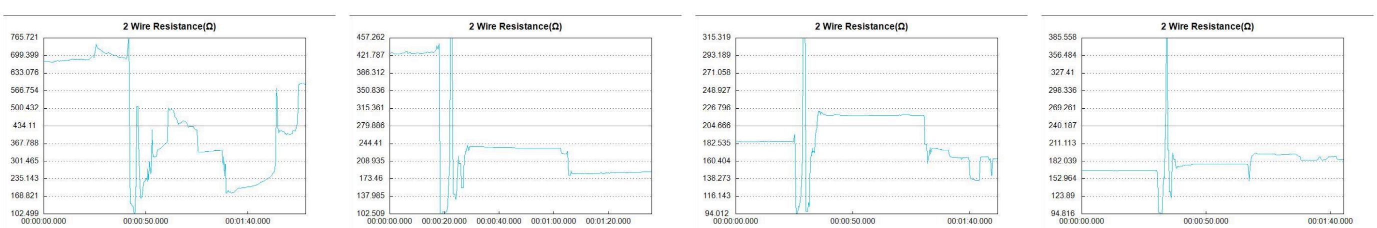

Sensor 3




Sensor 4



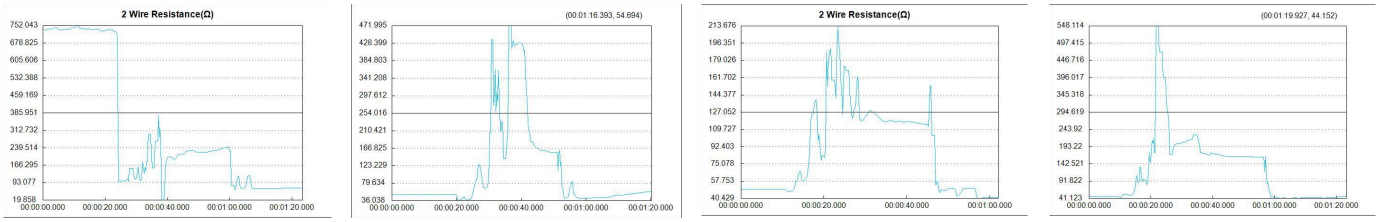

Sensor 5



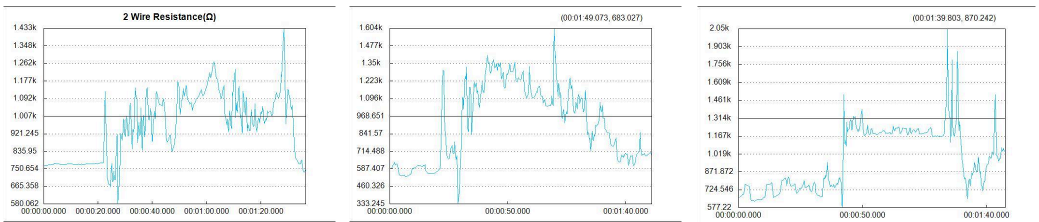

Sensor 6

# Tests: Exploration 2

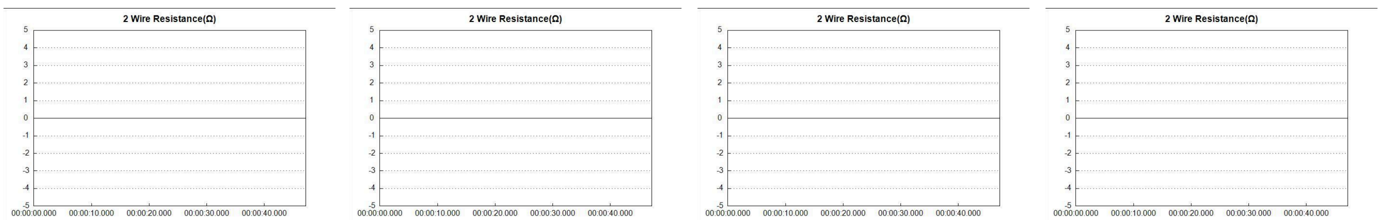
| Test 1 | Test 2 | Test 3 | Test 4 |
|---|---|---|---|



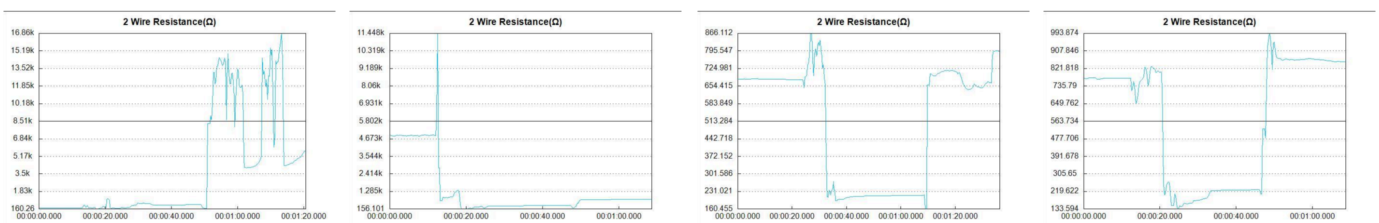

Sensor 1



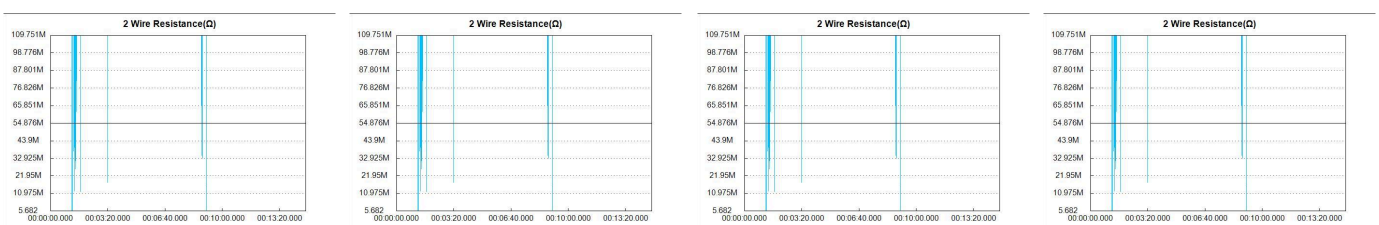

Sensor 2



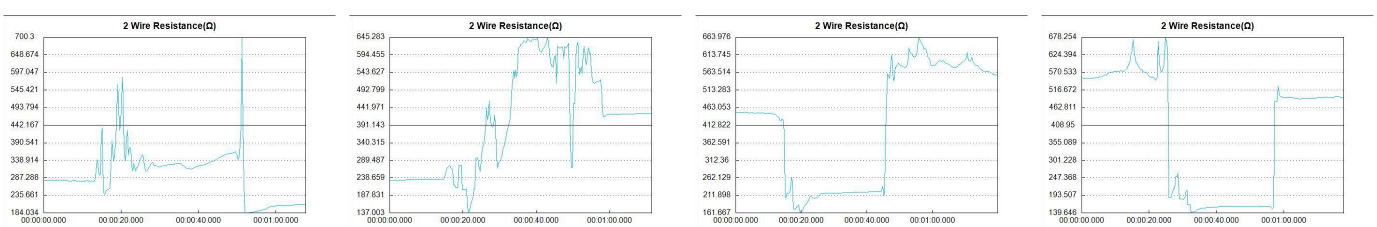

Sensor 3




Sensor 4

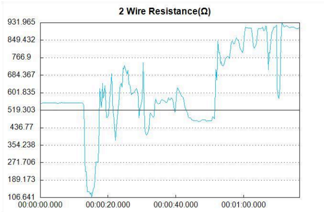


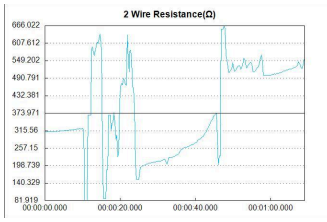

Sensor 5

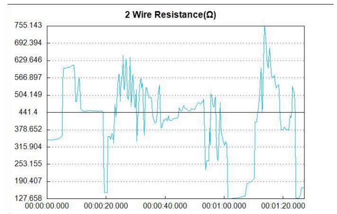


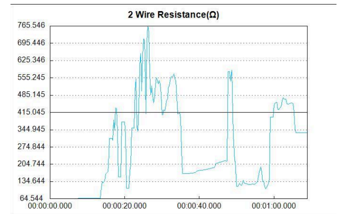

Sensor 6

Test 1 | Test 2 | Test 3 | Test 4

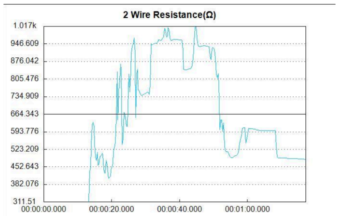


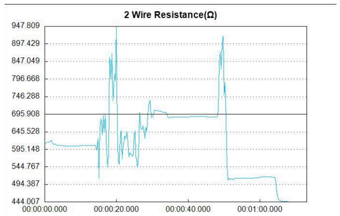



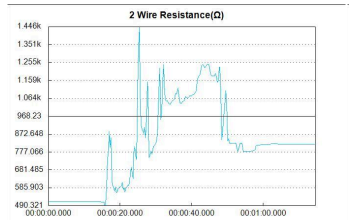



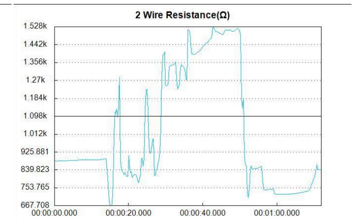




Sensor 7



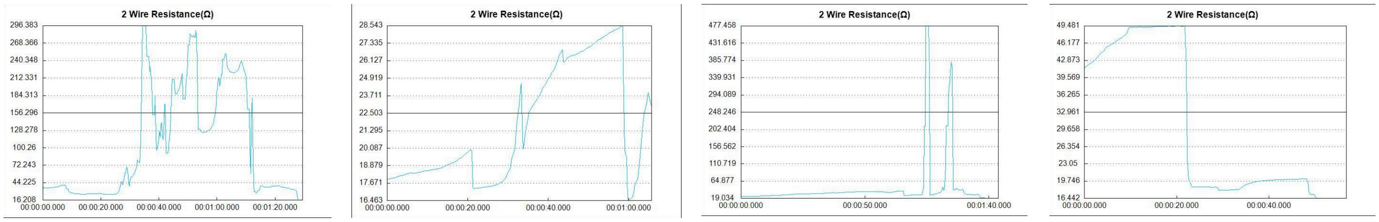



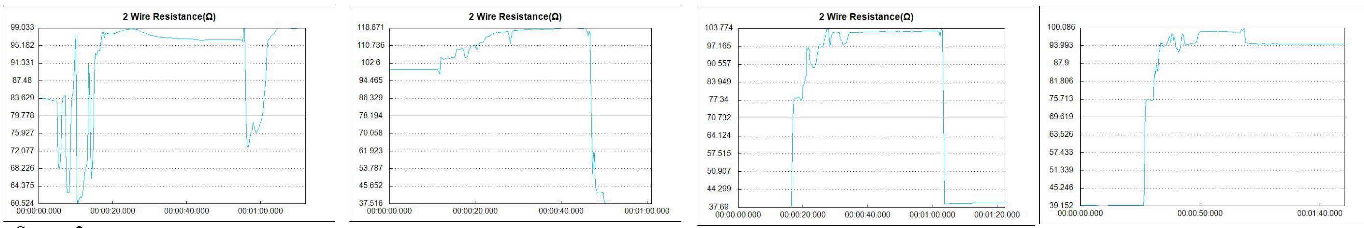

Sensor 8

# Tests: Exploration 3

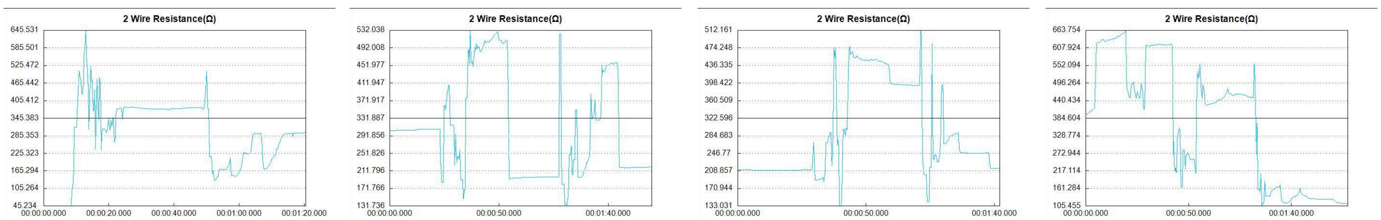
Test 1 | Test 2 | Test 3 | Test 4



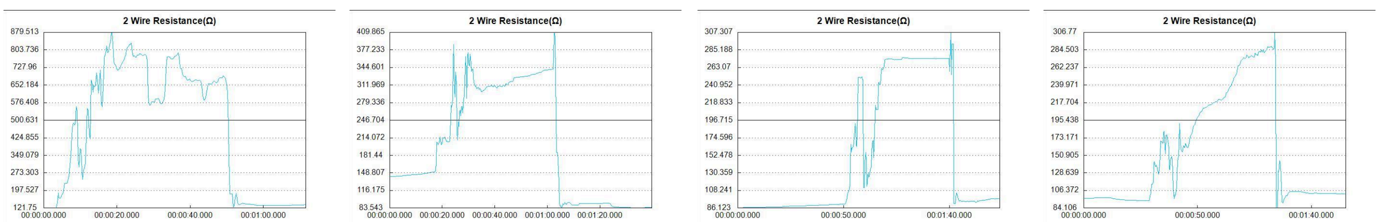
Sensor 1



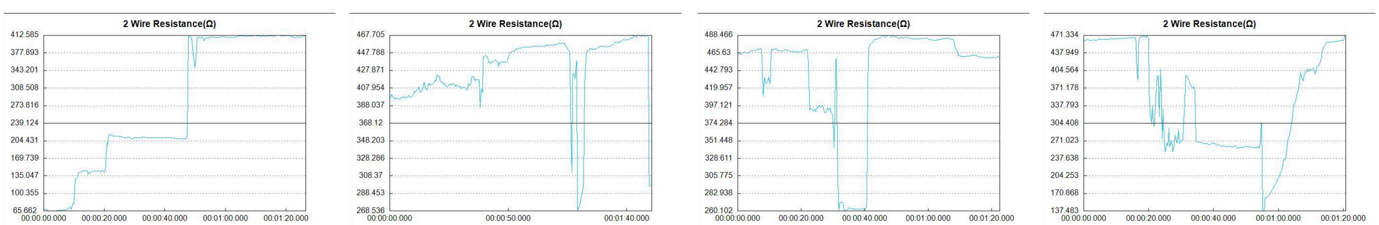
Sensor 2



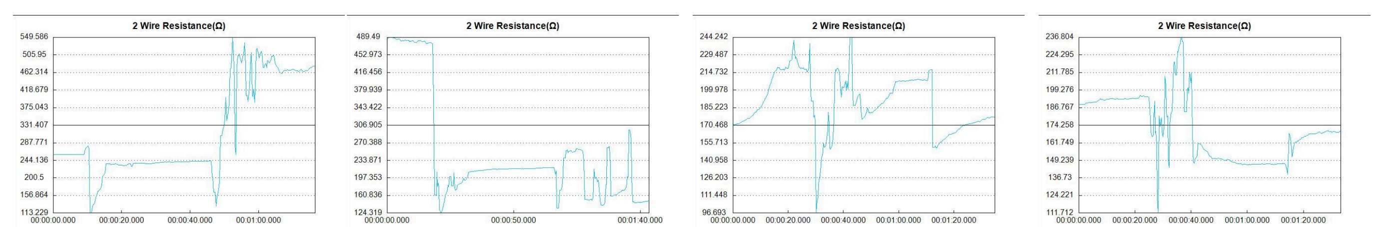
Sensor 3



Sensor 4

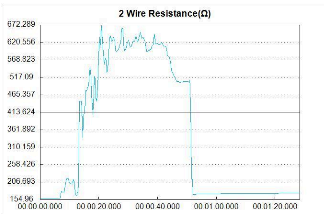


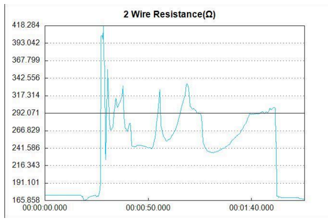
Sensor 5

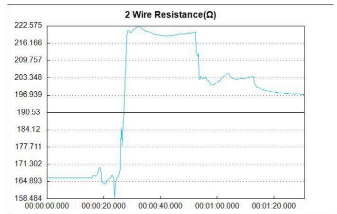


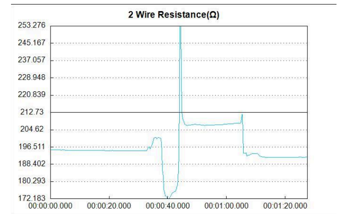
Sensor 6

Test 1 | Test 2 | Test 3 | Test 4

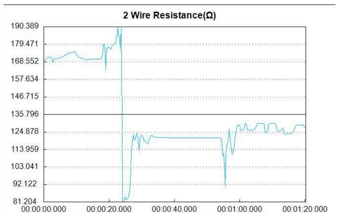


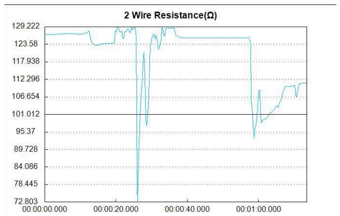


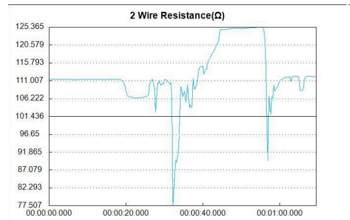


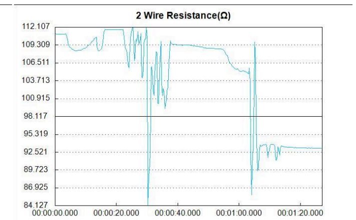



Sensor 7





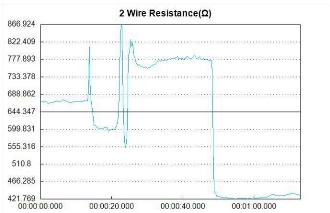


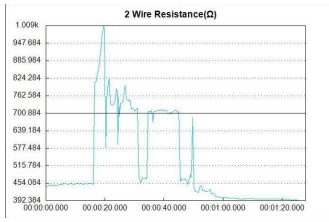


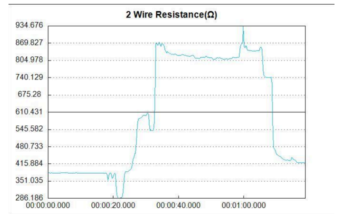

Sensor 8

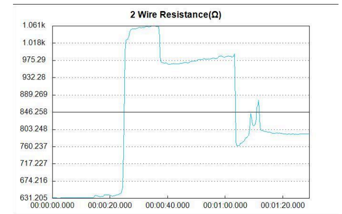
# Tests: Exploration 4

Test 1 | Test 2 | Test 3 | Test 4

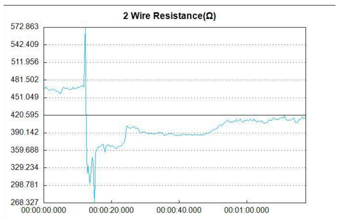


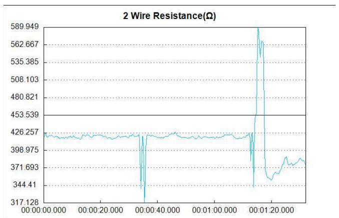


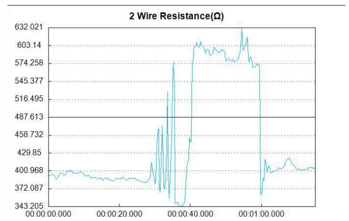


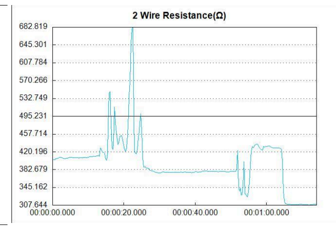



Sensor 1

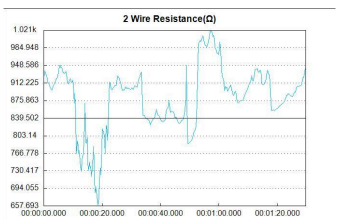


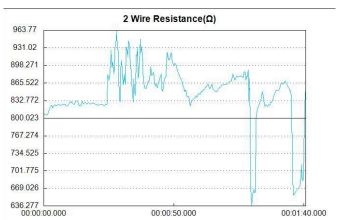


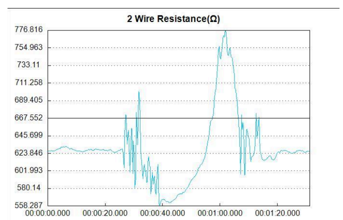


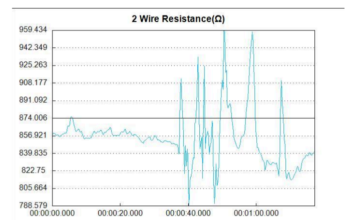



Sensor 2

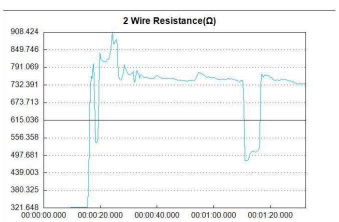


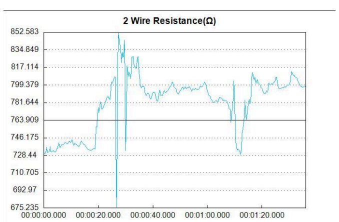


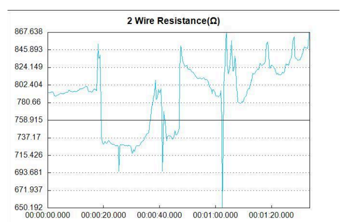


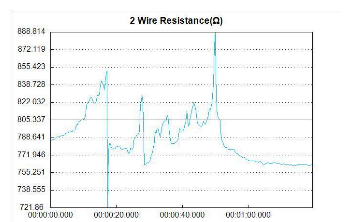



Sensor 3

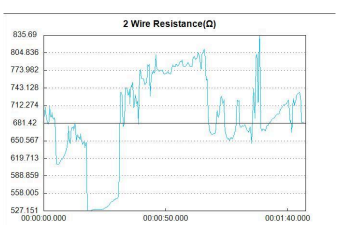


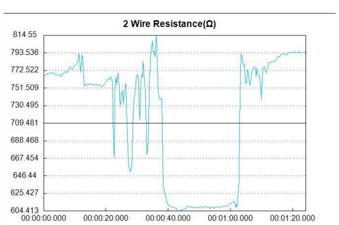


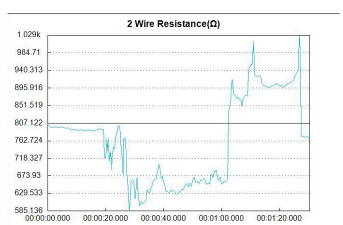


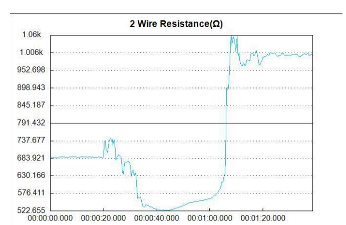



Sensor 4

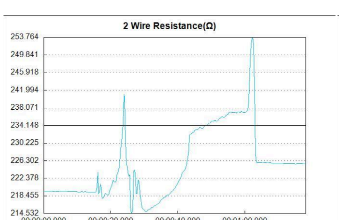


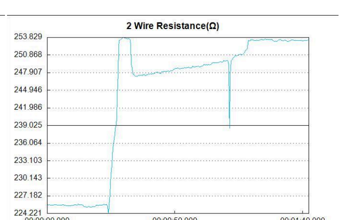


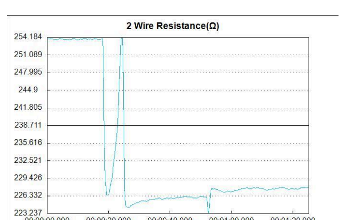


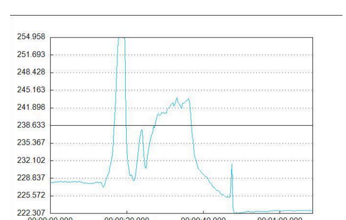



Sensor 5



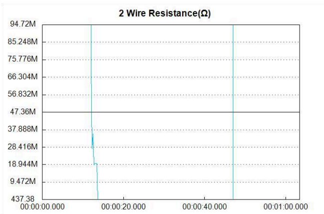


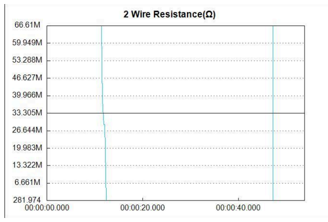


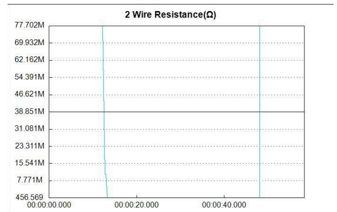


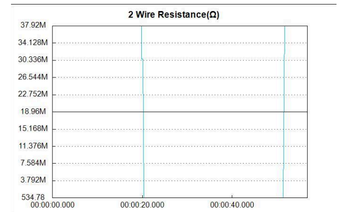
Sensor 6

| Test 1 | Test 2 | Test 3 | Test 4 |
|---|---|---|---|

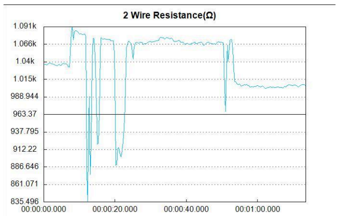


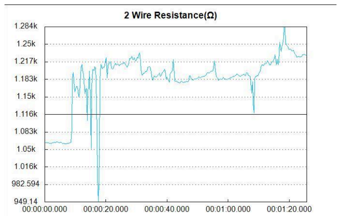



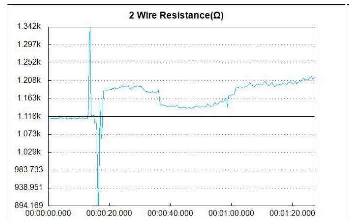



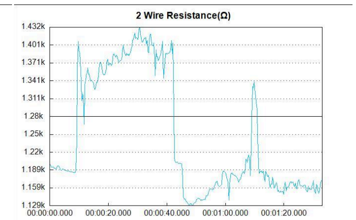




Sensor 7



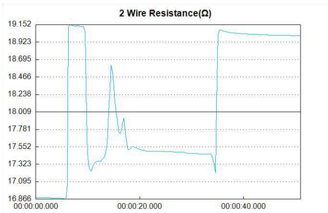



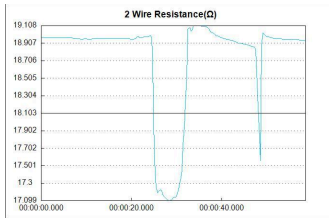



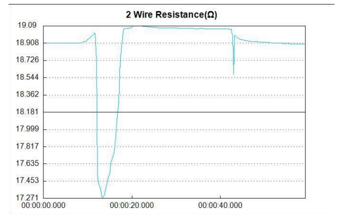

Sensor 8

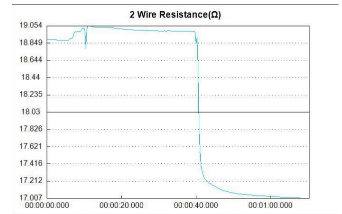
# Tests: Exploration 5

Test 1 | Test 2 | Test 3 | Test 4

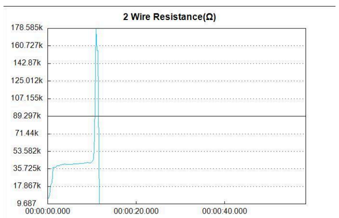


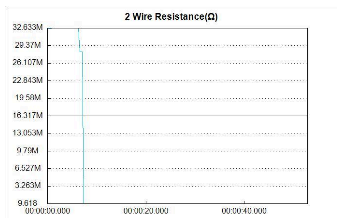


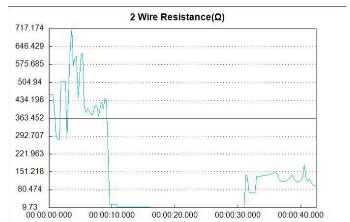


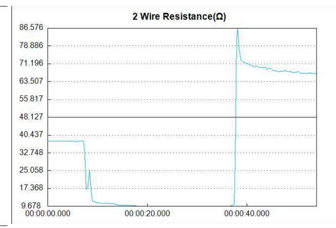



Sensor 1

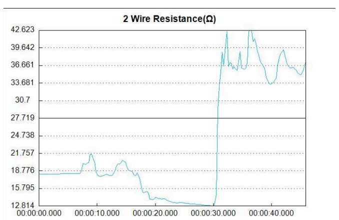


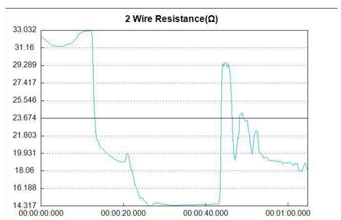


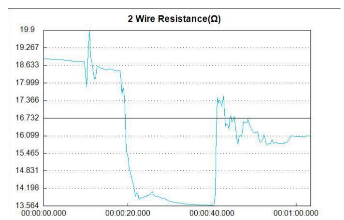


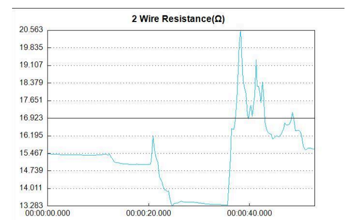



Sensor 2







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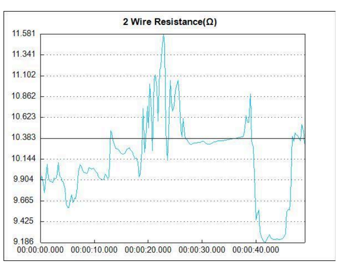

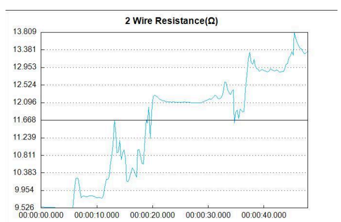


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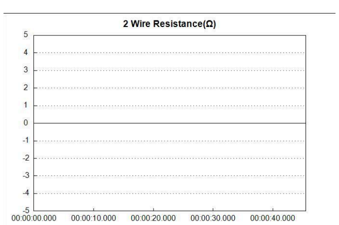
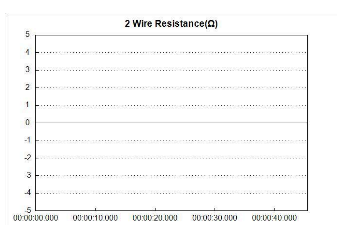
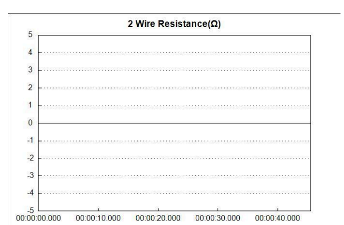
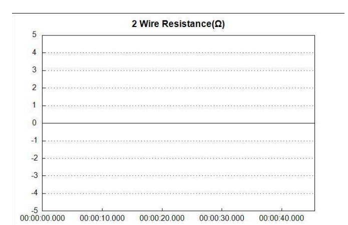
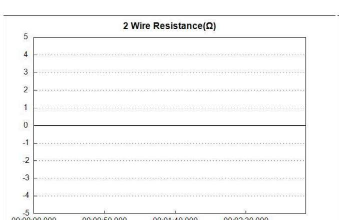


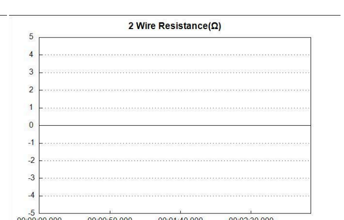


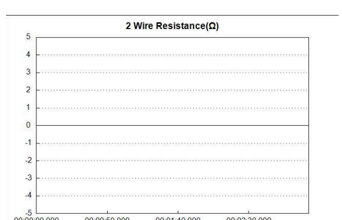


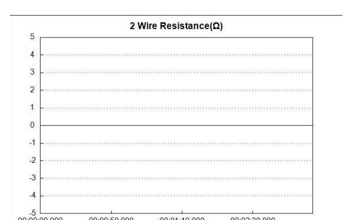



Sensor 5



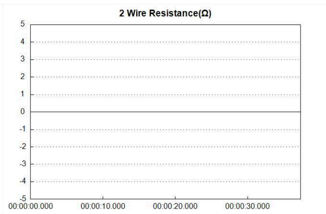


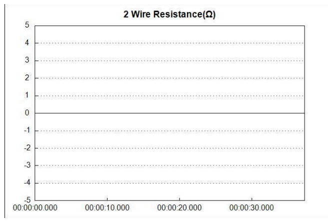


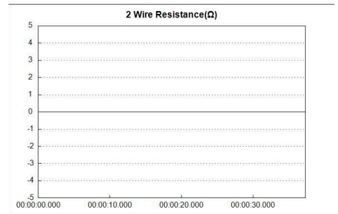


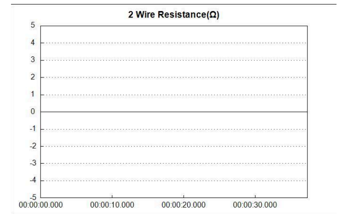

Sensor 6

Test 1 | Test 2 | Test 3 | Test 4

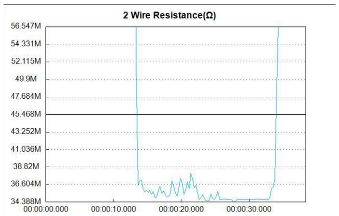


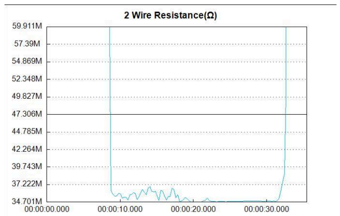



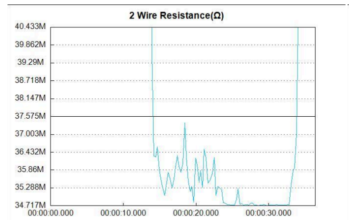



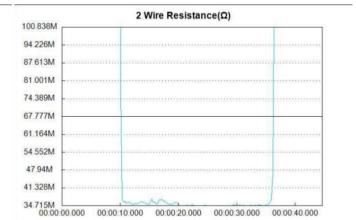




Sensor 7



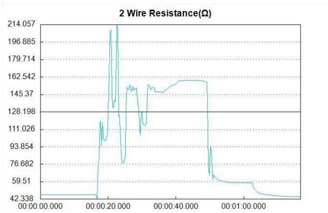



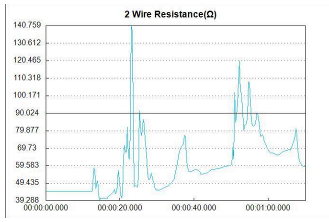



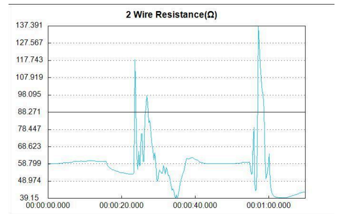

Sensor 8

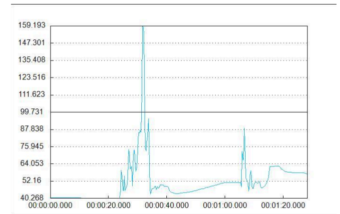
# Tests: Exploration 6

Test 1 | Test 2 | Test 3 | Test 4

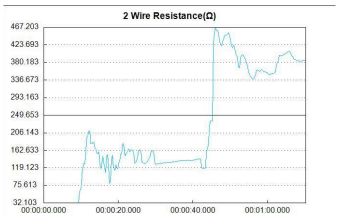


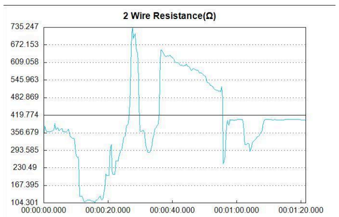


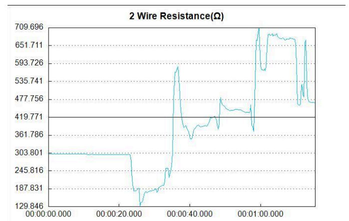


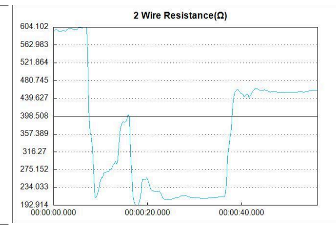


Sensor 1

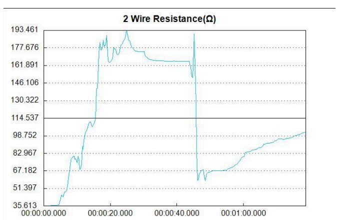


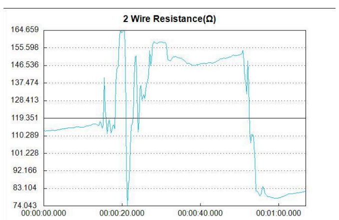


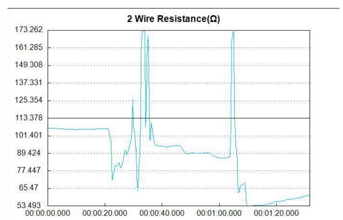


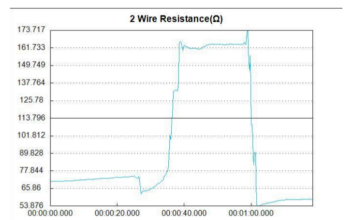



Sensor 2

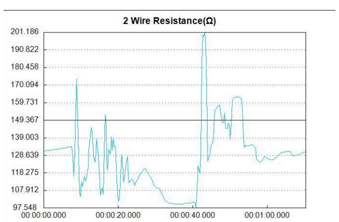


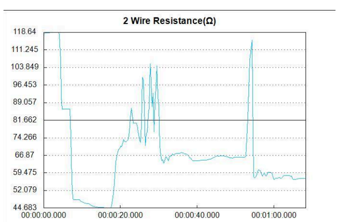


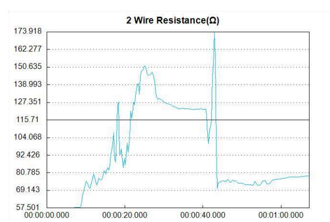


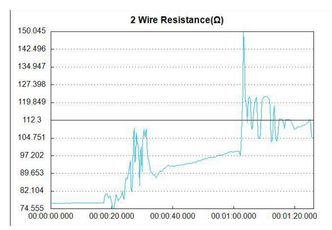



Sensor 3





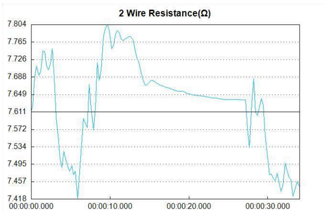


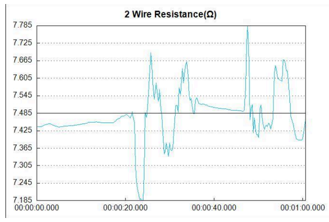



Sensor 4

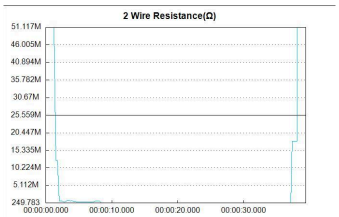
# Tests: Exploration 7

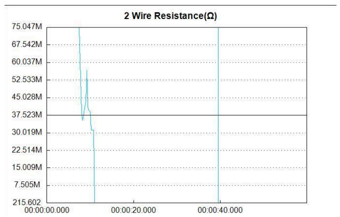
Test 1 | Test 2 | Test 3

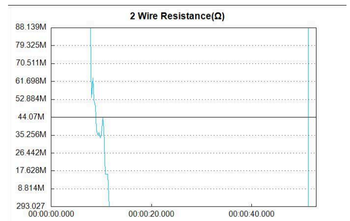


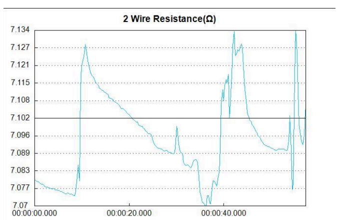

Sensor 1



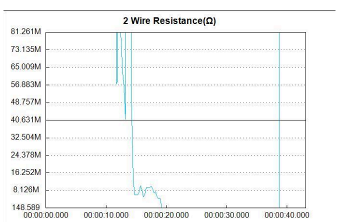



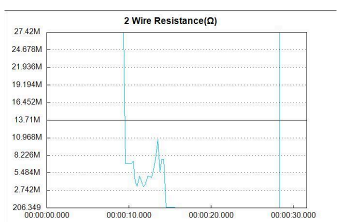




Sensor 2




Sensor 3

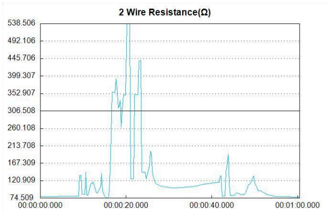


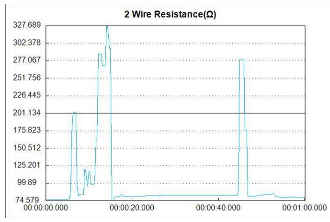



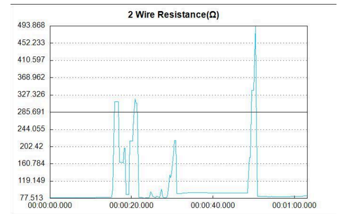

Sensor 4

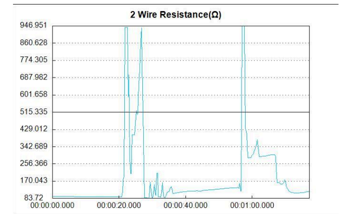
# Tests: Exploration 8

Test 1 | Test 2 | Test 3 | Test 4

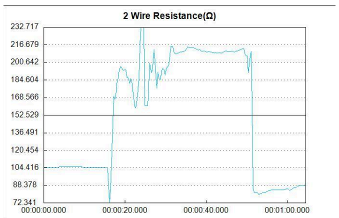


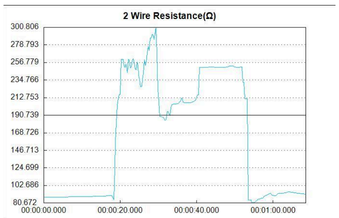


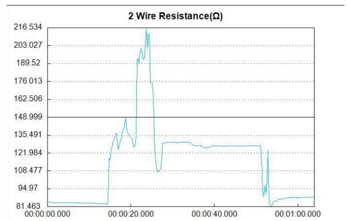


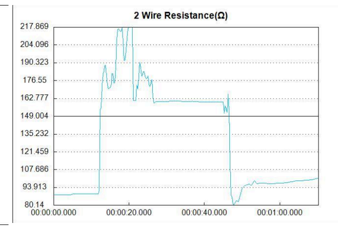



Sensor 1

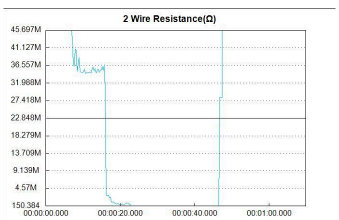


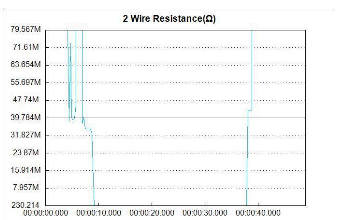


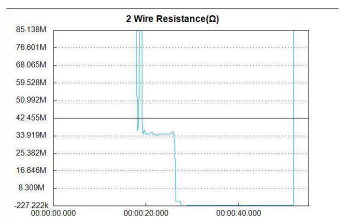


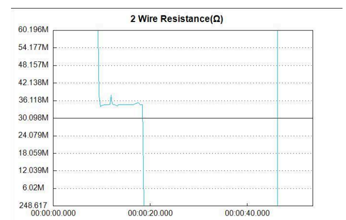



Sensor 2

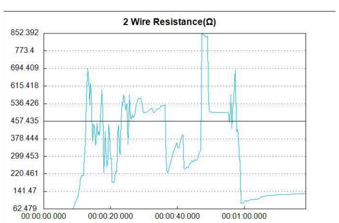


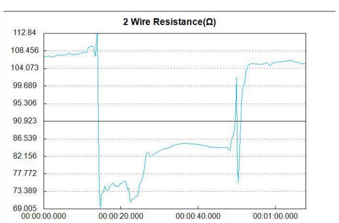


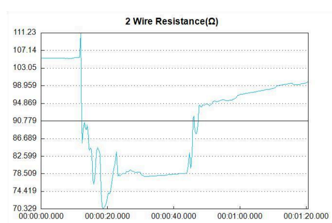


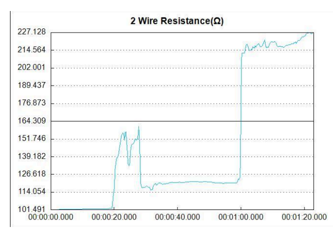



Sensor 3





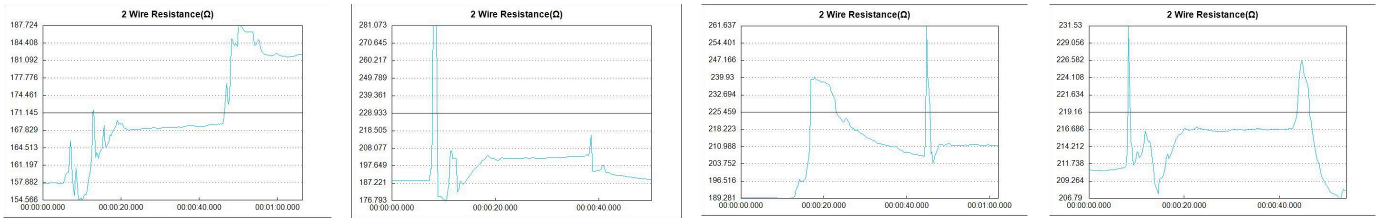




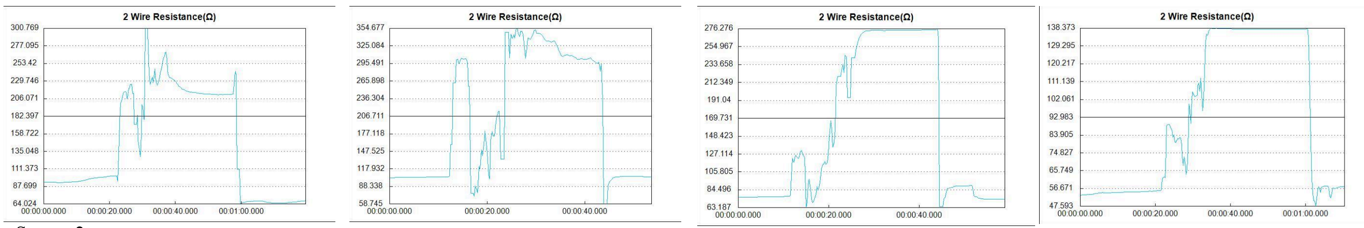

Sensor 4

# Tests: Exploration 8a

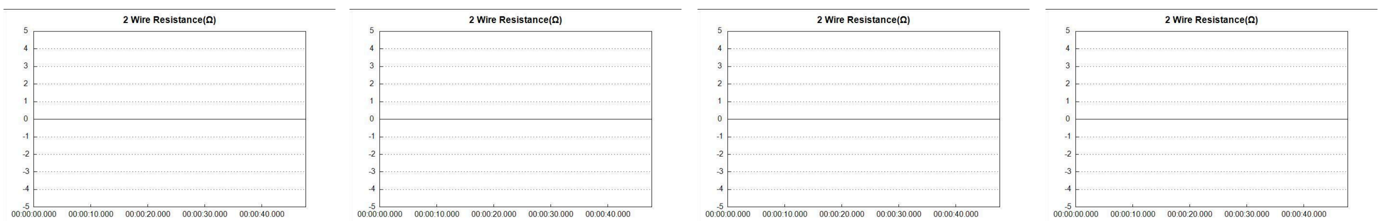
Test 1 | Test 2 | Test 3 | Test 4



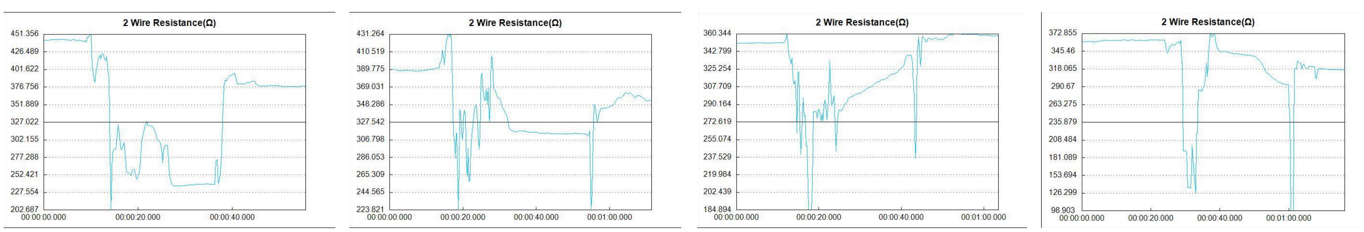

Sensor 1




Sensor 2

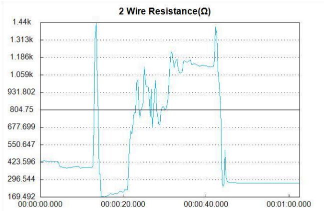
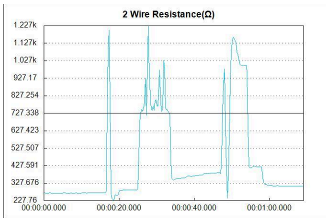
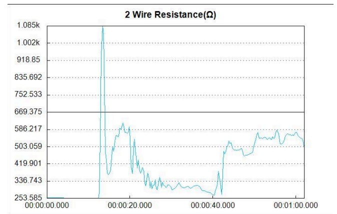
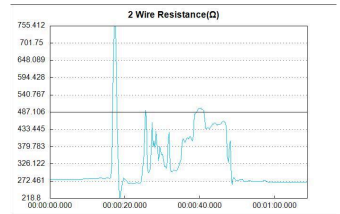



Sensor 3




Sensor 4

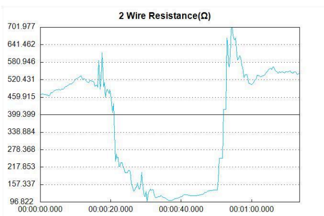
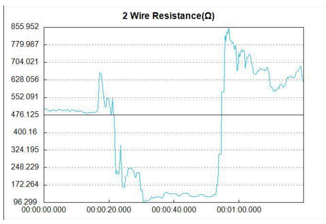
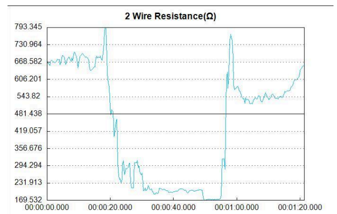
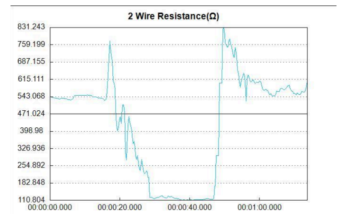
# Tests: Exploration 9

| Test 1 | Test 2 | Test 3 | Test 4 |
|---|---|---|---|
|  |  |  |  |



Sensor 1

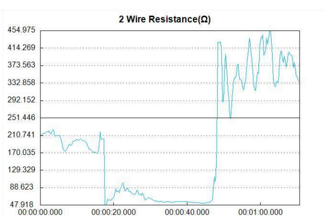
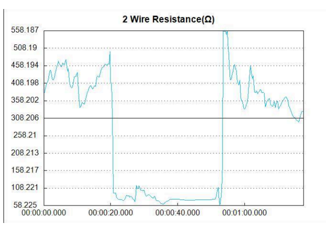
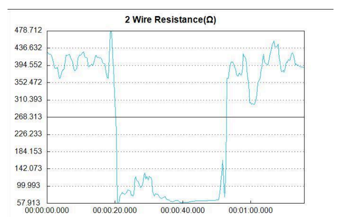
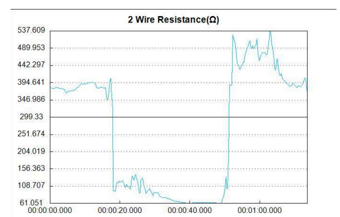
# Tests: Exploration 10

| Test 1 | Test 2 | Test 3 | Test 4 |
|---|---|---|---|
|  |  |  |  |



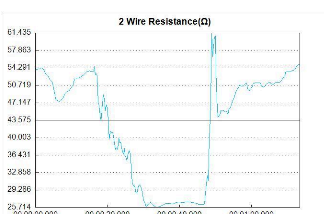
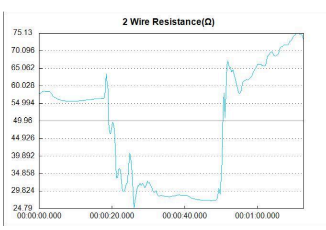
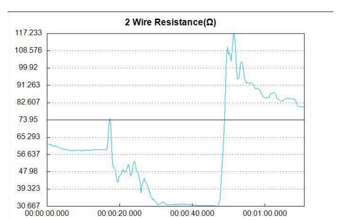
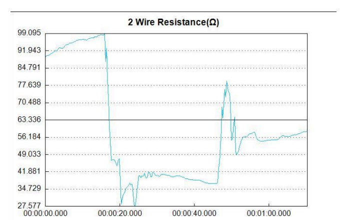
Sensor 1

# Tests: Exploration 11

| Test 1 | Test 2 | Test 3 | Test 4 |
|---|---|---|---|
|  |  |  |  |



Sensor 1

| | | | |
|---|---|---|---|
|  |  |  |  |



Sensor 2

## F. Press Zoom Arduino code

```
#include <Keyboard.h>
#include <Mouse.h>

const int sensorPin = A0;
const float R_fixed = 470.0; // 10kΩ resistor
const float V_in = 5.0; // Arduino voltage
int prevStep = -1; // Stores previous resistance step

void setup() {
    Serial.begin(9600);
    Keyboard.begin();
    Mouse.begin();
}

void loop() {
    int rawValue = analogRead(sensorPin);
    float V_out = rawValue * (V_in / 1023.0);
    float R_sensor = (V_out * R_fixed) / (V_in - V_out);

    Serial.print("Resistance: ");
    Serial.println(R_sensor);

    // Handle values above 75Ω by rounding down to 70Ω
    if (R_sensor >= 75) {
        R_sensor = 70;
    }

    // Determine step boundaries (5Ω increments)
    int currentStep = (int)(R_sensor / 5) * 5;

    // Zoom in if resistance decreases past steps
    if (currentStep < prevStep) {
        int zoomInSteps = (prevStep - currentStep) / 5;
        Keyboard.press(KEY_LEFT_CTRL); // Hold Ctrl
        for (int i = 0; i < zoomInSteps; i++) {
            Mouse.move(0, 0, 1); // Scroll up (Zoom In)
            delay(50);
        }
        Keyboard.release(KEY_LEFT_CTRL); // Release Ctrl
        Serial.print(" | Zooming In (Scroll Up) - Steps: ");
        Serial.println(zoomInSteps);
    }

    // Zoom out if resistance increases past steps
    else if (currentStep > prevStep) {
        int zoomOutSteps = (currentStep - prevStep) / 5;
        Keyboard.press(KEY_LEFT_CTRL); // Hold Ctrl
        for (int i = 0; i < zoomOutSteps; i++) {
            Mouse.move(0, 0, -1); // Scroll down (Zoom Out)
            delay(50);
        }
        Keyboard.release(KEY_LEFT_CTRL); // Release Ctrl
        Serial.print(" | Zooming Out (Scroll Down) - Steps: ");
        Serial.println(zoomOutSteps);
    } else {
        Serial.println(" | No Scroll");
    }

    // Update previous step
    prevStep = currentStep;

    delay(200); // Update every 0.2 seconds
}
```

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# 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

Initials

Given name

Student number

IDE master(s) IPD ✓ Dfl SPD

2nd non-IDE master

Individual programme *(date of approval)*

Medisign

HPM

### SUPERVISORY TEAM

Fill in he required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair | dept./section

mentor | dept./section

2nd mentor

client:

city: | country:

optional comments

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

! 2nd mentor only applies when a client is involved.

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

Sign for approval (Chair)

Kaspar Jansen

Digitally signed by Kaspar Jansen
Date: 2024.09.24 11:44:20 +02'00'

Name | Date | Signature

## 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 2nd 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 |

| | | |
|---|---|---|
| ★ | YES | all 1st year master courses passed |
| | NO | missing 1st year courses |

Comments:

Sign for approval (SSC E&SA)

Robin den Braber
Digitaal ondertekend door Robin den Braber
Datum: 2024.09.25 08:25:14 +02'00'

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 | ★ | Supervisory Team approved |
| NO | | Supervisory Team not approved |

Comments:

Based on study progress, students is ...

| | |
|---|---|
| ★ | ALLOWED to start the graduation project |
| | NOT allowed to start the graduation project |

Comments:

Sign for approval (BoEx)

Monique von Morgen
Digitally signed by Monique von Morgen
Date: 2024.09.26 11:30:51 +02'00'

Name | Date | Signature

DESIGN FOR our future

TUDelft

# 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** Developing a smart textile structure for a force sensor using conductive thread

*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)*

Smart textiles, as defined by Vladan Koncar, are textiles capable of sensing and responding to changes in their environment. This concept, first introduced in Japan in 1989, has been continuously evolving. Various sensors have been developed to measure factors like strain, pressure, temperature, and more.

This graduation project will explore the viability of a force sensor. Although force sensors exist, they are often large, bulky, and impractical for many applications, highlighting the need for a more compact solution. Figure 1 shows a knitted prototype developed by Kaspar Jansen. Figure 2 shows a sock claiming to have integrated pressure sensors. Its still questionable if these socks work or keep there performance over time.

The yarn provided for this project is claimed by its manufacturer to have the necessary conductive and material properties to produce fabric capable of functioning as a force sensor.

The project will culminate in a prototype that demonstrates the performance of this new force sensor, accompanied by a concept presentation of a potential use case. The suitability of this use case will be closely linked to the performance of the force sensor.

→ *space available for images / figures on next page*

*introduction (continued): space for images*

**image / figure 1** Pressure sensor by Kaspar

click to add picture

**image / figure 2** Footfalls Smartex Ltd.

## 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 current challenge with existing force sensors lies in their size and thickness. This issue primarily arises from the use of a double-knitted matrix, which significantly increases the sensor's thickness. Reducing the size and thickness of the force sensor would enhance its applicability across various concepts like paraplegic sitting aid and music controllers in everyday clothing.

A major concern in smart textiles, in general, is reliability. Textiles are prone to tearing or wearing down over time, and the electrical components embedded within them must be waterproof. Addressing these issues is crucial in developing a reliable and durable force sensor.

## 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:*

Develop a smart textile structure for a force sensor to measure the input force generated by a user in a yet to be determent concept product.

*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)*

The graduation project will begin with an in-depth review of literature on smart textiles and force sensors. This research phase will explore the current state of the field, examining what has already been achieved, identifying what works, and understanding the limitations and challenges that remain.

Building on this theoretical foundation, a testing plan will be designed to evaluate specific hypotheses formulated based on the research findings. This plan will guide the development and testing of prototypes. As prototypes are created and their performance assessed, the testing plan may be revised or refined based on observations and results.

If the project successfully yields a prototype that meets the desired criteria, a concept will be developed that leverages the unique characteristics of the prototype. Finally, the performance, prototype, and concept will be presented in a final presentation.

## 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 | |
| Mid-term evaluation | |
| Green light meeting | |
| Graduation ceremony | |

*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 | |
| For how many project weeks | |
| Number of project days per week | |

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)*

During this project I would like to increase my theoratical understanding of smart textiles. I like to go into the nitty-gritty details and really comprehend the topic at hand. Furthermore I would like to improve my academic literature research and reasoning. This is a topic often neglected at IDE.

I also want to increase my coding performance when measuring and evaluating the data collected by the tests. I think I can learn a lot of new skills and it would be great if I can learn this in Python as it is a great asset to have in my further carreer.