Knitted smart textile sensors



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Master thesis

Integrated Product Design

Delft, June 2020

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Preface

In front of you lies the report on "Knitted smart textile sensors". The process of this project that lead to a final prototype garment is described in this report.

This project has a quite technical approach, which might make it a difficult read for some. The report is split into five sections. Each chapter has a different focus and is thus targeting a different type of reader. The following part gives a short overview of the information each chapter offers.

The first chapter highlights what is **State-of-the-art in textile sensors.** It contains information from mostly from literature. This chapter is interesting for people that have no knowledge on textiles and technology in textiles.

Literature knowledge is not enough to make an actual knitted strain sensor. The second chapter talks about: **Making knitted strain sensors work**. It contains information on how to make a knitted strain sensor on a Stoll knitting machine. Read this chapter if you want to just make a knitted strain sensor.

Making a knitted strain sensor is fun, but the process of how it came to be is not known yet. The third chapter is about: **Improving the knitted strain sensor**. It contains information on how the knitted strain sensor is improved. This chapter is more focussed on people with more technical knowledge.

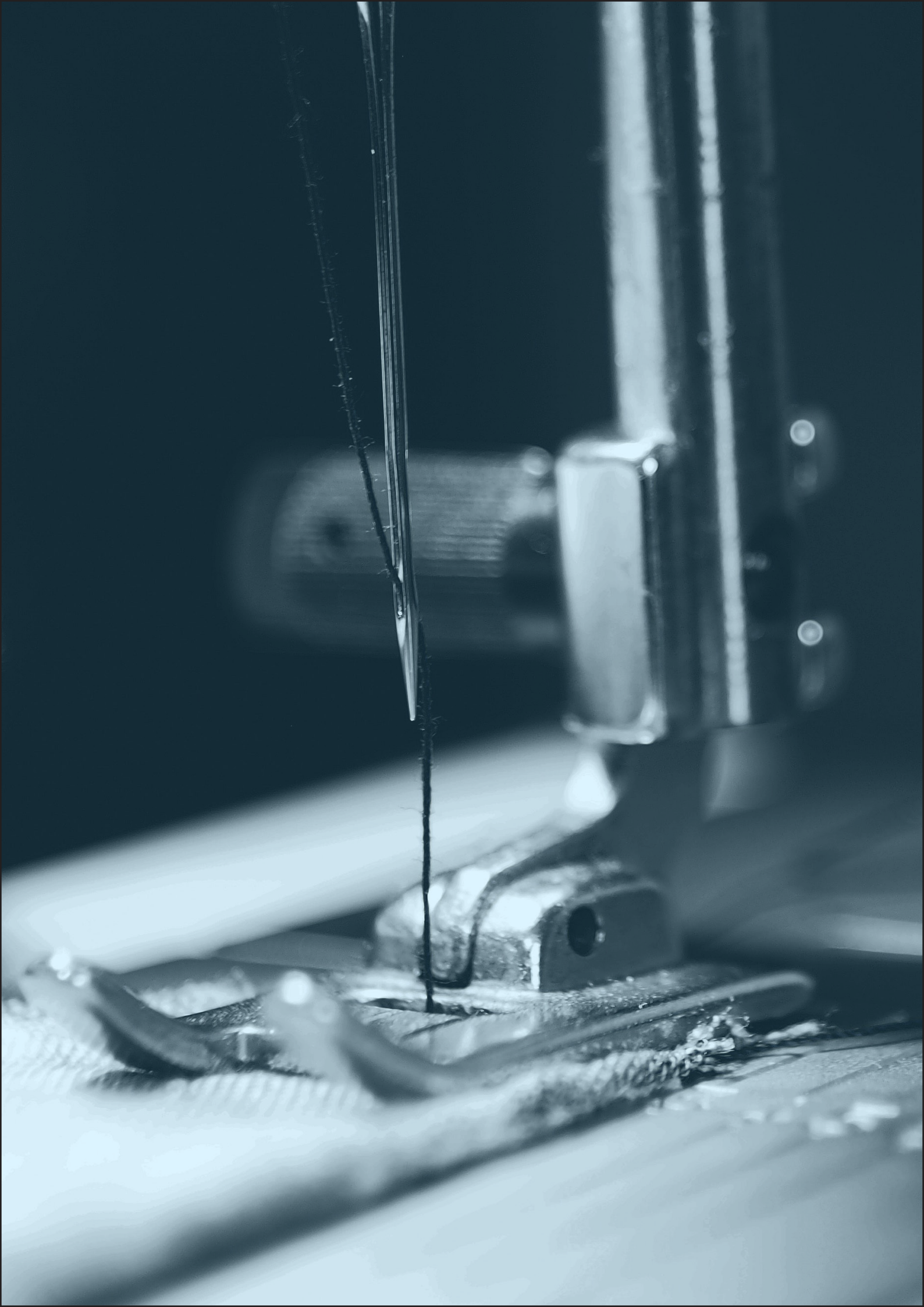
Now that all technical knowledge is treated, it is time to implement the technology into a product. The fourth chapter talks about: **Designing with knitted strain sensors.** It contains examples on how the knitted strain sensor can be used and is more focussed on designers wanting to use this technology.

The final chapter is about: **Evaluating.** It contains a evaluation on the final prototype and looks back on the project as whole. This part is wrapped up with recommendations for the future of this technology.

A separate **appendix** en **knitting sample folder** is included to support the results written in this report.

I hope you enjoy reading my final thesis.

Daan van der Valk



Glossary

Acronyms

ECG = Electrocardiography
The process of tracking heart activity through measuring voltage changes.

EMG = Electromyography
The process of tracking skeletal muscle activity through measuring voltage changes.

Terms

Singeing
To burn protruding loose fibres on the surface of a woven fabric.

Strain sensor
A sensor that can measure the amount something is stretched.

Wale direction
Knitting direction that is parallel to the movement of the knitting machine carriage.

Course direction
Knitting direction that is parallel to the movement of the knitting machine carriage.

NP value
A value on the knitting machine that changes the size of the knitted loops in the fabric. A higher NP value makes larger loops and a lower NP value smaller loops.

Dtex
This is a way to determine the thickness of a yarn. The unit of Dtex is gram per 10.000 meters of yarn.

Tex
A way of determining yarn thickness. The unit of Tex is gram per 1000 meters of yarn.

Nm
A way to determine yarn thickness. The unit of Nm is 1000 meters of yarn per kilogram

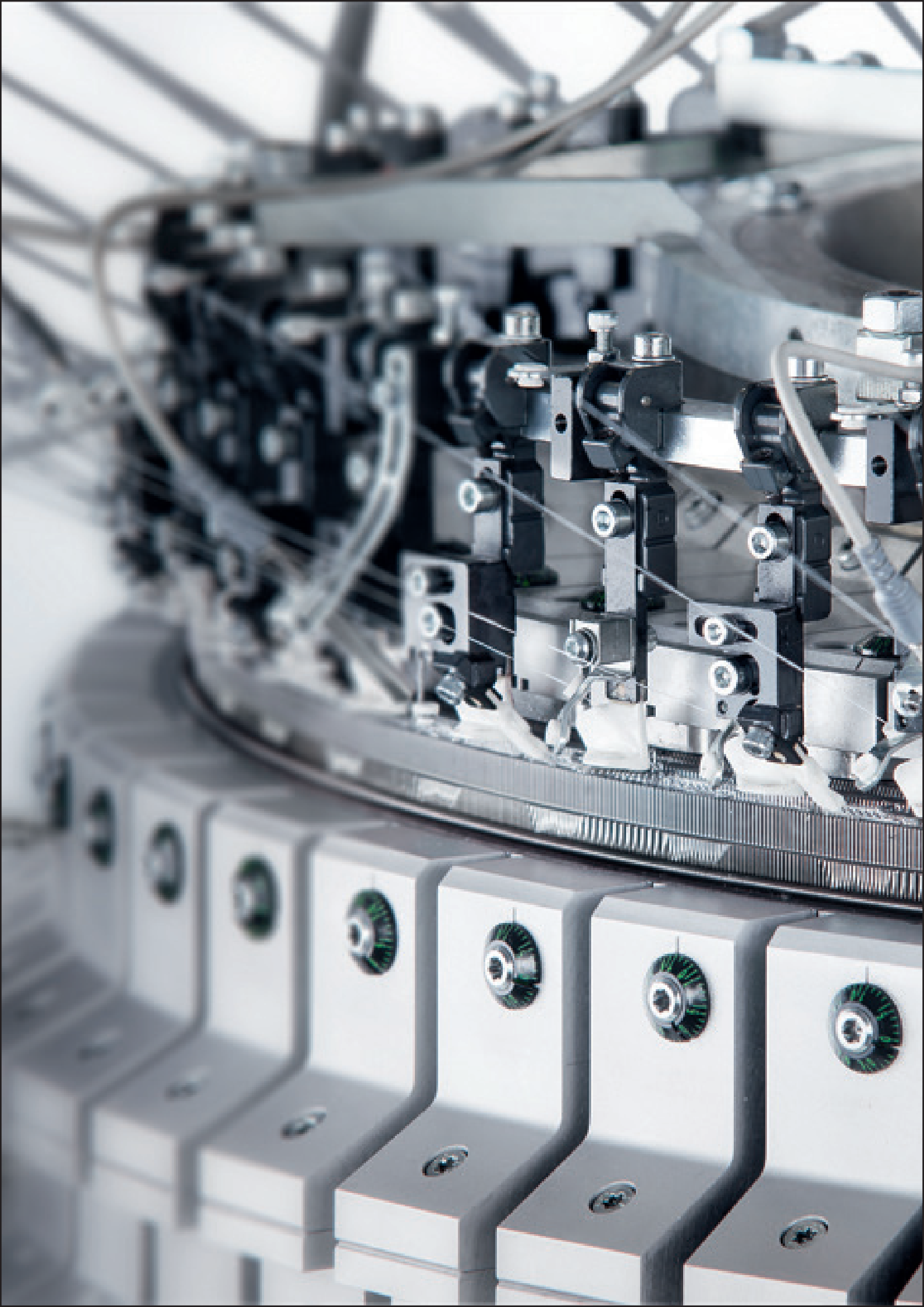
Jacquard
A knitting technique that is used to create intricate knitting patterns.

Intarsia
A knitting method to create larger parts of a different colour in a knitted fabric.

Plating
A knitting technique where two yarns are used at once. Plating makes it that one yarn is always on top of the other.

Lycra
A synthetic yarn that has elastic properties. Also called Spandex or elastane.

Gait analysis
The study of human motion.



Executive summary

Nowadays, people are using more and more technology to measure their body performances like smart watches, heart rate sensors etc. These are all separate devices. What if it were possible to integrate these into something we wear daily.

Textiles are something everyone wears daily. It is a promising medium to integrate electronics in. Especially through knitting new possibilities arise.

Different conductive and non-conductive yarns are explored with a focus on off-the-shelf available materials. The main yarn needing to be elastic to get the fabric back to its normal position after stretching.

Knitted fabrics have a unique structure which is perfectly suited to create sensors with. A knitted fabric is stretchable without the yarn needing to be stretchable. This makes searching for good working conductive yarns easier, as non-stretchable conductive yarns are a lot more common.

Previous research shows that creating sensors through knitting is possible and can be achieved with simple yarns. The structure of knitted fabrics is mainly useful for creating strain sensors.

Using elastic yarn with silver conductive plated yarns, different sensor test samples are created. Optimization is done to improve the sensors' signal output. Two directions for knitting a sensor were tested.

The optimized sensors are used in two prototypes that are able to measure the movement of the arm and the breathing pattern of the wearer.

The arm movement prototype is tested with two sensors knitted in the vertical (wale) direction and the breathing sensor was made with a long strip of a sensor knitted in the horizontal (course) direction.

Both arm and breathing sensors are integrated into a full garment prototype. This prototype is tested by doing different movements and seeing how movements affect the sensor behaviour.

Possible designs of a shirt with integrated arm and breathing sensors are briefly discussed to show how the look of the shirt and the integrated sensors could complement each other.

The final prototype's sensor data is evaluated and recommendations are made for follow up projects based on this research.

This research sets a new and fruitful step in the direction of producing commercially viable body measurement clothing for the near future.

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Chapter 1

Introduction

Chapter 1.1

Introduction

Keeping an eye on body performance and personal health, also called E-health, is becoming more and more popular. Smart wearables like fitness bands and smartwatches make this type of monitoring possible. Being able to track the performance of the body opens ways for people that would otherwise need regular doctor check-ups to do this remotely. Moreover, tracking sport performance is in high demand, as even the smallest improvements can make a difference between becoming first or second place. New technologies provide the opportunity to improve this performance. As technology changes and improves constantly, clothing would be a perfect new medium to integrate technology in, as we are in contact with textiles daily.

Current sensors can sense small deformations less than 5% strain, which are mostly used in structural health monitoring (Seyedin et al., 2015). Which includes material fatigue in vehicles and infrastructure. Measuring body movements can go up to 40% strain, which makes these solid sensors unusable (Pei et al., 2019).

Textile based strain sensors are able to measure body movements without increasing discomfort. These knitted sensors can be integrated directly into garments unlike existing sensors which are rigid and attach onto a garment instead. As the textile based sensors are made of nearly the same material as the garment, they exhibit similar tensile properties.

Embedding conductive yarn into a garment makes the working of a textile based sensor possible. There are multiple ways to implement the conductive yarn such as sewing, embroidery, weaving and knitting (Castano, 2014). However, the structure of knitted fabrics is the most suitable for created garments with strain sensing properties, as the knitted structure is better able to adapt to the body shape of the user. 3D shapes are now also able to be knitted (Figure 1). Elasticity and adjustability to the body shape compared to other fabrics also improves the comfort. Knitting also provides the opportunity to manufacture garments with integrated sensors in one step, where the sensor parts are integrated during the knitting process of the garment. Advanced knitting machines also are able to knit complex 3D structures.

There are clear opportunities when it comes to body tracking with integrated sensors. However, this technology is still in its infancy and needs to be further researched to make it marketable. Although the technology is new, there are some examples available on the market, such as the sensoria socks (Sensoria, 2020).

This paper presents a research into creating knitted strain sensors, improving the output of these sensors and applying them in different use cases. Sensors were created with stainless steel yarn and silver coated yarn.

This report will answer the following question: How to make smart textiles with a knitting machine, and is divided into four sections each written with a different reader in mind. The first is main research on textile based sensors (chapter 2), the second part goes deeper into knitting and yarn types (chapter 3), the third part describes the technical details of improving the strain sensor (chapter 4) and the fourth part is about how these sensors can be used by designers (chapter 5).

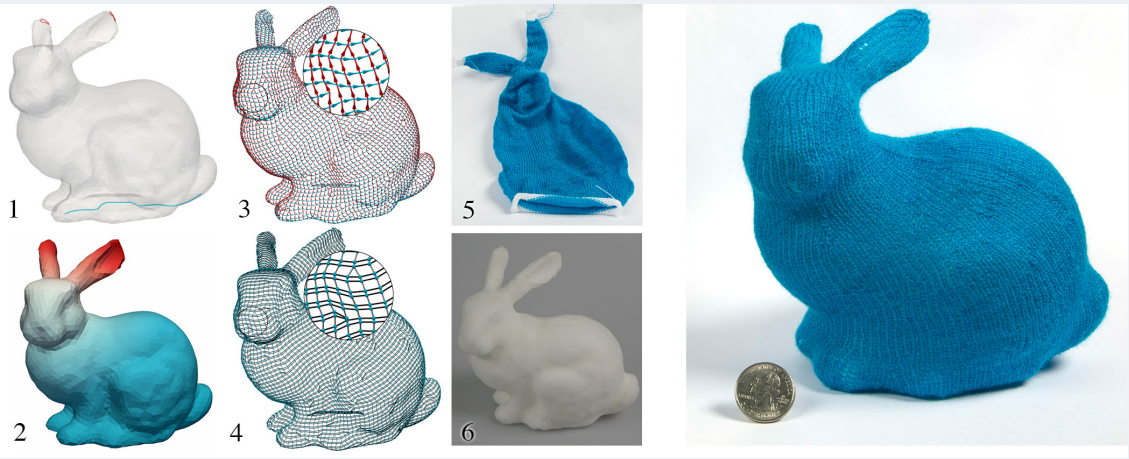


Figure 1. 3D knitting process. (Narayanan, 2018)

Chapter 1.2

Approach

This project will focus on exploring textile based sensors using a Stoll CMS 530 multi gauge knitting machine. Before the approach will be determined, a few key aspects of this project need to be taken into account.

The production of textile sensors can be achieved in multiple ways. As the Technical University of Delft has purchased an industrial knitting machine, the main focus of this project is to look at knitting.

No prior knowledge of this machine was available, that is why a week of machine lessons were planned in the week of the machines arrival.

The main method used for this project is the basic design cycle in a triple diamond setup (Van Boeijen, 2019). A method where there is continuous switching between design, analysis and synthesis. A circular process, but for sake of clarity, the approach is illustrated as linear (Figure 2).

For this project, it is crucial to understand what has already been researched and what deemed successful from these researches. Therefore, the first part of this project is the analysis phase. The goal of this phase is to get a better understanding of knitting and textile sensors and their workings. This is done through literature research, mechanical and software lessons on the Stoll knitting machine and simple knitting tests.

The next phase consists of using the gathered information from the analysis phase and combining them and try to replicate their results as well as possible and improve them. This knowledge will then be used to develop the eventual showcase model.

The last phase will be the design phase. This is where all gathered knowledge will be combined to create a final model. This showcase model will be used to demonstrate what is possible with combining electronics with industrial knitting. A Reflection on the used methods can be found in chapter 6.6

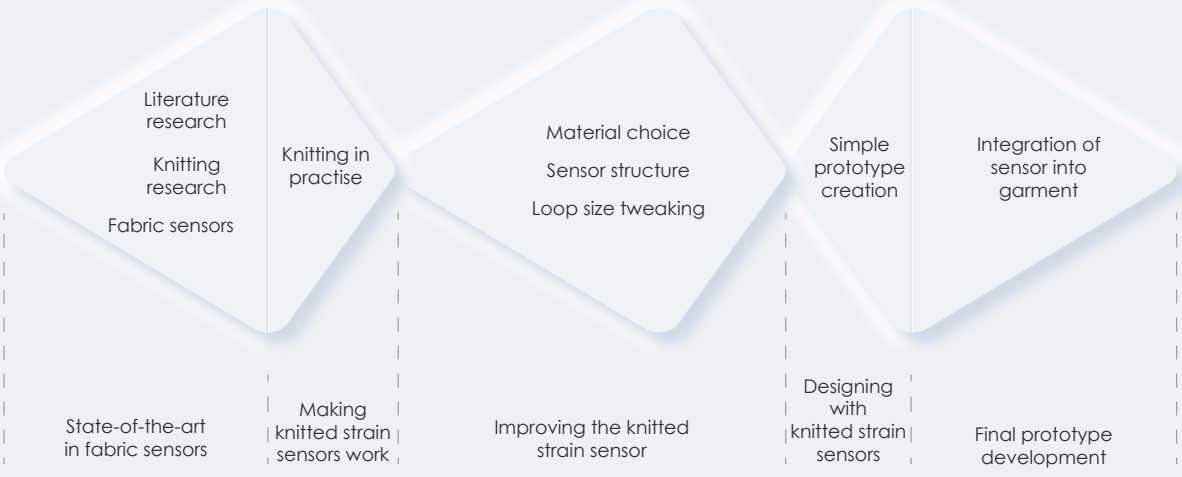


Figure 2. Triple diamond design method project overview.

Chapter 1.3

Hardware & software

For this project a Stoll CMS530 double gauge knitting machine (Figure 3) is used in combination with M1plus software. The Stoll knitting machine has 8 yarn carriers and has a 699 needles per needle bed (2 beds) with a gauge of 14, which means 14 needles per inch.



Figure 3. Stoll CMS5330 multi gauge knitting machine

No prior knowledge of this machine and software was available. Therefore, a week of lessons were taught to me and some other staff from the lab. This week consisted of learning the hardware and software side of the machine.

The M1plus software (Figure 4) is used to create knitting designs in a programming language the knitting machine can read. It has a similar features as G-code has for 3D printers. Namely, a translation from a visual programming language to instructions for the knitting machine.

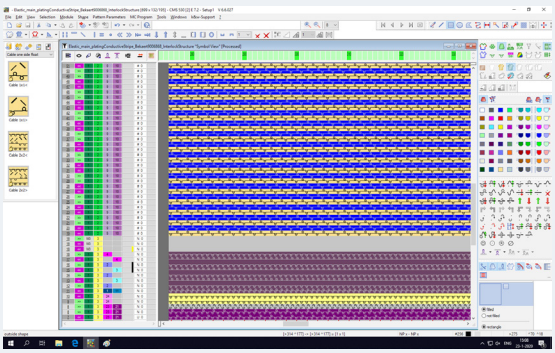


Figure 4. Screenshot of M1plus software

The machine can be controlled by the touch screen interface on the front of the machine (Figure 5). Here it is also possible to change certain settings that can also be changed in the M1plus software like stitch size, carriage speed, fabric take down values etc. Mainly the interface is used to load a knitting file and start this file.

In Appendix A a more detailed explanation of the all the parts is given.



Figure 5. Machine interface main screen



Too tight knitting: torn sample

Chapter 2

State-of-the-art in textile sensors

This chapter starts with the basics or textile sensors and expands on knitting. It continuous with yarn types and how to connect them. Finally, an overview of different fabric sensors and their workings from literature is presented and discussed.

Chapter 2.1

Textile sensors, how?

To get a good understanding of what is involved in creating knitted smart textiles, an overview of important elements to consider is given. Not only looking at manufacturing of the fabrics, but also looking at yarn types, yarn finishes and connection techniques. Using conductive yarn to create electronics in fabrics can be done in different ways. In short these possible methods will be explained and why they would not be ideal to create fully integrated textile based sensors. The chapters on knitting and strain sensors are more comprehensive, as these are the main focus of this research.

Sewing

The easiest way to implement conductive thread into a garment is by using sewing. Sewing is mostly used to attached woven pieces of fabric to each other to create garments. A sewing machine creates stitches to achieve this. Sewing can also be used to implement conductive yarn to create electrical connections and can be used to create smart textiles. Unfortunately, it is not ideal, as it is a rather manual process and requires someone to manually control a sewing machine.

Embroidery

Decorating a fabric can be done with embroidery (Figure 7). Patches of color, but also other materials like pearls or beads are possible. Embroidery creates stitches onto fabrics that are not stretchable, unless stretchable yarn is used. Embroidery can used to implement conductive parts onto a garment. Capacitive touch buttons are possible to be embroidered (Castano, 2014). Embroidery nowadays can be an automated process, but the fact that it cannot stretch and is not able to be fully integrated into a fabric, makes it not suitable to create textile sensors with.



Figure 7. Embroidery up close (Bastings, 2019)



Figure 8 Weaving up close (Nowaja, 2019)

Weaving

An automated way to create fabrics with the possibility to integrate conductive thread is weaving. Weaving is done in a loom which creates fabrics with straight lines (Figure 8). Because weaving is a process that creates fabrics, it is possible to implement conductive thread in the fabrication process in an automated way. Project jacquard (Poupyrev et al., 2016) is a good example of integrating electronics

into fabrics.
Weaving has the disadvantage of having extreme requirements for the threads that are used. The thread needs to be strong as pulling forces are high, it needs to be high temperature resistant as the fabric will be singed (burn the ends of the fabric off) (Figure 9) and it needs to be chemical resistive for color dyeing and finishing (Poupyrev et al., 2016). This makes it more difficult to create different sensors, as not all conductive yarns can meet these requirements. Also, woven fabrics are only stretchable when the yarn that is used is stretchable.



Figure 9. Singeing fabric (ABC. n.d.)

Knitting

Besides weaving, knitting is also a way to create fabrics. Most knitted fabrics are made on a knitting machine. Knitted fabrics are created with basically a periodic structure of slip knots (Figure 11) (Andrei, 2019). These knitted slip knots give the fabric elastic properties without the need for elastic yarn. Knitting also gives more flexibility in creating different patterns and 3D shapes (Figure 10) and the yarn that is used for knitting has lower requirements than the yarn for weaving.



Figure 10. 3D knitted Nike shoe (NIKE, 2012).

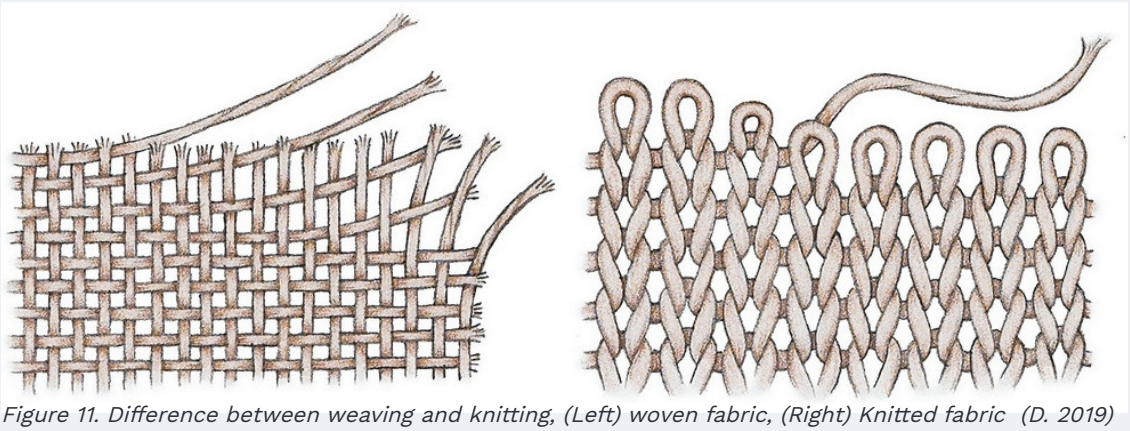


Figure 11. Difference between weaving and knitting, (Left) woven fabric, (Right) Knitted fabric (D. 2019)

When considering more automated ways of creating fabrics or garments, weaving and knitting are good options. Weaving can only create flat fabrics that need to be sewn together to create a garment. Knitting however, provides the possibility to produce intricate three dimensional pieces that have elastic properties through their structure Figure 10 en 12. Additionally, an industrial knitting machine can create a whole garment in one go including integrated extras like sensors or pockets for electronics. This makes knitting the best option to implement sensorial features in garments during the production process. The following chapter will go more into detail on knitting and its possibilities.



Figure 12. 3D knitted bunny (Coxworth, 2018).

Chapter 2.2

Knitting

Now that a basic knowledge integrating technology in fabrics is known, a more in depth research into knitting is done to find the possibilities and details on how to knit with conductive yarn create knitted fabric sensors.

Knitting is seen by most people as something your grandmother would do at home as a hobby, but a lot of the clothing we wear daily is produced via knitting on an industrial knitting machine. Most people think of knitted clothing as roughly knitted (Figure 14), but most clothing is fine knitted (Figure 15). Almost all clothing that is stretchable is made through knitting and products like jeans and shirts that are mostly not stretchable are made with woven fabrics. Knitting machines are able to produce full garments within minutes and supply the high demand the clothing industry desires.

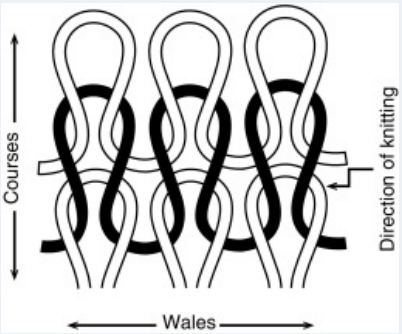


Figure 13. Course and while direction (Miao, 2017).

The basics of knitting are creating rows of loops, which are either flat or round. When talking about knitted fabrics, there are two directions in which a knitted structure spans. The horizontal direction is called the course direction and the vertical direction is the wale direction Figure 13).



Figure 14 Rough knitted sweater (Asitasahabi, n.d.).



Figure 15. Fine knitted sweater (Cottonblues, n.d.).

Knitted fabrics have different structures in the course and wale directions (Figure 13). This results in different behavior when stretched in course or wale direction. The course direction is more stretchable than the wale direction. That is why clothing that needs to stretch, the arms on a sweater for example, the course direction is in perpendicular to the length of the arm. This way, when someone has a thicker arm, the fabric is able to stretch and still fit a thicker arm.

Every part in a knitted fabric also has a different name. The top of the loop is called the head, the middle is called the leg and the bottom is called the foot (Figure 16).

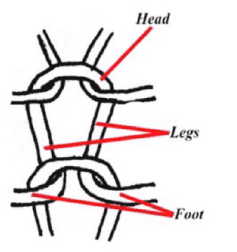


Figure 16. A knitted loop and b. Wale and course directions of loops (Balcioglu, 2019).

Knitting is done by hand or on an industrial knitting machine, which comes in two variants. A flat bed knitting machine or a circular knitting machine.
A flat bed knitting machine has its needles in a horizontal position. A carriage slides over the needles beds and carries the yarn from left to right (Figure 17).

A circular knitting machine, as the name implies, knits in a circular way. The needles are positioned in a circle (Figure 17). This circle defines the maximum diameter of the created fabric. Flat bed knitting machines have a lot more flexibility in the design they can produce, but circular knitting machines have a much higher output capacity. Circular knit fabrics are mostly used for cut & sew garments.

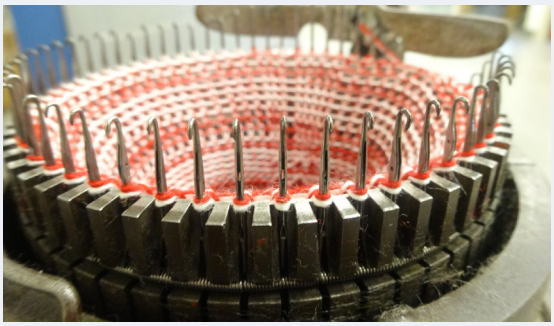


Figure 17. Circular knitting machine (marketreleases, 2017).

Circular knitting machines' purpose is to create tubular knits. However, this can also be done on a flat bed knitting machine, but is much slower. This is because the machine needs to move from side to side, while a circular knitting machine can keep going in a circle.
An important aspect of knitting on a



Figure 18. Stoll CMS 530 double gauge flat bed knitting machine from Technical University Delft.

knitting machine is the machine gauge. This number defines how many needles are used in one inch.

For industrial knitting machines the gauge ranges from 12 to 22, where gauge 14 and 16 are the most common.

Circular knitting machines have a gauge ranging from 12 - 32, where gauge 14 and 16 are the most used (Betterton, 2020). A higher gauge machine means that it can knit finer fabrics.

Stitch types

When knitting there are two main stitches that are being used to create different patterns. These are the purl and the knit stitch (Figure 19). The most used stitch is the knit stitch, which looks like little V's. The purl stitch is basically the reverse of the knit stitch and can be recognized by the horizontal lines, both highlighted in red in figure 19.

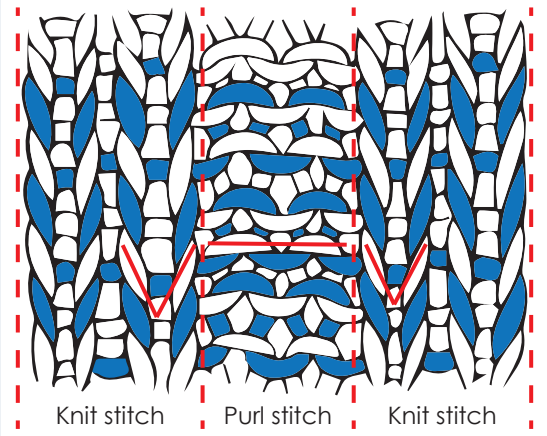


Figure 19. Knit and purl stitch.

Combining yarns

Other than the knit and purl stitch, there are other useful stitches when knitting with two different yarns. These stitches are different ways of incorporating a secondary yarn in multiple directions. These are the full milan double stitch, 2x2 rib stitch, full needle stitch, tubular stitch, intarsia stitch, plating stitch, jersey stitch and colour striping stitch as described by (Li et al., 2009) and figure 20 - 23.

For the creation of textile sensors that measure physiological signals the 2x2 rib stitch and the full needle stitch are preferred, because of their elasticity.

Plating stitch being useful to isolate conductive yarn without having to create a double layered fabric.

Intarsia stitch is useful to create vertical lines and patches with other yarn.

Tubular stitch can also be used to separate conductive yarn. Compared to plating stitch, the tubular stitch exists of two layers.

In chapter 3.1 some of these knitting techniques are tested on the knitting machine.

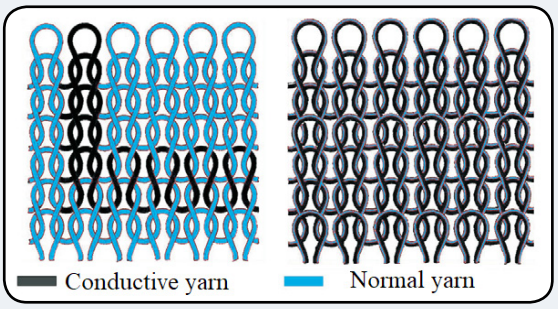


Figure 20. Intarsia stitch and plating stitch (Li et al, 2009).

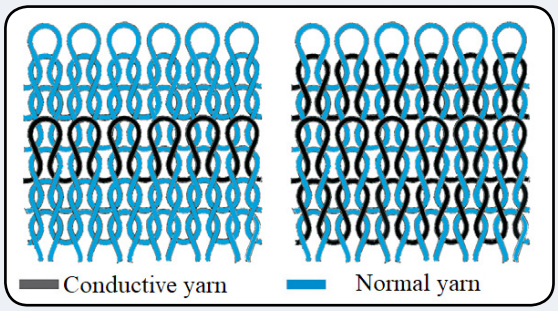


Figure 21. Jersey stitch and colour striping stitch. (Li et al, 2009).

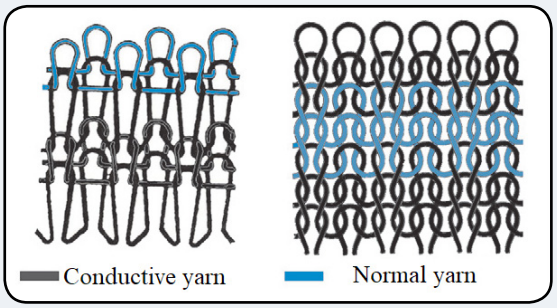


Figure 22. Full milan double stitch and 2 × 2 rib stitch (Li et al, 2009).

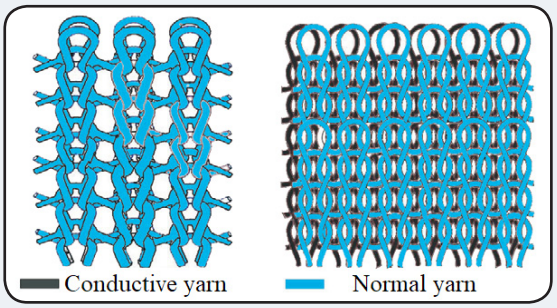


Figure 23. Full needle stitch and tubular stitch (Li et al, 2009).

Plating

When using conductive yarn in a knitted piece, it might be beneficial to insulate one side of the fabric. There are multiple ways to achieve this, but the easiest is by using an intarsia yarn feeder. With an intarsia yarn feeder it is possible to insulate conductive yarn in one layer. A intarsia yarn carrier has two spots to insert yarn (Figure 24b). One for the main yarn, and one for the secondary yarn. The secondary yarn goes through a slid instead of a hole, which makes the secondary yarn always trace behind the primary yarn.

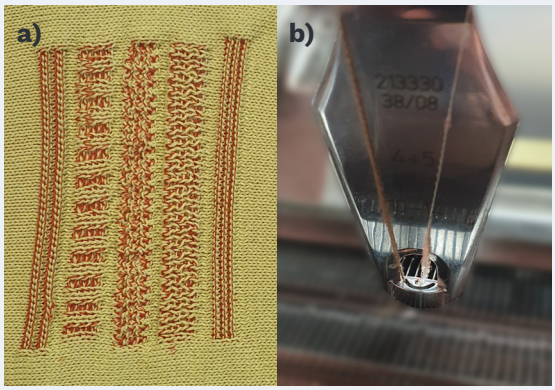


Figure 24. a) Plating example. b) Plating yarn carrier with two inserted yarns.

Intarsia

To create 'blocks' of multiple colours or different materials, intarsia technique can be used. Intarsia is mostly used when a design has bigger patches of a different colour (Figure 25). The yarns replace each other when the pattern of the knitting changes.



Figure 25. Intarsia example

Jacquard

Creating patterns can also be done with jacquard method. When using two colours of yarn to create a pattern, the colour that is not used is floated on the back of the fabric. Unfortunately, when larger patches of a different colour are made, the floated yarn can drape and get pulled, eventually damaging the fabric piece. For vertical lines it can be useful to implement jacquard technique as long as the line is not too wide. Jacquard is mostly used with patterns, and often switching between colours (Figure 26).



Figure 26. Jacquard example

Chapter 2.3

Yarns

To create knitted fabrics, yarns are needed. Yarns are for knitting machine as what filament is for 3D printers: the raw material needed for production. Yarns come in a variety of types and sizes. From natural to synthetic or from elastic to conductive. There are a lot of possibilities, which will be discussed in this chapter.

Yarns thickness is measured in its own way. There are a lot of systems used around the world to determine the thickness of yarns. The most used are dtex or tex and NM. Dtex is the weight in grams of 10.000 meters of yarn, tex is the weight in grams but of 1000 meters of yarn and Nm is 1000 meters of yarn per kilogram (Figure 27. Dtex and tex are more used with technical yarns and Nm is mostly used with thicker yarns for garments (Rots, 2020). Dtex will be used throughout this project.

Different types of yarn have different aspects when it comes to knitting, conductivity and attachment to electronics. For example, copper yarn is highly conductive, but is hard to use in a knitting machine as it deforms plasticly. Other yarns like stainless steel are better knittable, but are more difficult to attach to electronics as they can not be soldered.

The types of conductive yarn that are used the most can be divided into five types of materials. Most used conductive yarns that are stainless steel, copper, silver plated and carbon yarns. These material types come in varying qualities and configurations. Some have an insulating outer layer and others are made of fine strands of the pure material that are woven together to create the yarn.

	tex	dtex	den	(gr/yd)	NeL or Lea	Nm	NeC or Ne	NeK or NeW	NeS
type	direct	direct	direct	direct	Indirect	Indirect	Indirect	Indirect	Indirect
Units	Grams per 1km	Grams per 10km	Grams per 9000m	Grains per yard	300 yards per lb	1000m per kg	840 yards per lb	560 yards per lb	256 yards per lb
tex	1	dtex/10	den/9	(gr/yd)*70.86	1653.5/NeL	1000/Nm	590.5/NeC	885.5/NeK	1937.7/NeS
dtex	tex*10	1	den/0.9	(gr/yd)*708.6	16535/NeL	10,000/Nm	5905.4/NeC	8855.8/NeK	19377/NeS
den	tex*9	dtex*0.9	1	(gr/yd)*637.7	14882/NeL	9,000/Nm	5314.9/NeC	7972.3/NeK	17439/NeS
gr/yd	tex/70.86	dted/708.6	den/673.7	1	23.33/NeL	14.1/Nm	8.33/NeC	12.5/NeK	27.34/NeS
NeL	1653.5/tex	16535/dtex	14882/den	23.33/(gr/yd)	1	Nm *1.6535	NeC*2.8	NeK*1.87	NeS*0.8533
Nm	1000/tex	10,000/dtex	9000/den	14.1/(gr/yd)	NeL/1.6535	1	NeC*1.6934	NeK*1.13	NeS*0.516
NeC	590.5/tex	5905.4/dtex	5314.9/den	8.33/(gr/yd)	NeL/2.8	Nm/1.6934	1	NeK/1.5	NeS/3.28
NeK	885.8/tex	8858/dtex	7972.3/den	12.5/(gr/yd)	NeL/1.87	Nm/1.13	NeC*1.5	1	NeS/2.187
NeS	1937.7/tex	19,377/dtex	17,439/den	27.34/(gr/yd)	NeL/0.8533	Nm/0.516	NeC*3.28	NeK*2.187	1

Figure 27. Different types of yarn units (Wikipedia, 2020)

Non-conductive yarns

Non-conductive yarns are the most used yarns today, as almost all garments are made from non-conductive yarns. These type of yarns come in natural or synthetic form.

Natural yarns are created from natural resources. These are either from plants, animals or from minerals. Cotton is a natural plant based fibre and wool an animal based fibre. Both are used a lot in the production of fabrics and garments. There are also mineral based fibres like asbestos (Eichhoff et al., 2013), but these will not be discussed.

To create yarns that can be used in producing textiles, different production techniques can be used (Figure 28). Cotton and wool yarns are created using staple fibre spinning, where bundles of parallel fibres are twisted together. Other methods are Rotor spinning, Airjet spinning, melt-spinning and solution spinning (Eichhoff et al., 2013).

Most synthetic yarns are created through melt-spinning. In this process plastic granulates are melted and extruded into fines strands that are called filaments. These filaments can be wound together to create multi filament yarns. These yarns can be made out of different materials including but not limited to Polyester (PES), Polyethylene (PE), Polypropylen (PP), polyvinylidenfluoride (PVDF). Another name for filament yarns is 'endless fibres', because every filament is one continuous piece (Eichhoff et al., 2013). Synthetic yarns are also available in stretchable form.

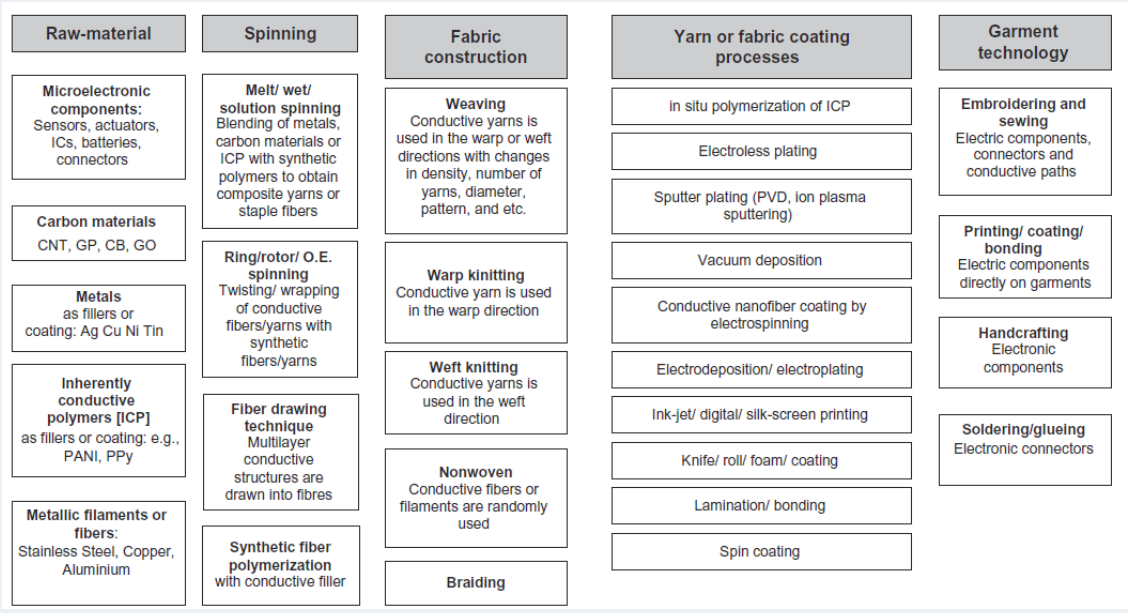


Figure 28. Yarn production methods (Eichhoff, 2013).

Conductive yarns

To create integrated sensors into fabrics, not only normal yarns are necessary, but also conductive yarns. For both the sensor itself and for transferring data through interconnections between the sensor and the processing unit different types of conductive yarn are needed.

Creating the conductive part in a yarn can be done in multiple ways. Metallic yarns are either a single core or multi-core or are coated. Single core yarn is one strand of a solid material. This improves conductivity and signal transfer, but makes the yarn not very flexible. When knitting with such a yarn, the material will deform plastically which is unwanted. When it is thinner, plastic deformation might not happen, but it will most likely break due to being too thin.

Multi-core, as the name states, has two or more core wires. These core wires can be made very thin, down to the micron range. The thinner these core wires are, the more flexible the yarn becomes.
Conductive yarns can also be created by coating a non-conductive yarn with a conductive layer.

These conductive yarns can either be kept 'pure' or they can be combined with other yarns. This is done to improve the feel of the yarn, as metallic yarns can be rough to the skin. Combining yarns and thus their properties can make the non-conductive yarn the load carrier or it can insulate the conductive yarn.

Important with conductive yarns is to know the resistance. The resistance is a material property that says something about how easy electricity can flow through the material and is defined in ohm per meter or Ω/m or in Siemens S, which is 1/Ω. In this paper Ω/m will be used.

For the fabric sensors it is desired to have a higher resistance, because these are then easier to read by a processing unit. The resistance change is larger when the overall resistance of a yarn is higher. Resistance of a sensor is best to be from 10 to 200 Ω/m. For interconnections it is best to have a low resistance. This way sensor signals can travel as fast as possible.

Some readily available materials are discussed in the following part.

Stainless steel

Stainless steel wires are used extensively in the creation of interactive textiles. The main disadvantage is that stainless steel yarn is difficult to reliably attach to other conductive cables as stainless steel yarn cannot be soldered (Poupyrev et al., 2016). The benefit of stainless steel yarn is that it is corrosion resistant and very strong. When used as a multi-core fibre it will almost not plastically deform.

Silver

Solid core version of silver yarns are mostly made from copper with a coating of silver on top. This gives the copper anti corrosion properties, while still being highly conductive. There are also synthetic yarns that are coated with silver to add conductivity (Figure 29). These base yarns can be natural or synthetic. Coatings are most of times much cheaper than their solid core versions.

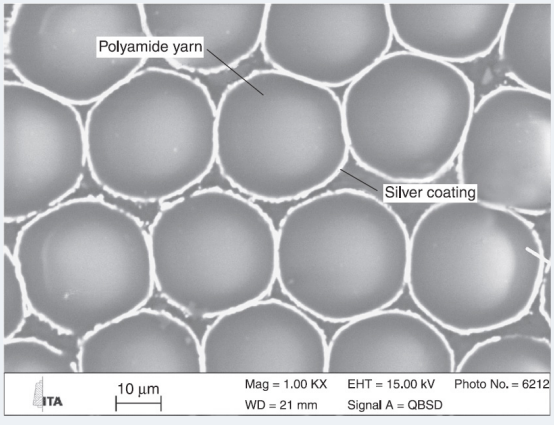


Figure 29. Silver coated polyamide fibres (Eichhoff, 2013).

Copper

Copper is a very good conductor, but when copper is not insulated, skin contact can cause it to corrode. Copper is available in thin multi core and single core yarns. Insulated copper yarn is a good corrosion prevention, but limits the yarn to being only useful as interconnections. Copper is also easy to solder to other electronics.

Carbon

Carbon fibre is a strong material mostly used in combination with resin to create solid structures that are stronger and lighter than steel. Carbon fibre yarns are also highly conductive and could be used to transfer data through fabrics. Carbon yarns can be made by spinning carbon fibres or by rotary spinning carbon nano tubes (Johnson, 2020). Unfortunately, carbon fibre yarns are only strong in the longitudinal direction. When being bent, the material easily breaks. This makes it not usable with knitting, due to the harsh bending of yarns in a knitting machine.

Stainless steel and silver yarns are the most used in knitting fabrics and show the most potential for use in smart fabrics. They show the most promise for creating sensors, as they are available in resistances varying from low to high. Insulated copper can be used to transport sensor data, because uncoated it will corrode and its resistance is too low to create sensors from.

Chapter 2.4

Finishing and coatings

A finish or coating can add conductivity or corrosion protection to a yarn. Metal coatings can add conductivity to a non-conductive yarn. Common metal coatings are silver, copper or gold (Eichhoff et al., 2013). This coating is a small layer deposited on the main yarn that makes the yarn conduct electricity. A silver coating can be applied to several materials including but not limited to copper, but also nylon, polyester, cotton and wool. Copper coating is not suitable for creating sensors, as the sensor needs to be uninsulated to produce output.

Piezoelectric yarns are possible to be made using a coating. Piezoelectric materials generate electrical potential as a reaction to mechanical deformation (Eichhoff et al., 2013). Yarns that have a piezoelectric coating can be used as a sensor. PEDOT:PSS is an example of a piezoelectric coating. Another coating that could be used is carbon-loaded rubber, which is explained by Paradiso (2005). Lycra fabric is coated with the carbon-loaded rubber which is then inserted in the knitting process to create a strain sensor.

A coating can also be applied after a fabric is created (Wicaksono, 2017). Here they create a strain sensor using a coating that is applied to a knitted fabric.

Although piezoelectric yarns have useful properties for creating sensors, they are more interesting to apply in weaving, because the yarn is straight in woven fabrics (Figure 30). Knitted fabrics can be stretched due to their structure, which makes piezoelectric yarns less usable for sensor creation. A knitted sensor made from piezoelectric yarn would not perform well, as the yarn itself will hardly be stretched.

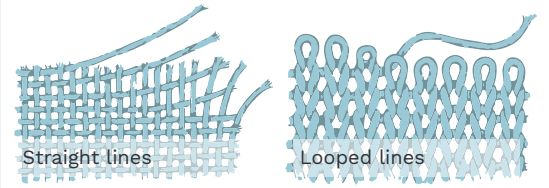


Figure 30. Structure difference between woven and knitted fabrics.

There are also yarn finishes to isolate a conductive yarn. These can be useful to prevent signal interference and corrosion. These coatings mostly consist of thermoplastics like PVC, PE or Nylon (J, n.d.).

Comfort also needs to be taken into account when creating textile sensors. As the sensors will be worn on the body. Pure metal yarns do not feel the same to the touch as non-conductive yarns. Coating the conductive yarns with a special oil or combining them with natural or synthetic yarn can improve comfort.

For creating textile sensors stainless steel yarn has the most potential as it has a higher resistance than for example silver. Although, a silver coated yarn with a resistance of 200Ω/m is used by (Atalay et al., 2014), this might also be a viable option.
For transferring data from the sensor to the processing unit, insulated copper or steel might be good, as these have low resistance, can be insulated and a flexible enough to integrate into the less stretchy parts of apparel.

Chapter 2.5

Connection techniques

To transfer data from the sensor to the processing unit, interconnects are being used. These interconnects need to be attached to the processing unit and the sensor. There are several ways of achieving this that will be explained in this chapter.

Soldering

Soldering is done with a soldering iron using solder (Figure 31). It could be a possibility to use this method as connection, but not all the yarns can be soldered. Stainless steel cannot be soldered, but copper on the other hand can. Soldering is a very good way of connecting wires and is strong. Unfortunately, it is not that flexible. In combination with for example a flat wire cable a good connection can be made from conductive yarn to a printed circuit board (PCB).



Figure 31. Soldering a conductive yarn to a metal wire.

Metal sleeve crimping

Another technique is to use metal sleeves that can be pressed tightly to mechanically connect the yarn with electronics (Figure 32). This connection is also very strong, but not that flexible and requires a special tongs to create a connection.



Figure 32. Metal sleeve crimping with sleeve crimping tongs (Demo product, 2016).

Gluing

Conductive glue might also be an alternative, to connect different conductive wires. Glue creates a strong connection and will stay more flexible. The downside is that conductive glue is not insulated. Silver Adhesive epoxy is an example of this type of glue (Figure 33).



Figure 33. Conductive silver epoxy glue (Rs-online, 2007).

Heat shrink tubes

Heat shrink tubes might also be an option, as these connect and insulate a wire. They are sleeves that shrink when heated (Figure 34). These might also be useful when combined with other attachment methods like glue or soldering to isolate connection.

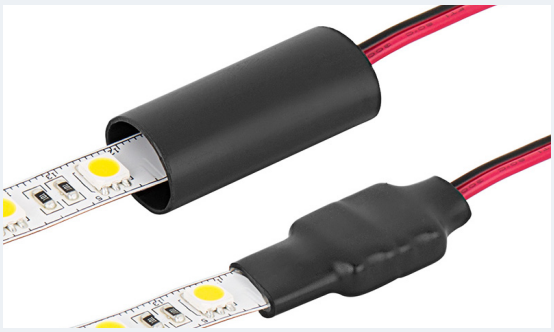


Figure 34. Shrink sleeving example (M, 2017)

Press buttons

Sewable metal buttons (Figure 35) might also be an suitable option for connecting the sensor to a Printed Circuit Board (PCB). They can create connections which can be removed and connected at any time. This can be useful when the processing unit needs to be removed when the garment needs to be washed. Unfortunately, they are not insulated.



Figure 35. Press buttons (Amazon, 2019)

When fixating the conductive yarn to a processing unit a few things need to be considered:

- **Resistance**

Connections create resistance. To get the best possible connection in metal wire, soldering is the best option. To decrease resistance between yarn and a metal wire (which cannot be soldered), a shrink tubing can be used.

- **Interference**

Wires that are loosely connected can cause interference. It is best to keep connections non-movable. This can be achieved with shrink tubing for example.

- **Corrosion**

As wearable garments are worn on the skin, it might be that some metal parts come in contact with the skin which might lead to corrosion. It is best to insulate the metals or use non-corrosive metals.

- **Flexibility**

A problem with creating connections is that these might become less flexible and can be felt by the wearer. To prevent this, the connections can be knitted in a pocket or to make the connection as small as possible so that it will be felt less.

- **Stress relieve**

The connections from conductive yarns to electrical wires has to be strong enough to survive stresses put upon it. Implementing some kind of stress relieve is essential with parts that move a lot.

- **Durability**

In order for the connections to have a long lifespan, it is essential that they are durable. Flexibility, stress relieve and the type of connection all help to achieve this.

Chapter 2.6

Sensor types and their constraints

The goal of this project is to develop sensors created with conductive yarns that are embedded in fabric by using a knitting machine. Most types of sensors can theoretically be created from conductive yarns, but every sensor type is dependent on yarn and fabric structure properties. The most straightforward sensors that can be created with off-the-shelf conductive yarns are the capacitive touch sensor, pressure sensor, moisture sensor, electrodes for ECG and EMG, breakage detection sensor, interconnects and strain sensors as seen in Figure 36. The main focus lies on strain sensors, short literature samples will be provided on the other possible sensors

Type of sensor	What does it measure	How does it measure	Possible applications	Isolated yarn: yes/no	Conductivity
Touch	When touched or not	Capacitance	Touch controls	No	Low
Pressure	Force on surface	Resistance		No	Low
Moisture sensor	Humidity	Resistance	Wetness indicator (pee, sweat)	No	High
ECG	Electrical signals	Electrical signal strength	Heart rate sensor	No	High
EMG	Electrical signals	Electrical signal strength	Muscle activity	No	High
Breakage detection	Breakage	Voltage flow or not	Replacement warning of life saving products.	Yes	High
Power lines	-	-	Transfer signals from sensor to controller	Yes	High
Strain	Elongation	Resistance or capacitance	Breathing, Arm or leg movement.	No	Low

Figure 36. Sensor types with function explanation and conductive yarn type

Capacitive touch sensor

We wear textiles daily, which makes our bodies accustomed to touching it. Even more so, making physical contact with it actually feels nice. Touch interfaces are also used daily, like our phones or tablets. Creating a textile touch interface is therefore totally a logical step in creating smart garments.

Creating a capacitive touch sensor is as easy as replacing a yarn with a conductive yarn and connecting it to a processing unit. Touch sensitive parts can be integrated in all kinds of shapes and places on a garment. When combining multiple touch inputs a touch sensitive grid can be realized. This is also done with the jacket that is developed by Google and Levi's, project Jacquard (Figure 37) (Trucker Jacket Levi's®, n.d.).



Figure 37. Capacitive stripes on sleeves of Google and Levi's Jacquard jacket (Google, 2019)

The yarn that is used is specially developed by Google and has a copper core that exists of several strands that are twisted five turns per meter. This core has a braided insulation layer to protect against corrosion and to increase comfort when touching (Poupyrev et al., 2016). This yarn is only suitable for capacitive touch or data transfer in woven fabrics.

Touch sensors can also be made by using conductive fabrics. By adding for example a small patch at the end of a conductive yarn a touch sensitive patch can be made. A combination of conductive and non conductive fabrics that are knitted can be seen in the fabric keyboard project (Figure 38) (Wicaksono et al., 2017). The fabrics are knitted to give the keyboard stretchability. For the data transfer they use steel yarn that is connected through a customized connector. Where the thread is tied to stripped metal loops, which are then soldered and encapsulated. They achieve touch sensing by using the Grove MPR121 Proximity Touch Controller with 12 inputs. To create proximity detection, the 12 inputs of the Grove Touch Controller are combined to increase capacity detection.



Figure 38. Fabric keyboard (Wicaksono et al., 2017)

Pressure sensor

Pressure sensors mostly consist of a three layer sandwich (Figure 38), where the outer two layers being a conductive material and the layer in between being a piezoresistive layer or dielectric layer (Castano et al., 2014). The type of layer in between the two conductive layers depends on the type of pressure sensor. Pressure can be measured through capacitance and through resistance.

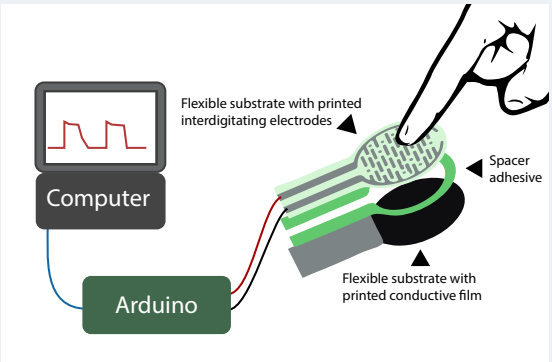


Figure 40. Different layers used in to build up a pressure sensor.

The outer two layers of a pressure sensor always exist of a material that is conductive. In non fabric pressure sensors this is mostly copper or other conductive material. Conversely, these conductive parts can also be made using other techniques. When looking at fabrics these conductive parts can be woven, sewn, embroidered or knitted from conductive yarn (Castano et al., 2014). The conductive parts can also be painted or printed on the fabric.

In a pressure sensor that uses resistance as a way to measure pressure difference, the middle layer is a piezoresistive layer. This layer changes resistance when pressure is applied. An extra layer can be added into the sandwich to prevent accidental presses (Wicaksono et al., 2017). When foams are used it has to be kept in mind that it has a few drawbacks. Mainly, creep, poor resilience, signal drift and hysteresis (Castano et al., 2014). A knitted pressure sensor example is shown in figure 39.

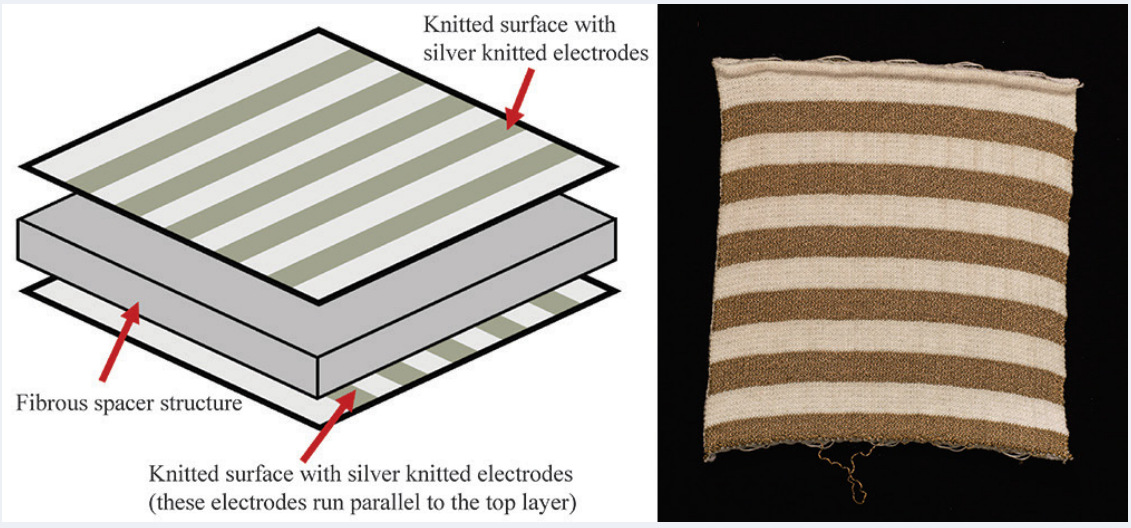


Figure 39. Pressure sensor created through knitting, alternating conductive and non-conductive stripes (Hughes-Riley et al., 2019)

A pressure sensor that uses capacitance to measure pressure difference has a middle layer made of a dielectric material. This is a material that is electrically insulating and is used in capacitors. By applying pressure to this material, the capacitance the dielectric material can hold will change. Hughes-Riley et al., (2019) talks about a pressure sensor that is made with a spacer fabric. Inserting the spacer fabric during production showed improved consistency in sensor data. A structure of lines were knitted on both sides of the pocket, where the electrodes run perpendicular from each other. The electrodes where knitted form silver yarn (Figure 39).

When looking at pressure sensors, these can also be made using a conductor encapsulated in the fibre (McKnight et al., 2018). This makes the sensor area much smaller, but to prevent hysteresis, the outer layer cannot be a soft fibre, which will decrease comfort for the user. The outer two layers of a pressure sensor can be also be knitted. These layers will need to have a pocket like structure with a patch of conductive yarn on both sides. In between these patches a dielectric layer can be placed.

Another way of creating a pressure sensor is described in (Ou et al., 2019). They knit a conductive patch that sits looser than the rest of the knitted piece (Figure 41). Which can both be used as a touch input and a pressure sensing area. The pressure sensing is done by measuring capacitance change when the finger presses down on the conductive part. For accurate measurement a 32-bit processing unit was used (32-bit ARM-CORTEX M4).



Figure 41. Pressure sensor through looser knitted conductive yarn (Ou et al., 2019).

A piezoresistive approach was also tried by (Ou et al., 2019). Where they inject a combination of conductive and dielectric yarn into pockets, it was found that the resistance changed in a reliable way, but that hysteresis still occurred.

Moisture

Moisture sensors can also be knitted (Decaens et al., 2016)(McKnight et al., 2018). This sensor will detect a change in resistance, when the sensor gets wet. By having two poles next to each other that are not touching, this sensor can be realized. When the fabric in between these two poles gets wet, the resistance between them will change. The wetter the sensor will get, the lower the resistance will be.

Possible applications for this sensor would be to measure if someone is sweating and how much this person is sweating, for example for sports players. It is also useful for people that have urinal problems like elderly or babies. It can detect when the urethra is leaking and notify the person or a medical assistant of this.

Breakage detection

When inserting conductive yarn in a piece of fabric it can also be used to detect breakage. For example for people that have to work in life threatening situations it can be very helpful to know if some part of their protective suit breaks. By checking if a current can run through the conductive yarn, a system can detect when this yarn breaks (Decaens et al., 2016). For this to function correctly, the materials need to have similar mechanical properties.

Electrodes

Measuring heart rate or muscle activity can be done with electrodes. These are mostly loose patches that can be stuck to the skin and have a wire attached to it that connects to a processing unit. These electrodes can also be knitted. By knitting them, they are always correctly placed (Decaens et al., 2016), but when they shift they can generate noise.

Applications that electrodes can be used in are heart rate detection through ECG or muscle activity through EMG. These can be useful for tracking patients heart rate in a hospital or athletes to prevent muscle damage or maximize performance.

Temperature

Research has been done to create temperature sensors that could be integrated into fabrics. Unfortunately, this is not possible with off the shelf materials and requires complex strips of metallic materials on a kapton base substrate. This is done by photo lithography (Decaens et al., 2016). These strips can then be attached to conductive yarn in order to transfer sensor data. Because of the complexity of this sensor, this sensor type is not included in this study.

Interconnects

To transfer data from the sensors to the processing unit, a data connection is needed. This can be done by knitting conductive lines into the fabric. Compared with the conductive yarn that is used to create sensors, the interconnection needs to be insulated and have a low resistance. Copper wire coated with polyurethane also used by (Pei et al., 2019) is a suitable candidate for this purpose.

Chapter 2.7

Strain sensors

Strain sensor

Tracking limb movement and breathing patterns can be done with a strain sensor. A Strain sensor can measure how much something has stretched. Strain sensors that are made today are mostly used to detect small ranges of motion and are built for precision. Body movements on the other hand, cover a much larger range of motion, which makes current strain sensors unusable. Creating knitted strain sensors in textiles can alleviate this problem, as textile sensors are able to be stretched much more. Strain sensors can be created in three different ways (figure 42), namely:

- **Resistive strain sensor**
  A strain sensor that measures the difference in resistance that can be translated to the amount of strain.
- **Capacitive strain sensor**
  A strain sensor that measures the difference in capacitance that can be translated to the amount of strain.
- **Piezoelectric strain sensor**
  A strain sensor that measures the difference in electric signal to define the amount of strain.

The focus of this research will be on resistive strain sensors, as these are the easiest to make in a knitting machine.

There are different knitted strain sensor variations to be found in literature with the most common strain sensor using the structure of the knitted loops in a fabric. This is well documented by a number of papers (Atalay et al., 2013), (Atalay et al., 2014), (Atalay et al., 2017) and (Dupler et al., 2019). These make use of the interlock structure in knitting (Figure 43). This structure is created using double bed knitting where every other needle is used to create a structure that interlocks with itself.

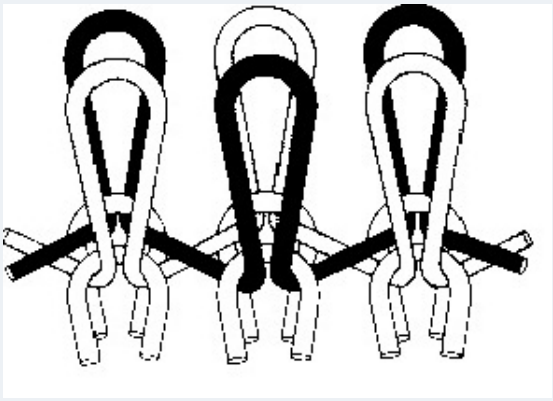


Figure 43. Interlock fabric structure (Kiron, 2020).

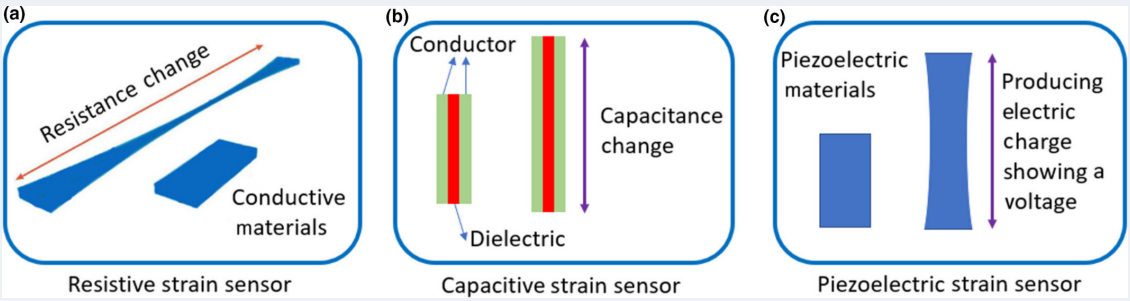


Figure 42. Three types of strain sensors, resistive, capacitive and piezoelectric (Wang et al., n.d.).

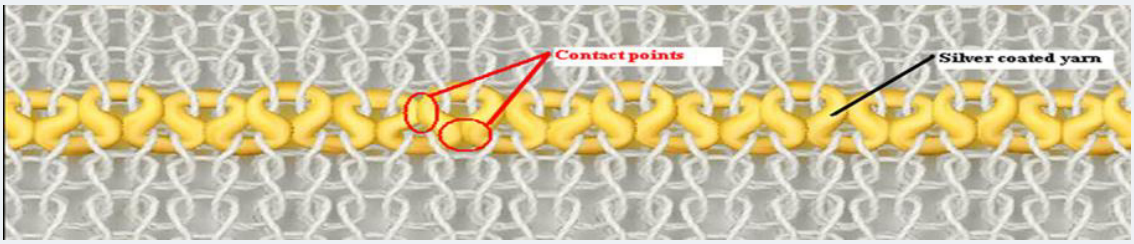


Figure 44. Knitting strain sensor structure (Atalay et al., 2014).

The interlock structure is well described in (Atalay et al., 2014). They manage to create a working strain sensor using the structure of the knitted fabric as the structure of the sensor. Strain up to 40% has been tested, as this is similar to the displacement limbs make when flexing. The conductive yarn touches each other in resting state (Figure 44) and when it is stretched releases, increases length and thus resistance.

They create sensors with 4 and 6 courses of conductive silver yarn with a resistance of 2 Ω/cm with 800 dtex, 570 dtex and 156 dtex elastic. Dtex 800 has the highest resistance difference (Figure 45), due to increased contact points. Both four and six lines of conductive yarn seem to work well. Gauge factors are quite similar and both lie around 2.25.

The linear working range of the sample with six conductive lines starts at around ten percent strain (Figure 46). This most likely due to internal tension building up and the conductive yarn wanting to buckle. Also, an increased yarn input tension creates fabrics with a higher resistance.

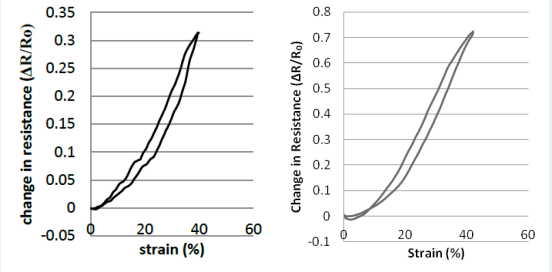


Figure 45. Dtex 570 and dtex 800 in a strain versus resistance change graph (Atalay et al., 2014).

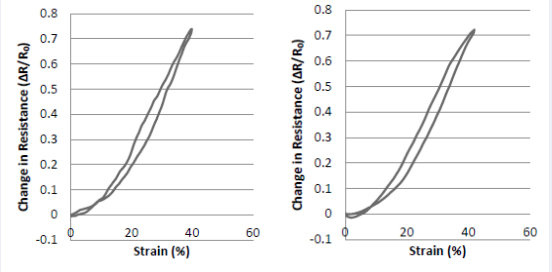


Figure 46. Four and six conductive lines in a strain versus resistance change graph (Atalay et al., 2014).

The difference between four and six courses is minimal (Figure 46), which is odd because an increase in conductive lines would decrease resistance in the sensing part. This cannot be seen in the graphs provided, as both four and six lines go up to a resistance change of 0.7.

(Atalay et al., 2013) uses 800 dtex elastic with silver coated yarn with a resistance of 200 Ω/m. They created three types of sensors (Figure 48).

Group 2 (Figure 49) has the shortest relaxation time and the lowest difference between the highest peak and the relaxing state. To fully relax the elastic fabric can take up to two minutes. The resistance of the group 2 sensor is also the highest. This makes the group 2 sensor the most suitable.

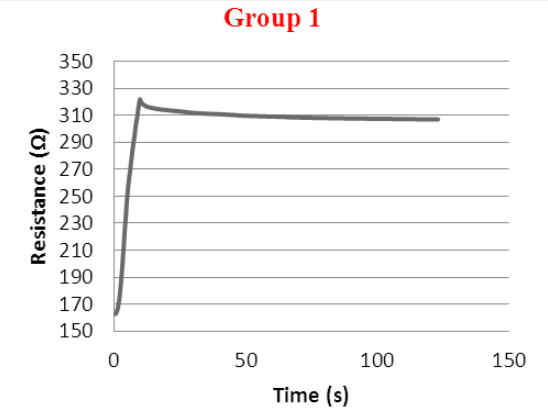


Figure 47. Relaxation graph at 40 percent strain group 1 (Atalay et al., 2013)

Sensor breaking point lies around 350 percent. This breaking point far exceeds how far the body can stretch, which makes it suitable for body measuring applications.

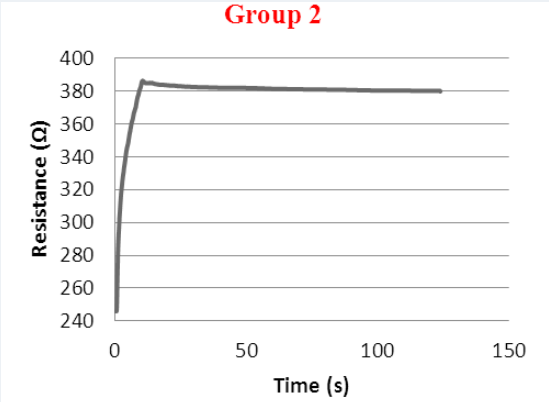


Figure 49. Relaxation graph at 40 percent strain group 2 (Atalay et al., 2013)

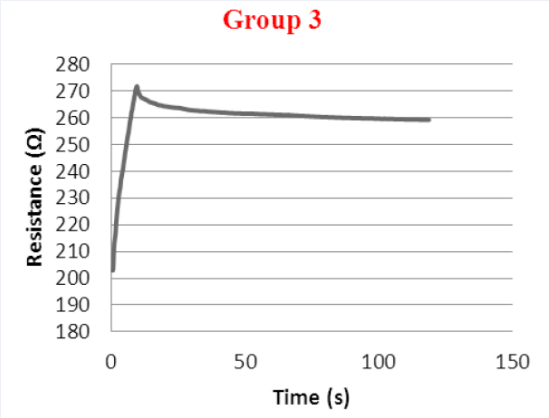


Figure 50. Relaxation graph at 40 percent strain group 3 (Atalay et al., 2013)

Table 2. Comparison of average electrical resistance and average base fabric parameters.

Sample Group	Elastomeric Yarn Input Tension (cN/Tex)	Elastomeric Yarn Linear Density (dtex)	Wale Density (wales per·cm)	Course Density (courses per·cm)	Structural-Cell Stitch Length (mm)	Tightness Factor	Electrical Resistance (Ω)
Group 1	0.125	800	8.67	15.55	15.36	1.84	166.47
Group 2	0.062	800	8.27	12.20	19.75	1.43	242.02
Group 3	0.125	570	8.88	17,15	10.97	2.17	206.58

Figure 48. Three types of strain sensors, resistive, capacitive and piezoelectric (Wang et al., n.d.).

Atalay et al., (2017) Continues research further in knitted fabric sensors. Specifically, testing different types of elastic yarn (Figure 51). Interlock structure is used to create the main knitted fabric.

They use a Wheatstone bridge (Figure 52) measuring setup, which is a precise way to detect small resistance changes.

Figure 53 shows the three different regions of strain versus resistance. In the first region the resistance drops because the length of the conductive yarn increases due to disconnecting loops in the knitted structure. While the resistance stays rather the same second region. The third region can be explained by increased contact pressure between the loops.

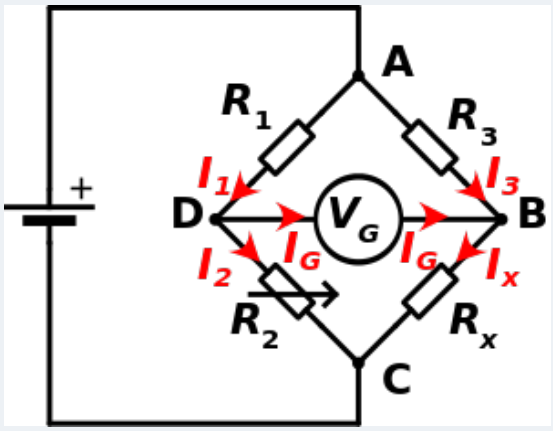


Figure 52. Wheatstone bridge (BMET, 2019).

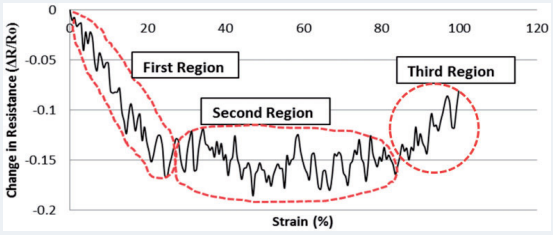


Figure 53. Graph showing different regions with strain up to 100 percent (Atalay et al., 2017).

Table 5. Properties of non-conductive elastomeric and polyester yarns.

Yarn type	Lycra yarn linear density	Covering material	Manufacturer
Double covered elastomeric yarn	800 dtex	1/33/10 PA 6.6	Wykes
Double covered elastomeric yarn	570 dtex	1/33/10 PA 6.6	Wykes
Double covered elastomeric yarn	156 dtex	44/33/2 PA6.6, 78/46/2 PA 6.6	Zimmermann
Yarn type	Linear yarn density	Structure	Manufacturer
Texture polyester	167 dtex	Multifilament	J H Ashworth

Figure 51. Types of elastic yarn (Atalay et al. 2017).

(Atalay et al., 2017) also compares plain knitted strain sensors and interlock knitted strain sensors. Both show a similar result (Figure 54 and 55), but the interlock structure is much more repeatable. Also the saturation of both sensors is different. The interlock knit sensor shows a working area up to 240% strain (Figure 56), while the plain knitted sensor has a range of maximum of 60% range (Figure 57). Both these results make the interlock structure a better choice when it comes to knitting strain sensors.

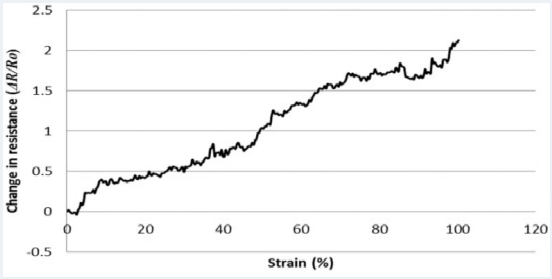


Figure 54. Plain knitted sensor (Atalay et al. 2017).

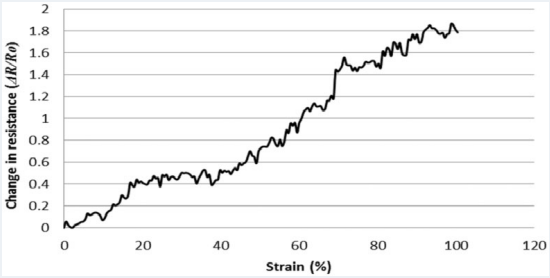


Figure 55. Interlock structure knit sensor (Atalay et al. 2017).

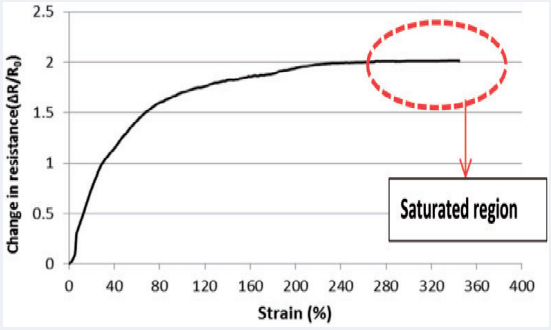


Figure 56. Interlock structure knit sensor range (Atalay et al. 2017).

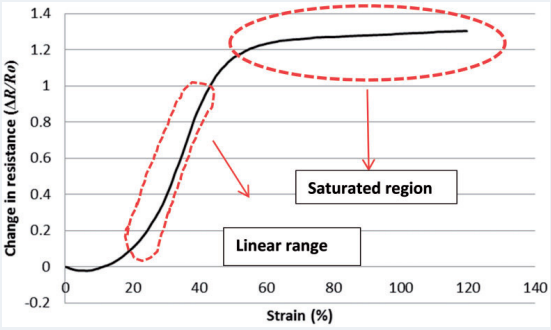


Figure 57. Plain knitted sensor range (Atalay et al. 2017).

An alternative method to create a knitted strain sensor is by using a different knitted structure. This is done by (Ou et al., 2019). They created a structure that is made on a double bed knitting machine. One layer exists of flaps of conductive yarn and the other layer of elastic yarn to retract the flaps and reduce hysteresis (Figure 58).

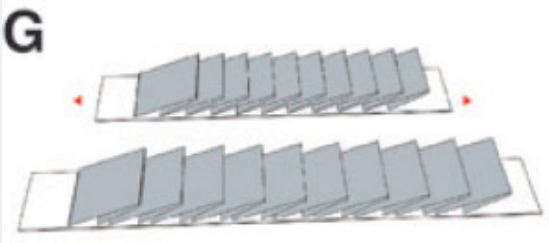


Figure 58. Strain sensor through conductive flaps (Ou et al., 2019).

These flaps overlap when the fabric is in its resting state, creating conductive pleats. When the fabric gets stretched, the overlapping flaps will move and the contact area and distance between them will decrease, resulting in an increase in resistance.

To prevent certain parts from not stretching they insert thermoplastic yarn, which is then ironed. Ironing melts the plastic causing the fabric to not be stretchable anymore, but remain flexible. To tweak the textile sensors, the yarn tension is the most important parameter.

The yarn used in this research is silver yarn twisted together with non conductive yarn. Which results in a resistance of 1 Ω/mm, which is 1000 Ω/m. Spandex is used to retract the sensor and is knitted tight so that the elastic behaviour comes from the elastic and not the knitted structure.

This different way of creating a strain sensor stands out, as most other research in fabric strain sensors the sensing part sits inside the fabric. This way of creating a strain sensor works and shows a good linear sensor response (Figure 59), but is too big and unreliable. The flaps needed to be ironed at 100°C to flatten the pockets. The flaps are free to move and could open up, which results losing contact and not being able to output sensor data. As these flaps move they might also increase fluctuations and noise in the sensor data.

To restore fabric to its original shape rapidly, Spandex yarn is used with 400 denier thickness, which is 444.4 dtex. Polyester used is 150 denier thickness, which is equivalent of 166,7 dtex. The Spandex used in this sensor is a lot thinner than previously created sensors.

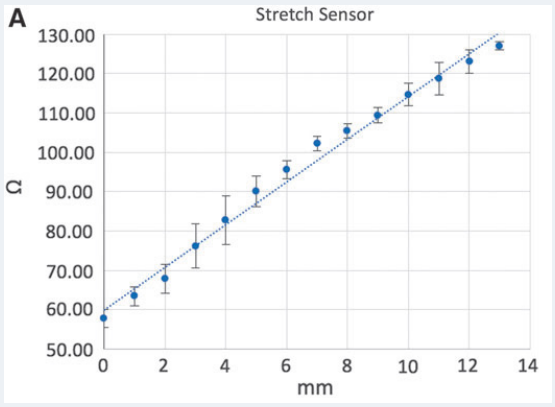


Figure 59. Graph of resistance in ohm versus displacement in millimeters (ou et al., 2019)

Another method to create a strain sensor is presented by (Dupler et al., 2019). Here they create a stitched strain sensor on a knitted fabric structure. The knitted fabric is used because of its elastic properties. The sensor is created on an interlock knit structure, because of its stability and easier sewability. Although, a stitched sensor is not what this research focuses on, it is interesting to see that both (Atalay) and (Dupler et al., 2019) use the interlock structure as their base for a strain sensor.

Coatings are also used to create fabric sensors. Wealthy (Paradiso et al., 2005) and the fabric keyboard (Wicaksono, et al., 2017) use this technique to create a strain sensor. The fabric keyboard project uses spandex that is coated with conductive polymers. Although using a coating is a way to create a strain sensor, this method will not be used in this research, because coating is an extra step in the production process and the focus lies on using off-the-shelf materials.

Strain sensing textiles can also be fiber spun. In (Seyedin et al., 2015) a special yarn is created from PU/PEDOT:PSS (Figure 60), which is fibre spun to create yarn with piezoresistive properties. Measurements with this sensor type can be seen in figure 61. This sensor type works better in the higher strain ranges, but will also not be used in this research.



Figure 60. Fiber spun PU/PEDOT:PSS (Seyedin et al., 2015).

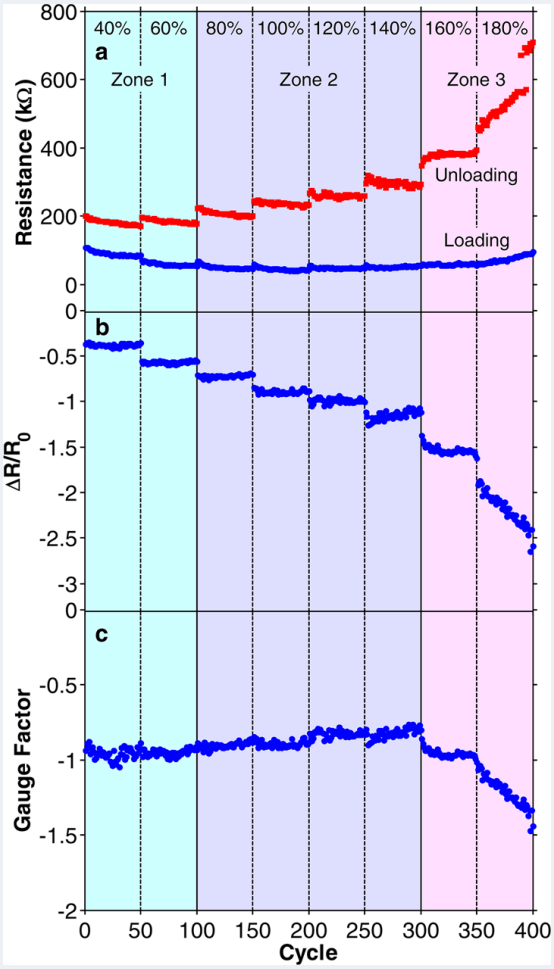


Figure 61. Fibre spun PU/PEDOT:PSS (Seyedin et al., 2015).

The sensors will be created using two types of yarn: Conductive and elastic yarn. The knitting methods that are useful to create the different sensors are:

- **Jacquard technique** for creating sensors knitted in the wale direction.
- **Jersey stitch** and/or **colour striping** for sensors in the course direction.
- **Plating** can be used to insulate the conductive layer on one side.
- **Interlock structure** seems to be the most used in papers about similar knitted sensor research.
- **Interlock structure** has a larger sensor range before becoming saturated compared to normal knitted strain sensors. It also is portrait as more stable and is used in multiple researches on fabric sensors.

Other important highlights from literature research:

- External flaps to create a knitted strain sensor is unwanted, because of its larger size, its higher possible fail rate and possibly increased sensor noise.
- Most knitted strain sensor signals are parabolic, but for processing reasons a linear signal is preferred.
- Inserting thermoplastic yarns that get heated to make the fabric non stretchable might be an interesting option, but can increase discomfort and freedom of movement.
- At larger strains, the resistance decreases again due to higher pressure between knitted loops.
- More lines has shown to create a better signal output.
- There are only a few garments created with integrated fabric sensors.
- No commercial products exist yet with knitted strain sensors
- Silver and stainless steel yarns seem to provide the most promising results when used in fabric sensors.
- Heat shrink tube seems to be the best way to connect conductive yarns to electronic wiring.

A clogged yarn feeder

Chapter 3

Making knitted strain sensors work

The previous chapter gave valuable insights on textile sensors and knitting. It became clear that knitting has a structure that is suitable for creating strain sensors with conductive yarns. This chapter is about how someone can create a knitted strain sensor using the M1plus software with a Stoll knitting machine.

Chapter 3.1

Initial testing

To get an idea of how the knitting software M1plus translates to actual knitted pieces, a few small tests have been done. Loop size, material choice, stitch choice, patterns and plating are a few of the small tests that have been done.

Figure 62(1, 2). During the last of the Stoll knitting lessons we created sensor structure samples. These consisted of parts for a pressure sensor and a sample for a strain sensor both with interconnect paths. 62(1) is made using jacquard technique and 62(2) the interconnects are done using jacquard and for the patch intarsia is used.

Figure 62(3). The first actual knitted pieces are small squares with different patterns of alternating knit and purl stitch. This was done in a normal brown yarn with a dtex value of approximately 650. This piece is a good example of how the programmed piece in M1plus software translates to an actual knitted piece.

Figure 62(4). The same sample has been knitted in elastic yarn. Interestingly, this sample came out of the machine around 4 times smaller than the one made from normal yarn. This most likely happened because the yarn stretched before the yarn feeder could transfer more yarn to the knitting machine.

Figure 62(5, 6). To see how plating would work with different stitch types, the same samples as figure 62(3, 4) were knitted. This time the yarn carrier was replaced by a plating yarn carrier. The first sample came out undamaged, because the secondary yarn was much thinner than the primary yarn in the second attempt. The thicker secondary yarn in Figure 62(6) resulted in breakage of the knitted fabric. Unfortunately, some needles also broke during the creation of this knitted sample. Increasing the NP value or stitch loop length could have prevented this breakage.

Figure 62(7, 8). To see how two materials combined would work, sample with stripes in horizontal and vertical direction were knitted. This was done with normal yarn and with conductive silver yarn. Unfortunately, the conductive silver yarn is only strong enough to withstand the lowest machine speeds and even then it would sometimes just break.

Figure 62(9). Horizontal lines are easy to create as they are parallel to the knitting direction. To create vertical lines, a different technique needs to be used: the jacquard technique.

Figure 62(10). Vertical lines were also tested with conductive yarn with an base fabric made from elastic yarn. Unfortunately, the conductive silver yarn broke because the NP value of the elastic was too low.

Figure 62(11, 12). Horizontal lines of conductive silver coated yarn (Electrisola) in a base of elastic yarn were created.

62(11) is not plated and shows random disappearance of silver yarn. In 62(12), the silver and brown yarn are plated, as can clearly be seen. The silver yarn stays on top of the fabric. Also, the silver yarn used deforms plasticly, which is unwanted. Plastic deformation makes it harder to retract the sensor from a stretched position and causes fatigue, which will eventually result in breakage.

Knitted samples can be found in the sample file

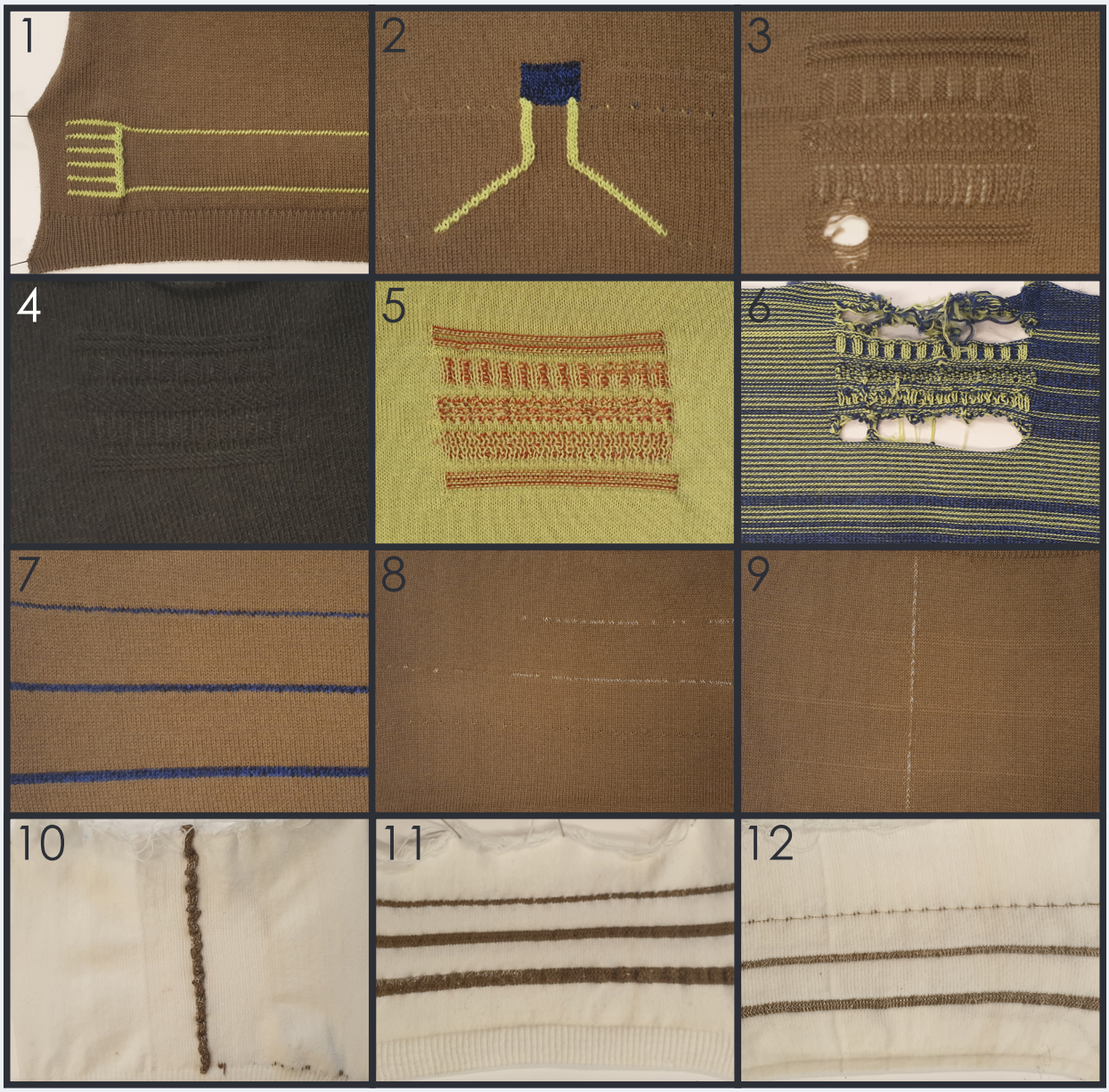


Figure 62. Fabric samples showing different knitting techniques.

Chapter 3.2

Gained knowledge

Setting up the machine

When setting up the machine there are a few key points that are important to remember:

- Have the M1plus software go through all checks and create a compiled program
- Check if the yarn fields in the software correspond with the yarn carrier setup of the machine.
- Do not forget to start the program after loading it in the machine

Np value

The size of the loop is defined by the NP value. Basically, the higher the NP value of a stitch, the bigger the loop is, the looser the fabric gets. This NP value is also influenced by the type of yarn that is used. If thicker yarn is used, the NP value also needs to be increased, otherwise it can lead to damaged fabric or even broken needles as in figure 61(6). A knitted fabric with a high NP value can be knitted so loose that you can see through the fabric. Although, a looser knit might seem better, a too high NP value can also lead to the system getting stuck and eventually needle breakage.

Intarsia knitting

When knitting patches of other colours or materials, intarsia knitting is used. What is important to know is that the M1plus software will divide the piece in multiple parts, using multiple yarn carriers. This means that the main yarn that is used will most likely be split and a second yarn carrier with the same material will be needed. This is why it is important to have at least two spools of the same material when creating more complex knits. Some yarns can be respooled, but special equipment is needed to do this correctly.

Elastic knitting

Knitting with elastic always turns out smaller than knitting with non elastic yarn with the same settings. To prevent the elastic from stretching too much and create a fabric piece that is more the same size a non elastic piece would be, a different stitch can be used. This is called the knit-cast off technique. With this knitting technique the back needle bed picks up the loop together with the front needle bed stretching the elastic more. The back needle lets go of the loop and a looser front stitch is created (Rots, 2020).

When knitting with elastic, the yarn tensioner (arm on the side of the machine) should be set to the lowest setting. The yarn can fall down too fast when pulled harder, which can clog the machine, which eventually can break the yarn.

An interlock structure is also good to create when using elastic yarn. This type of knitting structure uses two needles beds and creates a thicker fabric that is more stable and has less tendency to crumple up. This knitting technique is used quite often in literature.

Chapter 3.3

Knitting a strain sensor

In this chapter, the knitting of a strain sensor is explained in detail. This is done to encourage reproduction and to increase general adaptation.

To create a knitted fabric sensor the following yarns are needed:

- 800 dtex Lycra
- 600 dtex Silver plated conductive yarn

The structure of the knitted fabric sensor is called a interlock stitch. This stitch type is the most used by previous researches into fabric strain sensors and is regarded as very stable and reliable in its performance. Figure 63 shows a schematic of the interlock structure



Figure 63. Interlock stitch with conductive yarn schematic (Atalay, 2013)

Sensor in course direction

In between the interlock structure, horizontal lines of conductive yarn will be knitted. These lines will become the sensing part of the fabric. Figure 64 shows how the knitting has to look in the M1plus software. The yellow represents the interlock stitch, alternating front and back stitch and the green represents the conductive yarn lines which only exist of front stitches. The NP value for the interlock stitch should be set to 9 and the NP value of the conductive yarn to 10.

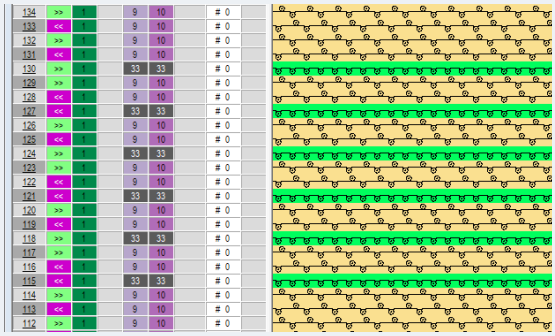


Figure 64. M1plus course sensor stitch arrangement.

When knitting a sensor in the course direction is done correctly, it should look like figure 65.

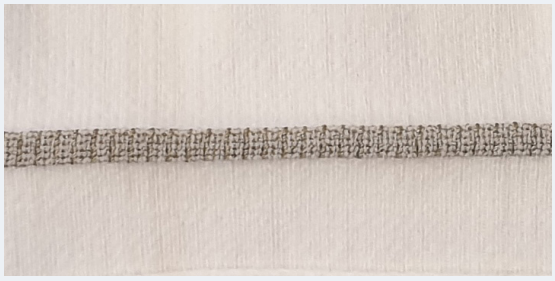


Figure 65. Knitted strain sensor in course direction.

Sensor in wale direction

To create a strain sensor in the wale direction, a different knitting technique needs to be used. This technique is called jacquard.

With the strain sensing part in the wale direction, the conductive yarn needs to go in a vertical line. The interlock structure can still be used as the main structure for this sensor direction. Instead of six green horizontal lines, there need to be two vertical lines next to each other (Figure 66). The sensing part cannot be to small, as the sensor will not work properly and not be too wide, as the elastic will hang loose on the back of the sensing region. Compared to the sensor in course direction, both elastic and conductive yarn is set to NP 9.

For a more detailed explanation of sensors knitted in both course and wale direction, Appendix B can be consulted.

When knitting a sensor in the wale direction is done correctly, it should look like figure 67. The conductive yarn sticks out more, due to the elastic pulling horizontal direction behind the conductive yarn.

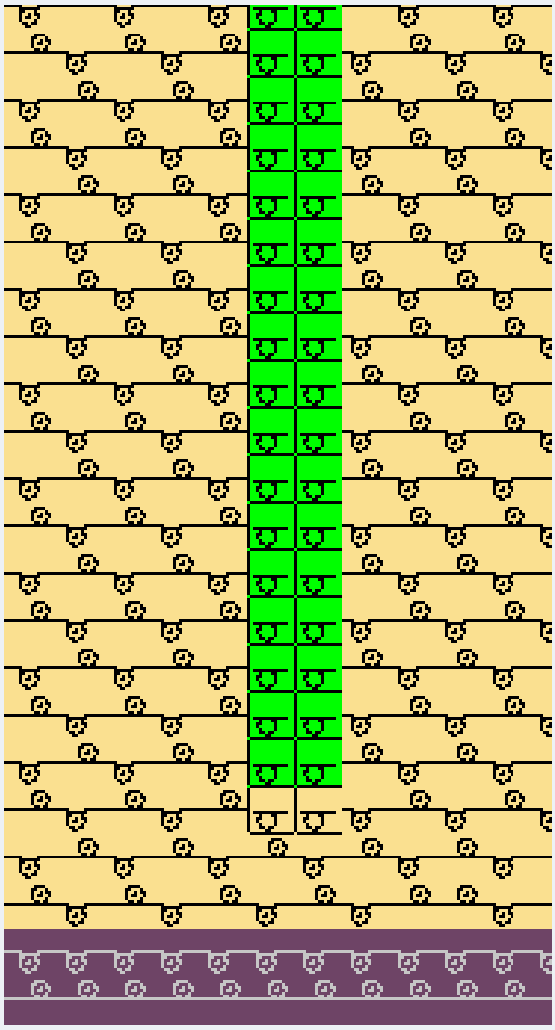


Figure 66 M1plus wale sensor stitch arrangement.



Figure 67. Knitted strain sensor in wale direction.

Conclusion

From literature research the interlock structure seems to be the most promising knitting structure to use in a strain sensor. Other knitting structure have been tested, but the interlock structure deemed far superior.

Trying out different knitting structures and patterns did help with learning knitting on the knitting machine. For anyone doing future projects with the knitting machine, I would highly suggest to try different knitting structures and patterns to really get the hang of the software and the machine. Although, a step by step guide is given on how to actually knit both wale and course strain sensors, it still might be too difficult to execute, as the software is complex and not very user friendly.



Chapter 4

Improving the knitted strain sensor

With literature research, knowledge on how to create a knitted strain sensor the following step can be taken. This chapter will show how the sensor is improved by testing different materials, knitting structures and changing knitting settings.

Chapter 4.1

Measuring setup

In total, ten different fabric strain sensors were created to end up with an improved version of the sensor. Material choice, amount of conductive lines and the NP value are taken into account. The resistance change and gauge factor are compared. The results will help in determining which strain sensor is best suited for the final showcase model.

Strain and resistance measuring device

To measure the resistance change while the fabric sensor is stretched a special device is used. In this report the device will be referred to as: tensile tester. The tensile tester is a device that measures the resistance when certain strain is applied by using a 4-point or Kelvin measurement setup. A 4-point measurement setup, has 4 contact points with the sensor (Figure 68). Where the outer contact points supply a current and the inner contact points measure the voltage difference. With the current and the voltage available, the resistance can be calculated with Ohm's Law.

$$R = U / I$$

Where U is the voltage, I is the current applied to the fabric sensor and R is the resistance to be calculated. By using this method of measuring the resistance over the connected wires and attachment clamps is taken out of the equation (Ghahremani Honarvar et al., 2017). This makes it easier to measure small resistance differences. Connections are soldered to decrease voltage fluctuations and noise and improve connection.

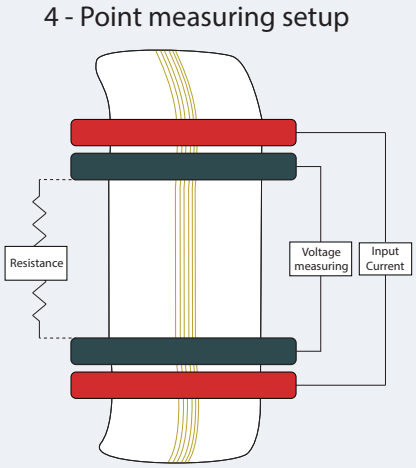


Figure 68. Schematic of the 4-point measurement setup.

To get a consistent connection to the conductive yarn embedded in the fabric strain sensor, silver coated conductive Velcro is used inside the clamp (Figure 69). Velcro has long single hairs that get pushed inside the fabric sensor making good contact with the conductive yarn inside the fabric sensor, ensuring a good connection with every measurement.



Figure 69. Fabric clamp with a conductive Velcro piece in the middle.

A schematic of this clamp shows how the different parts are connected (Figure 70). The tensile tester setup can be seen on figure 71.

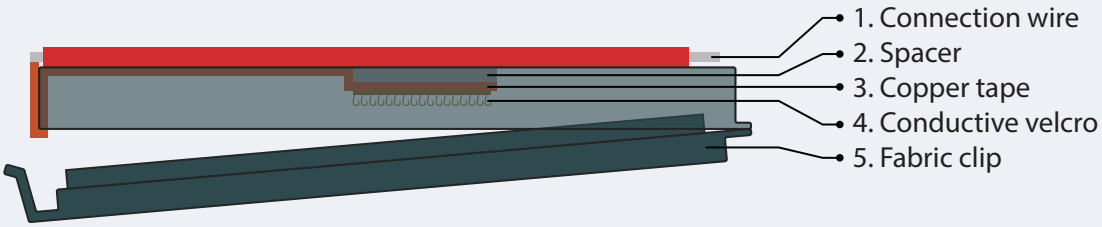


Figure 70. Schematic of fabric clamp

The complete tensile tester exists of many different parts (Figure 71).

1. Power supply - This supplies a current over the knitted strain sensor of 0.3Ω.
2. Fabric sensor sample
3. Voltage clamps - These are connected to the arduino and measure the voltage
4. Current clamps - These are connected to the lab power supply and provide steady current
5. Arduino - The arduino can transfer the voltage measurements to the computer
6. Tensile tester - This device stretches the fabric

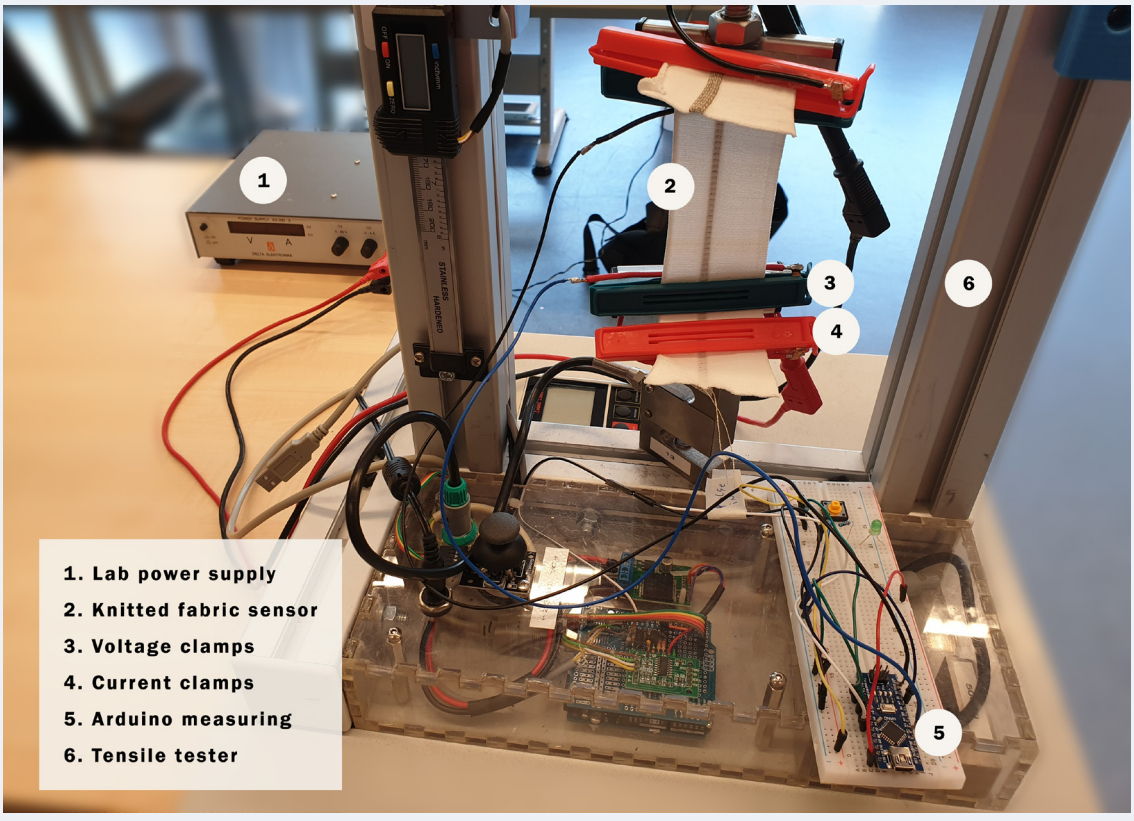


Figure 71. Tensile tester setup

Chapter 4.2

Strain sensor samples

Ten samples are created to be tested on the tensile tester. All samples were created using the interlock knit structure with elastic yarn with a Dtex of around 800. The interlock structure in combination with the elastic yarn provides the best stretch properties and creates a balanced fabric structure. The conductive yarn is silver coated yarn with a Dtex of 604.

Figure 72 shows all the strain sensor samples.



Figure 72. All created fabric strain sensors

Chapter 4.3

Method

All fabric sensor samples are pre stretched 5 times up to 50% to let the elastic yarn settle and approach their neutral position (Figure 73).

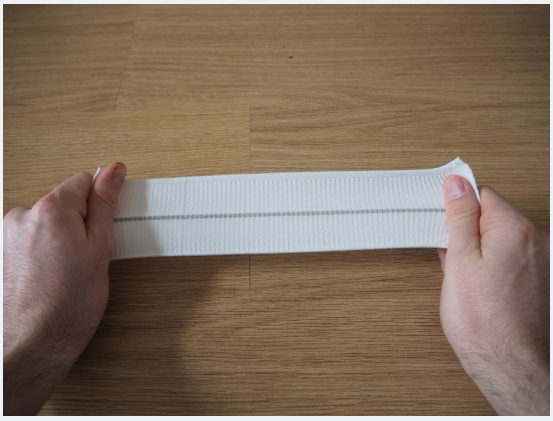


Figure 73. Pre stretching of fabric sensor

The knitted fabric sensors are then placed in the four clamps, making sure that the conductive Velcro in the clamps is aligned with the conductive yarn in the knitted sensor (Figure 74).



Figure 74. Aligning the sensor part with the conductive velcro.

The current is set with a lab power supply to 0.3 Amperes with the voltage open all the way, to make sure the current stays the same when the resistance in the sensor changes.

The fabric strain samples are stretched three times for 10, 20, 30 and 40 percent strain. After every extension or compression of the fabric sensor there is a delay of 3 seconds to get the sensor signal to stabilize. The maximum strain of 40% is chosen to be similar to human body extensions, because the sensor will be used to monitor the body. The minimum strain of 10% might be interesting for measuring smaller body movements like breathing.

When the sensor is in a stabilized position, the R0 and ΔR are measured to calculate the gauge factor with. The gauge factor says something about the strain sensors elongation and resistance change ratio. When the gauge factor is higher the resistance changes are larger, which increases the sensitivity of the sensor is (Instruments, 1998).

The gauge factor can be calculated with the following formula:

$$GF = \frac{\triangle R/R0}{\varepsilon}$$

Where GF is the gauge factor, ΔR is the resistance change in ohms, R0 is the starting resistance in ohms before being stretched and ε is the elongation in percentages.

When the sensor is in a stabilized position, the R0 and ΔR are registered to calculate the gauge factor.

Chapter 4.4

Material choice

Conductive yarn is needed to create a knitted strain sensor. There are many options to choose from when it comes to conductive yarns. By looking at research papers and testing a good conductive yarn is found.

Research in the field of fabric sensors shows that stainless steel and silver coated yarn are used the most.

(Atalay et al., 2013), (Atalay et al., 2014), (Atalay et al., 2017) and (Dupler et al., 2019) all use the interlock structure as a base structure for their sensors.

It is not always specified what the exact material is that is used, but the resistance and dtex values give a good indication.

The resistance of the yarn that is used in previous research mostly lies around 50 - 200 Ω/m.

Two yarns with measurable high resistances are chosen to be compared (Table 1) (Figure 75).

Material	Resistance	Dtex
Silver	80 Ω/m	616
Stainless steel	70 Ω/m	1096

Table 1. Yarn properties

Both materials are used to create a first knitted strain sensor with. The results of testing both materials as one line can be seen in Figure 76 en 77. In both graphs it is not visible that the sensor has been stretched three times.



Figure 75. Stainless steel and silver coated yarn.

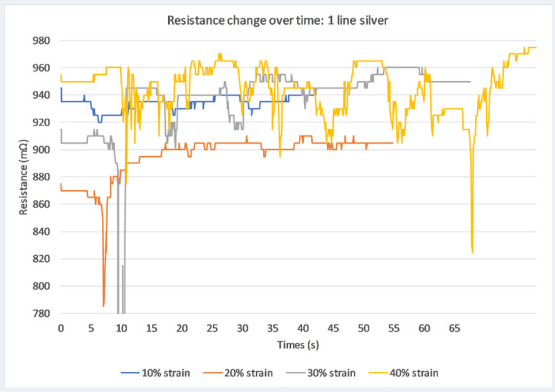


Figure 76. One line silver strain sensor

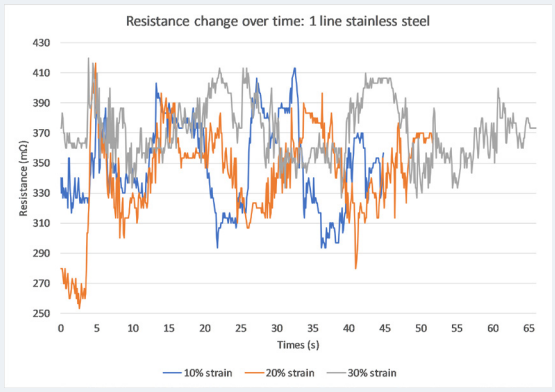


Figure 77. One line stainless steel strain sensor

One line of conductive yarn is not sufficient enough to determine what material is best to create a knitted fabric strain sensor.

To improve the sensor response more lines of conductive yarn are added. The same test is done with two lines of conductive yarn to determine the best material choice.

The stainless steel more or less shows the same characteristics as the one line version (Figure 79). Although, more clear peaks are visible, the sensor still suffers from noise. Especially in the higher strain range.

The two lines silver sensor on the other hand, shows a much cleaner signal (Figure 78). It consists of clear peaks and clear differences between the different strain amounts. Unfortunately, at 40 percent strain the sensor still has trouble producing a clear signal. More lines of conductive yarn might solve this problem.

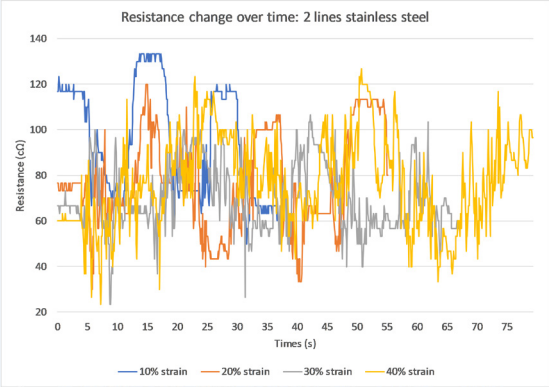


Figure 79. Two lines stainless steel strain sensor

All in all, silver coated yarn seems the best candidate to create knitted strain sensors with. The next chapter will focus on improving the sensor further using only the silver coated yarn..

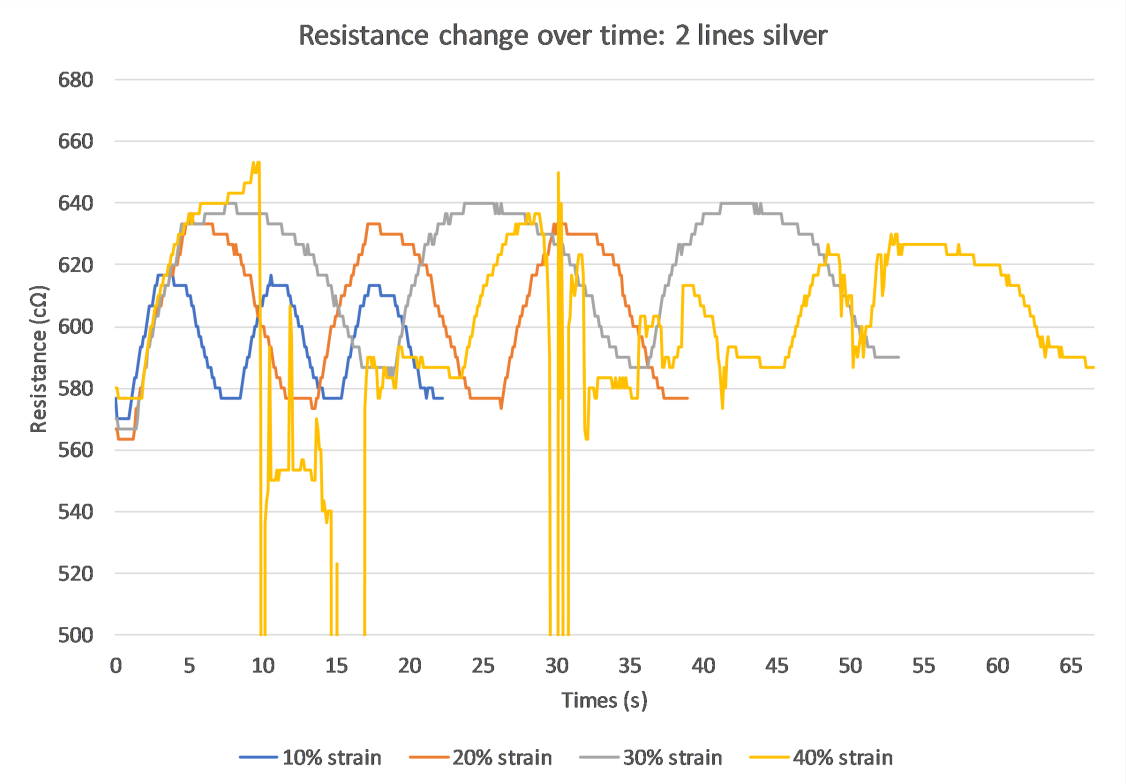


Figure 78. Two lines silver strain sensor

Chapter 4.5

Sensor structure

Now that it is shown that silver coated yarn seems to be the better choice in creating good working knitted strain sensors in the course direction, other fine-tuning can be done to improve the sensor performance.

To improve the sensor performance further, more lines of conductive yarn can be added. Increasing the amount of lines also lowers the resistance and decreases the amount of stretch in the sensor area due to conductive yarn replacing the Lycra yarn.

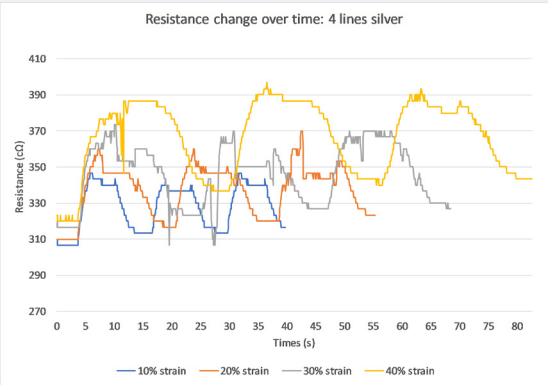


Figure 80. Four lines silver strain sensor

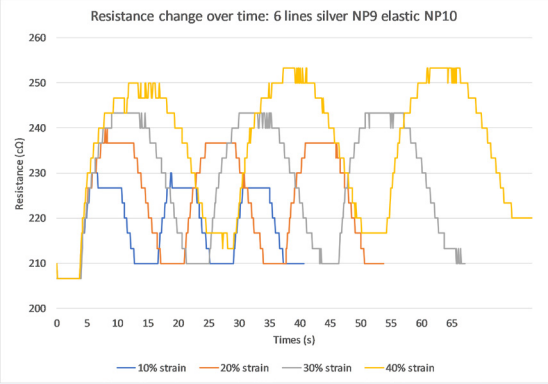


Figure 81. Six lines silver strain sensor

For the following tests, sensors with four and six lines are tested.

Figures 80 and 81 show the sensor output of the knitted strain sensors with silver conductive yarn with four and six conductive lines.

A clear difference in resistance can be seen when both graphs are compared. Lower resistance means less sensor resolution, as the resistance difference also is smaller.

As with the knitted strain sensor that was made with two lines of silver, the 30 and 40 percent range shows drops in resistance. 10 and 20 percent have a similar pattern an clearly show a more stable signal.

The knitted sensor with six conductive lines of silver shows the best sensor result when compared to the previous ones. Although the resolution is lower, the signal is much more constant and does not suffer from sudden resistance drops or spikes.

One thing to note is that the stabilizing resistance (R0) when not stretched on the 40 percent curve is not the same as the R0's from the 10 to 30 percent range.

A sensor with more than six conductive lines will make the sensor resolution too low, which is why six lines is chosen as the optimum between sensor output and overall resistance and retraction.

Chapter 4.6

Loop size tweaking

The knitted strain sensor with six conductive lines has shown to be the best option as it outputs a reliable signal and can show a clear difference between the different strain amounts. To further optimize this strain sensor, the loop size (NP value) of both the conductive yarn and the Lycra yarn can be altered.

The first version of the knitted strain sensor with six lines, the conductive yarn has an NP value of 9 and the Lycra yarn has an NP value of 10. For easy comparison this sensor version will be called type 1.

To see if the NP value can have a positive effect of the sensor output, two extra sensor are created with different NP values.

Sensor type	Lycra NP	Conductive NP	Figure
Type 1	10	9	80
Type 2	9	9	79
Type 3	9	10	81

Figure 82, 83 and 84 show the different strain graphs of the sensor six lines with different NP values.

Type 3, which has the smallest NP value has a higher overall resistance compared to type 1 and 2.

To define which NP value combination works the best, a relative resistance change to mechanical strain graph will help in determining the better sensor.

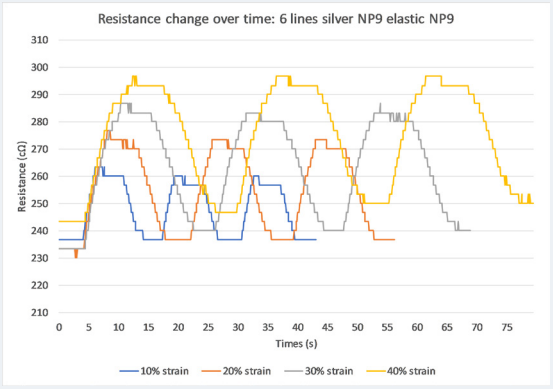


Figure 82. Strain graph 6 lines silver NP9 elastic NP9.

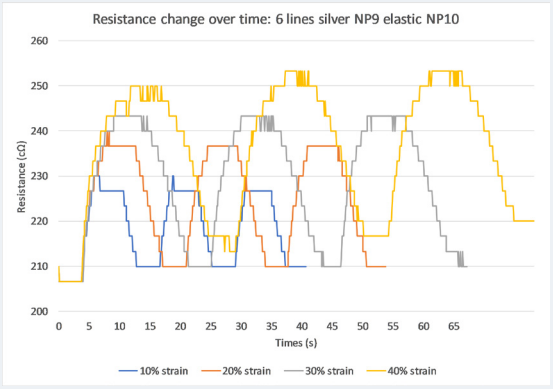


Figure 83. Strain graph 6 lines silver NP9 elastic NP10.

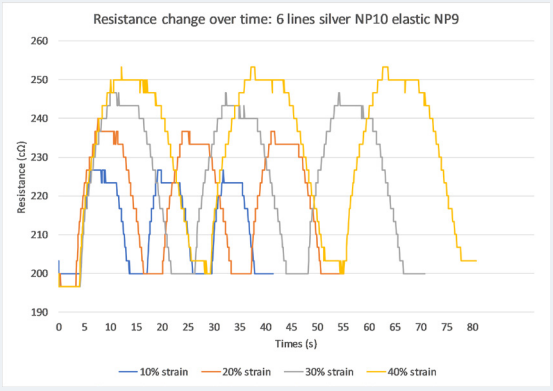


Figure 84. Strain graph 6 lines silver NP10 elastic NP9.

Figure 85, 86 and 87 show the change in resistance to mechanical strain. To choose the best working sensor, it is best to have the average line be as close to linear as possible. When the sensor output is linear with the elongation, the computation of data the sensor produces is easier for the processing unit and consequently use less power.

Strain percentage Type 1 sensor	Gauge factor
10%	0.107952381
20%	0.056357143
30%	0.038619048
40%	0.029222427

Strain percentage Type 2 sensor	Gauge factor
10%	0.094350784
20%	0.049288038
30%	0.0335625
40%	0.025168748

Strain percentage Type 3 sensor	Gauge factor
10%	0.11165
20%	0.058325
30%	0.040275
40%	0.030742745

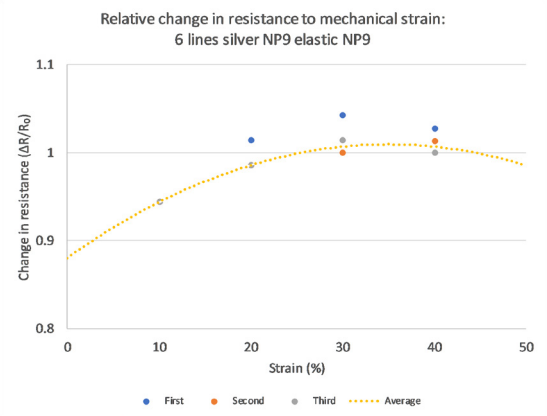


Figure 85. Type 2: Relative resistance change to mechanical strain silver NP9 elastic NP9

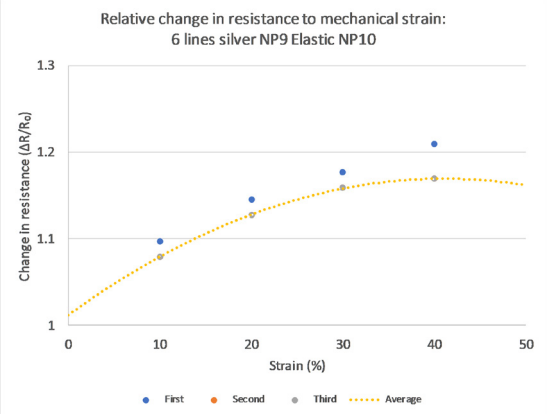


Figure 86. Type 1: Relative resistance change to mechanical strain silver NP9 elastic NP10

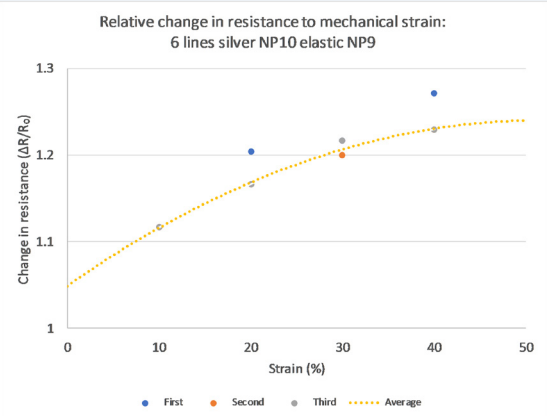


Figure 87. Type 3: Relative resistance change to mechanical strain silver NP10elastic NP9

Strain sensor in wale direction

For the sensor in the wale direction there was not much to tweak in terms of structure. Only NP values are tweaked.

The first sample was created using two lines of conductive yarn knitted in vertical direction by using the jacquard technique. The resulting sensor had more protruding conductive yarn than the sensor in the course direction. The produced sensor data can be seen in figure 88.

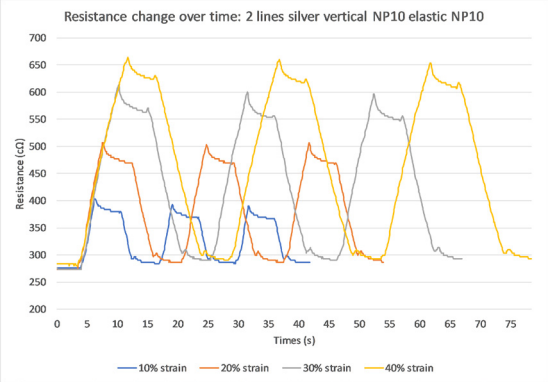


Figure 88 Strain graph sensor in wale direction 2 lines silver NP10.

to improve the feel and decrease the protrusion of the sensor, the NP value of the silver conductive yarn is lowered to 9. This increased the maximum resistance to 800cΩ (Figure 90).

Figure 89 and 91 show the change in resistance to mechanical strain. Lowering the NP value to 9 has increased linearity of the sensor output. Also, the starting point of the average line is now closer to 1 ΔR/R0, which is also wanted.

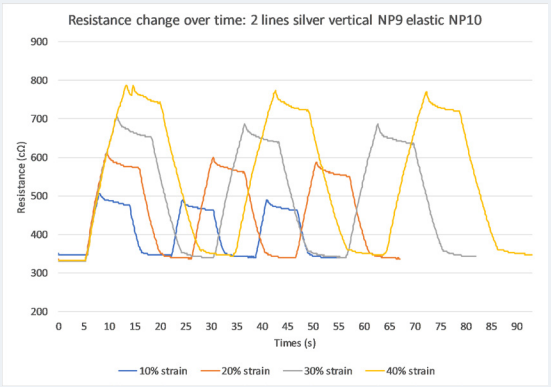


Figure 90. Strain graph sensor in wale direction 2 lines silver NP 9.

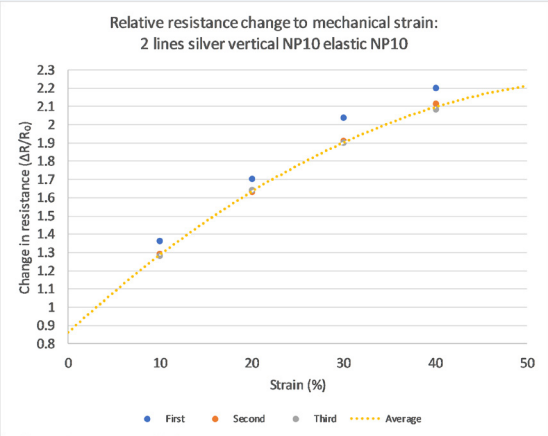


Figure 89. Type 1: Relative resistance change to mechanical strain NP10.

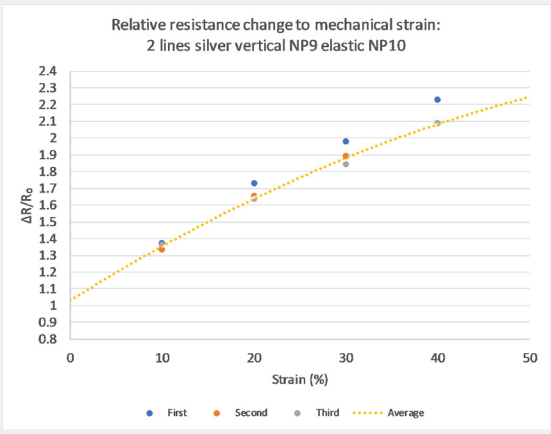


Figure 91. Type 1: Relative resistance change to mechanical strain NP9.

Type 3 knitted sensor show the best results compared to the other two.

The range from no strain to maximum strain is the largest and the average curve is the closest to being linear.

Having the conductive silver yarn looser and the elastic a tighter apparently produces better sensor signal.

Conclusion

When looking at improving the knitted strain sensor, the most important factor seems to be the material choice of the conductive yarn and the amount of conductive lines used. Silver coated yarn has shown the best results and six lines of conductive yarn in the knitted strain sensor seems to perform best. Increasing the NP size of the conductive yarn and lowering the NP value of the lycra seem to provide a small boost in performance. The strain sensor in the wale direction needed only small adjustments to be improved, as only the NP values could be altered.

The strain sensor in wale direction performs surprisingly well the first time. The only thing that has been improved is the protruding conductive yarn by lowering the NP value to 9. Unfortunately, this strain sensor has a long stabilization time, especially when stretched. It still performs well enough to be used.

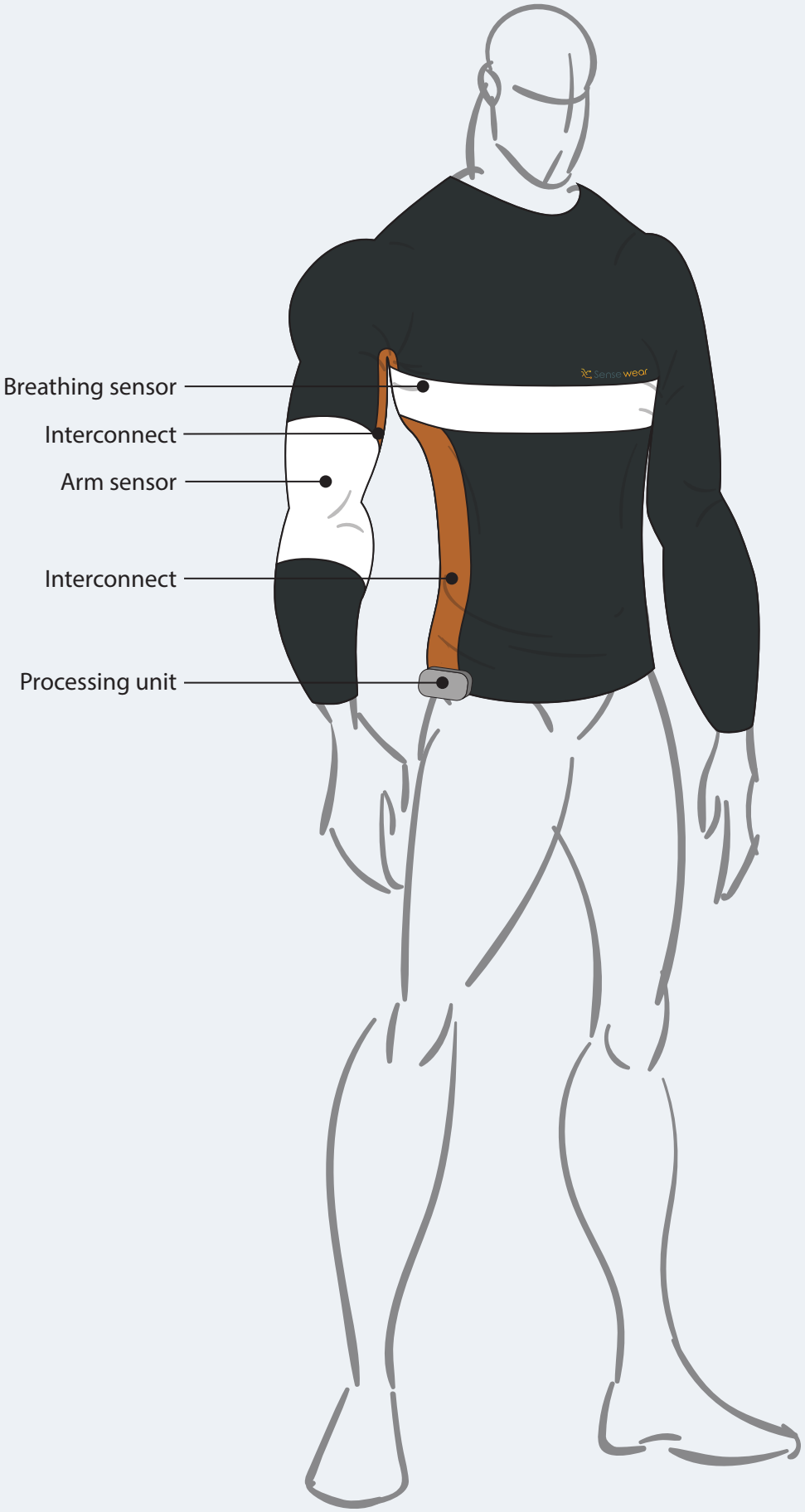
A larger version of all the sensor graphs can be found in Appendix C.

Discussion

The sensor in course direction has shown to be a lot more difficult to improve. A lot more steps are taken to get the sensor in course direction to produce usable data. This sensor could be further tested with for example eight lines of conductive silver yarn. Adding more conductive lines also decreases the contraction force and resistance of the sensor. A decreased resistance produces a lower resolution sensor output. A remedy for this might be to use a conductive yarn with a higher resistance, unfortunately this was not available. Nevertheless, the sensor already showed results that were usable and clearly definable.

Although the strain sensor in wale direction could be improved further, the result it provided the first time it is used is much better compared to the course sensor created with 2 lines of silver conductive yarn. Tweaking this sensor would most likely not make it produce significantly better sensor output.

Comparing the sensors with two lines in wale and course direction show a clear difference in sensor output. Why this happens is not clear. It could be that the sensor in course direction experiences more noise due to friction. Or the sensor in wale direction has better surface contact, due to the silver conductive yarn being pressed together by the elastic yarn.


Breathing sensor
Interconnect
Arm sensor
Interconnect
Processing unit
SenseWear

Chapter 5

Designing with knitted strain sensors

Now that the sensor is improved and can produce usable data, it can be integrated into a product. This chapter shows how these fabric sensors can be incorporated in a design. This is done with two small example prototypes and a final prototype.

Chapter 5.1

Possible applications

Building and improving a strain sensor is not enough to implement these in products that can be used by people. This chapter provides an extra step with example products to show how these knitted strain sensors could be implemented into wearable garments. Two small prototypes are made that can provide breathing pattern and arm movement data. Besides that, a final prototype garment is made, where both sensors are integrated. The design of the shirt is also taken into account. These can be used as inspiration for future projects that might want to implement these knitted strain sensors.

Method

To search for interesting areas to apply knitted fabric strain sensors, a creative session has been done with four people with a design and engineering background (Figure 92). From there, two example prototypes are created to find out how real world application could work.

For the creative session the following items were provided:

- Stoll performance plus magazine. This is inspiration on Stoll vision of fabric electronics (Appendix D).
- Two A3 pages of knitted examples (Appendix D).
- Knitted bag, knitted support stocking and knitted bra (Appendix D).
- Knitted sensor demonstrator connected to arduino with code (Appendix F) that turns on a series of LEDs when stretched (Figure 93).



Figure 92. Full needle stitch and tubular stitch (Li et al, 2009).

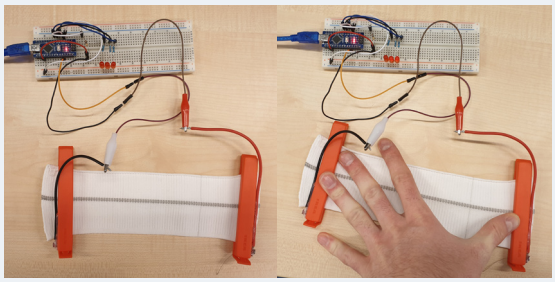


Figure 93. Demonstrator showing increased stretch will turn on LEDS sequentially.

Procedure

First a short introduction about knitting is given in combination with two A3 sheets of knitted example products. The knitted sample products are shown after this to get a feel of what is possible with knitting. After the participants are familiarized with knitting, the knitted sensor demonstrator is shown. The demonstrator transforms sensor data into something visible. It has three LEDs which light up sequentially the more the sensor gets stretched.

Now that the participants have an idea of how a fabric strain sensor works it is time to get creative. Everyone got an A3 sheet and post it's to write their ideas on. The first round was a warming up session where everyone could just write down ideas where fabric strain sensors could be applied. These were then discussed to give a general sense of what the possibilities are.

The second round was to dive deeper into the topic and generate more ideas. These ideas were then clustered.

Results

The ideas that resulted from the creative session can be categorized in five themes.

1. Sports
2. Medical
3. Gamification
4. Safety
5. Interfaces
6. Weight/volume measuring

The clustered ideas can be found in Appendix E.

Most Promising results from the session are the following:

- Arm movement measuring for Rehabilitation
- Breathing rhythm measuring
- Virtual reality controller
- Yoga flexibility measuring
- Posture measuring
- Stress ball: Strain to stress

The full list of ideas that came out of the creative session with included drawings can be found in appendix E.

Conclusion

Unfortunately, not all results are able to be created using the knitted strain sensor due to their physical limitations. The long term measuring for example does not work that well, as the fabric itself would also wear out over time, making the measurements unreliable. The best application would be for short movements that do not need a lot of precision.

The most interesting results from the creative session that can be applied to the body are the arm/leg movement measuring and breathing pattern measuring. Both have rhythmic movements that are repeated quite quickly after one another. The breathing measuring has a strain of approximately 10 percent, while the arm movement goes up to 40 percent. Both are interesting to test in real life prototypes to see if both strain ranges can be accurately measured.

Chapter 5.2

Example prototypes

Portable measuring device

To test the two prototypes a new method of measuring needs to be built that can work on a portable power source and store data locally and still provide enough precision to measure the differences in resistance in the knitted strain sensors.

For this purpose, a feather M0 Adalogger is used. This board has a built in SD card slot and a port to power and charge lipo batteries (Figure 94). Additionally, this board has a 12-bit (4096 bits) analog reading precision, instead of 10-bit on the tensile tester that is described in chapter 4.1.

The circuit that is attached to the feather board is a voltage divider with one resistance being 20 ohms, and the other being the knitted strain sensor. A button is added to start and stop the measuring. When a measurement is started, a new file is created on the SD card where the resistance data gets written to. Once the button is pressed the second time, the file will be saved. To prevent misunderstandings, the LED on the board will blink once, when the measurement starts and blink twice when the measuring is finished. To prevent overwriting, the board first checks if a file name already exist when it is creating a new file. This way, multiple measurements in a row can be done. The code that is on the portable measuring setup can be found in appendix G.

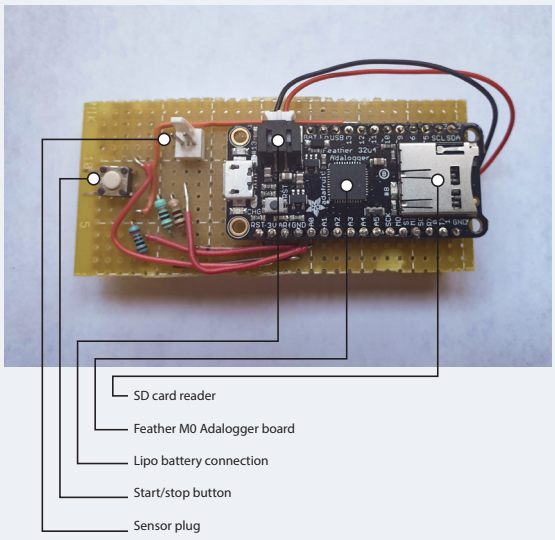


Figure 94. Feather M0 Adalogger measuring circuit.

Arm movement measuring

To test the longer ranges that the knitted strain sensor can reach, the arm movement is chosen to be measured. The arm can rotate up to 145 degrees (Figure 95) where fabric on the elbow will stretch up to 40 percent. This is one of the highest ranges of movement in the body and is ideal to test the higher strain ranges this sensor is capable of measuring. Strain sensors in both course and wale direction will be tested and discussed.

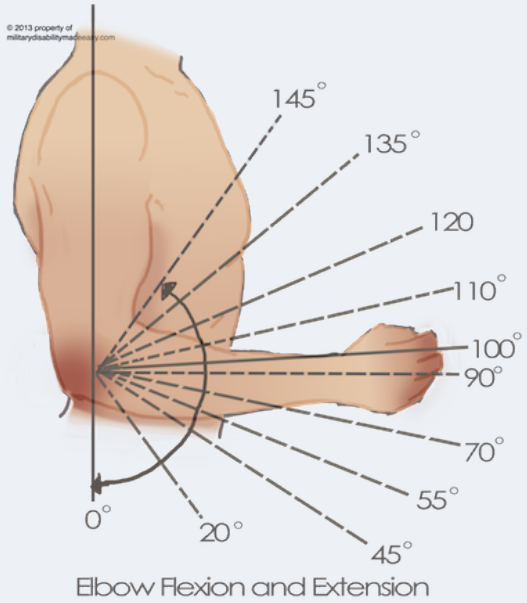


Figure 95. Degrees of elbow movement

Sensor in course direction

The horizontally knitted strain sensor that can be used to measure the arm is a longer piece of fabric with the sensor in the middle. The ends are sewn together to create a tube that can be worn on the arm (Figure 96). The improvements made for this sensor can be found in chapter 4.4 - 4.6.

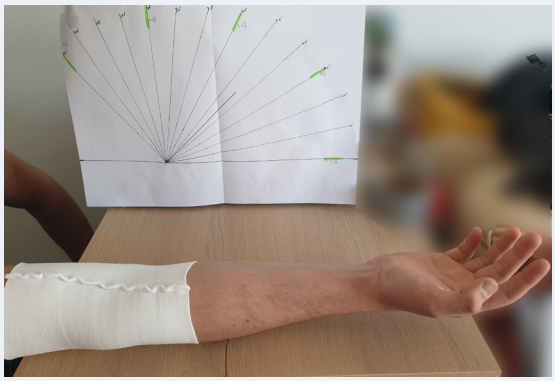


Figure 96. Arm measuring prototype sensor course direction

Sensor in wale direction

The vertically knit sensor is sewn to two elastic tubes, because this type of sensor takes a long time to knit so for this purpose it is made narrower. The functionality should not change because of the size difference (Figure 97). The improving of this sensor type can be found in chapter 4.7

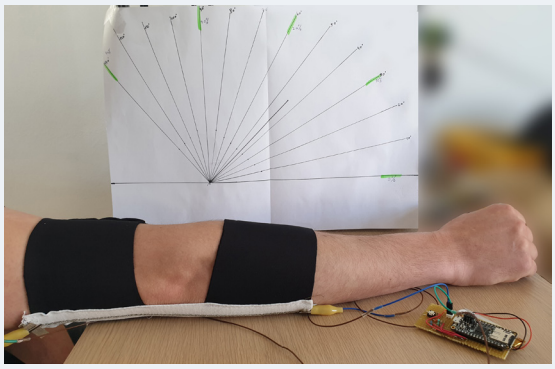


Figure 97. Arm measuring prototype sensor wale direction

Method

The arm is moved from 10 to 40% movement in 10% increments, which translates to 30, 60, 90 and 130 degrees. Every degree step is repeated three times with three seconds of rest in between arm movements.

Results

Results of both arm measuring tests can be found in figure 98 and 99. A line in the graphs indicate where the average threshold is per strain percentage.

The sensor in the wale direction (Figure 99) has a bigger voltage difference when going from 10 to 20 percent strain. Some variation in peak heights is also visible, but this is due to human error not stopping exactly at the same angle every time. The beginning peak after every stretch is much higher with the sensor in course direction. Sowing similar results as the tests done in chapter 4.7. It shows that this sensor type needs a long time to settle.

Looking at both graphs, both sensors perform quite similarly and could both be used. The sensor in course direction is more integrated, which gives it an advantage over the sensor in wale direction. Combining both sensor should also be possible, making diagonal measuring possible, but this is not looked into in this research.

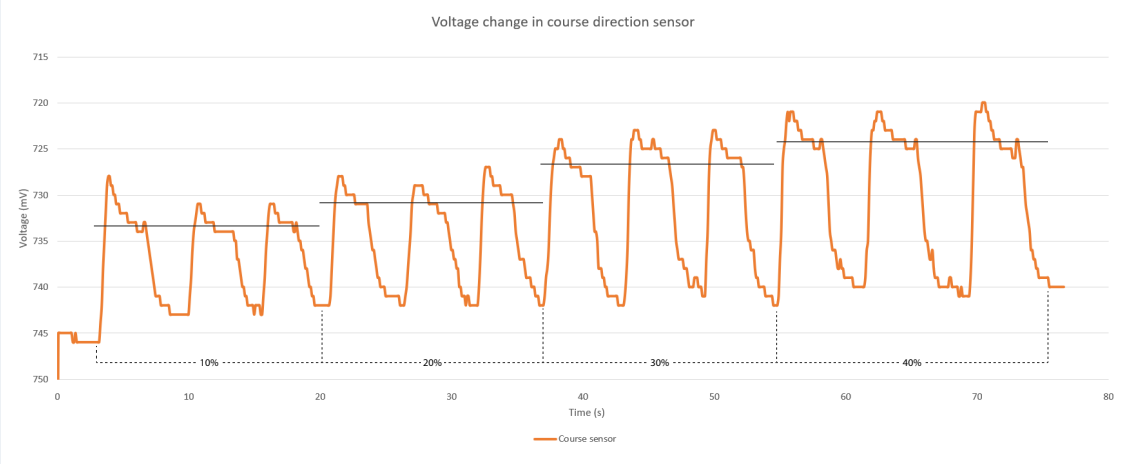


Figure 98. Graph arm measuring course sensor

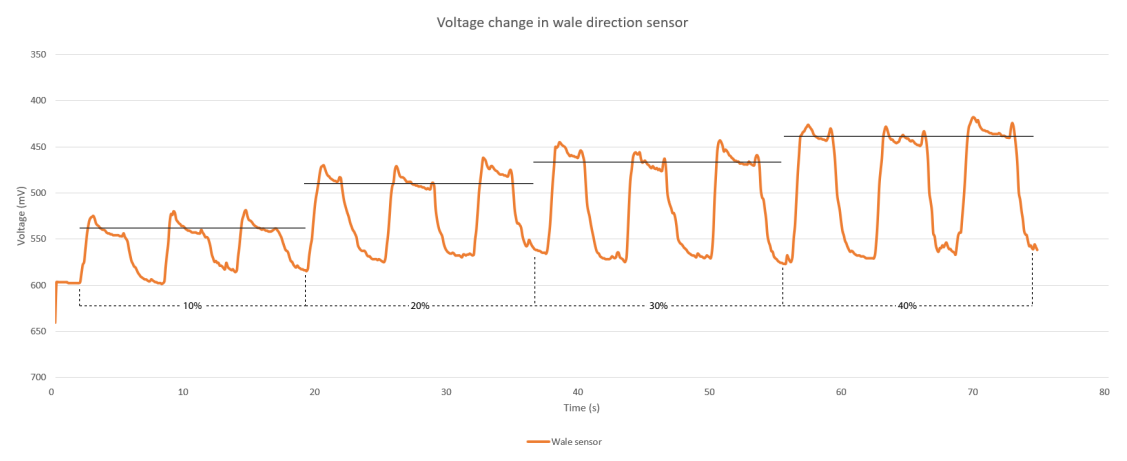


Figure 99. Graph arm measuring wale sensor

Breathing measuring

To test the more constant and smaller elongation, the breathing pattern is chosen to be measured. During breathing the average chest expansion is around 5 to 12 cm (Chest Expansion, n.d.). Average of chest circumference in adults lies around 85cm up to 105cm, which ends up in an average chest expansion of around 10 percent. Although this change in circumference is small, it should still be measurable with the knitted strain sensor.

Breathing sensor

The apparatus that measures the breathing pattern is a long strip of knitted fabric with the sensor part covering the whole length of the fabric. Two push buttons are used to connect the beginning and end of the fabric strip. Simultaneously, the buttons act as the two poles to connect to the processing unit (Figure 100).



Figure 100. Testing the breathing sensor

Method

To see how the breathing measuring would perform, it is tested in three different scenarios (Figure 101).

- Sitting still
- Walking stairs
- Cycling

The scenarios are chosen based on different intensity levels, while keeping the upper body mostly in a stable position. All scenarios were measured for 10 minutes.



Figure 101. Testing the breathing sensor

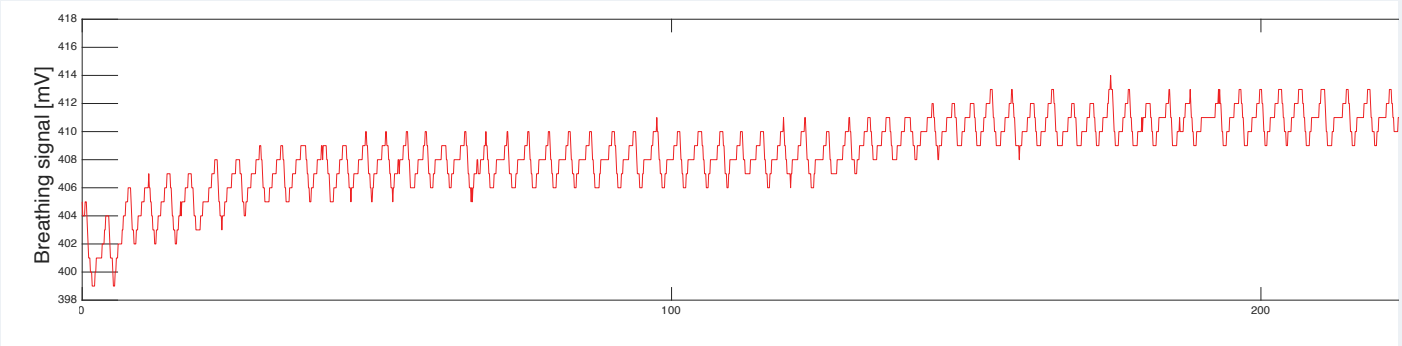


Figure 102. Partial breathing graph when sitting still for 10 minutes.

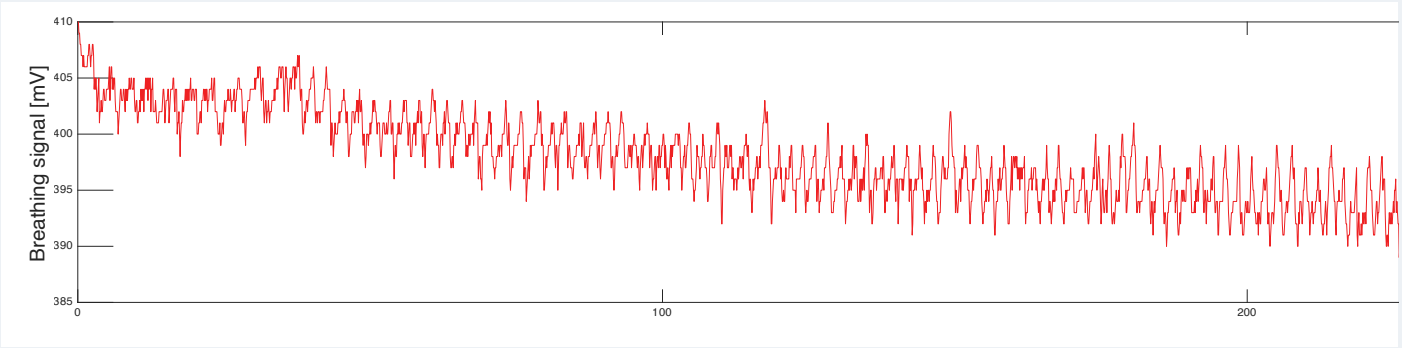


Figure 103. Partial breathing graph when walking up and down the stairs for 10 minutes.

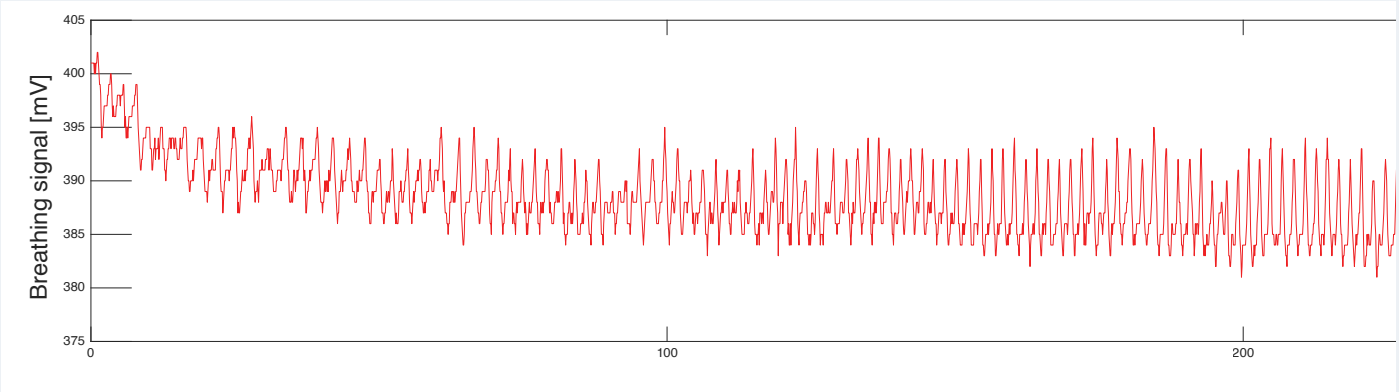


Figure 104. Partial breathing graph when cycling for 10 minutes.

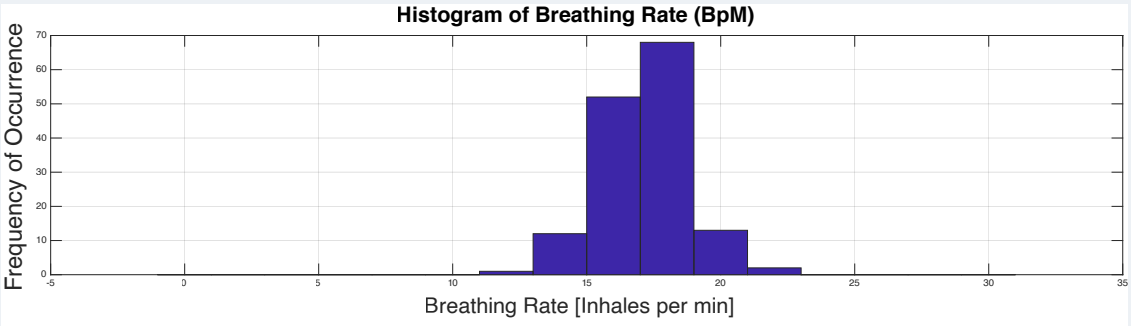


Figure 105. Breathing rate when sitting still for 10 minutes.

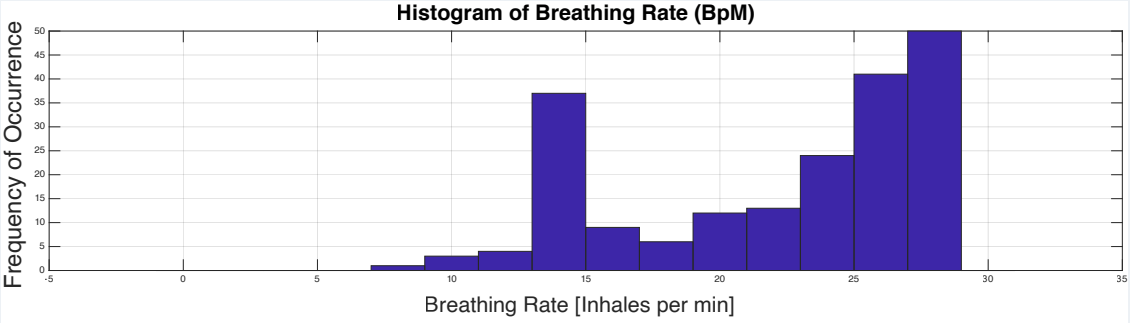


Figure 106. Breathing rate when walking up and down the stairs for 10 minutes.

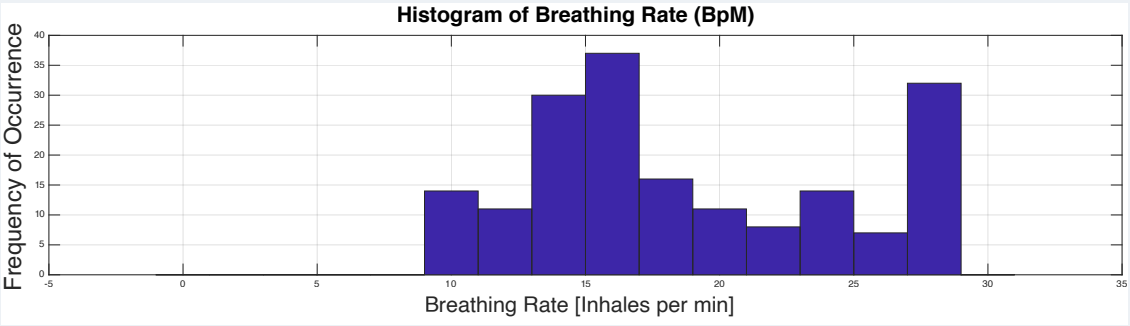


Figure 107. Breathing rate when cycling for 10 minutes.

Results

Figure 102, 103 and 104 all show the breathing pattern from 10 minutes sitting still, walking stairs and cycling respectively. All graphs look to be measuring the breathing pattern without any problem. There is some fluctuation with the graph slowly rising or falling, but the breathing patterns are still readable.

Figure 105, 106 ad 107 show the breathing rate per minute. Adults breath around 12 to 20 times per minute, during intense physical activity this can go up to 40-50 times per minute (Lindh, 2013).

The breathing rate for sitting still lies around 17 breaths per minute. Which lies right around the breathing rate for low intensity activities.

The breathing rate of walking up and down the stairs lies around 27 breaths per minute. Which equates to a medium intensity physical activity, which walking stairs is.

The breathing rate during cycling lies around 16 breaths per minute, but also has a peak around 27 breaths per minute. Cycling is also a medium intensity physical activity, which the breathing rate also shows.

The full sized graphs of all 10 minute scenarios can be found in appendix I along with a breathing rate graph showing the average breathing rate per minute. The Matlab code used can be found in appendix J.

Chapter 5.3

Final prototype

To take the prototyping one step further, a wearable garment is presented with previous sensors, discussed in chapter 5.2, integrated into it. Sewing is used to accomplish this. This chapter also discusses two target groups and their different needs considering such a garment. Alongside the looks and interaction with the shirt, the data visualization is also briefly discussed. The shirt design is mainly to show how the sensor could be incorporated into the design, instead of being hidden.

Data visualization

To make clear for the wearer what the shirt is doing and tracking it is useful to visualize the data that is gathered in a certain way. This chapter will briefly go over different ways of visualizing data.

The data that is gathered is different per sensor and each has a best way to visualize it. Take previously created sensors, the breathing sensor measures a constant change in resistance as the wearer is breathing, but with the arm sensor one might want the amount of times the arm has been flexed or how far the arm has flexed.

For measuring breathing, a graph might be the most useful method to display the data. Whereas with the arm movement, a counter or an LED increasing in brightness might be a more logical choice. A few possible visualizations are shown in figure 108.



Figure 108 Ways of visualizing data

Interaction with shirt

To get the shirt to start its measurement a trigger needs to be set off. This way the wearer knows when he or she is recording its performance data. There are multiple ways to interact with the garment to start tracking data. Interaction could be touching the garment on the arm or chest, doing a certain movement or maybe even voice activated (Figure 109).

The interaction with the shirt is important and needs to be well suited for the target group. For sports people it might be handier to touch the arm when for people that are measured in a hospitol for example might benefit more from voice commands or someone else starting the measurement.

Discussion

Although the data visualisation and shirt interaction are only talked about briefly, they should be seen more as inspiration for future projects. The focus of this research is not focus on developing a working shirt that could be sold to consumers, but to rather show what the technology is capable of and how it can be implemented into a garment with the included but not that meaningful 'data visualisation' and 'shirt interaction'.



Figure 109 Ways of interacting with the shirt

Chapter 5.4

Revalidation

Creating a shirt with integrated sensors for healthcare might be beneficial to people that are revalidating, but also the medical staff. The patient can track exercises at home and the doctor can also keep track of the patient from a distance. Especially for older people, that sometimes forget to do their exercises at home or lose track of the amount of repetitions they have done. In this chapter a possible design for this target group is proposed for inspiration purposes.

Interaction

The most logical interaction with the shirt for this target group is to start measuring when the user is moving. Revalidation patients already have trouble moving their arms, so making them move their arm to touch their chest or hand might not be the most convenient. Voice activation might also work, but is more difficult to implement.

Data visualization

For the visualization of data for this target group, the best might be a counter. As most often, the patient needs to do a certain amount of exercises. The counter is a simple form of data visualization and could be replaced with an app that keeps track of every exercise session.

Design

Possible designs for the shirt are shown in figure 110. As the sensors can be seen on the outside of the garment, it is logical to make a twotone design that merges the sensors into design of the shirt.

Colours are chosen based on a mind map (Figure 111) made for the revalidation target group.



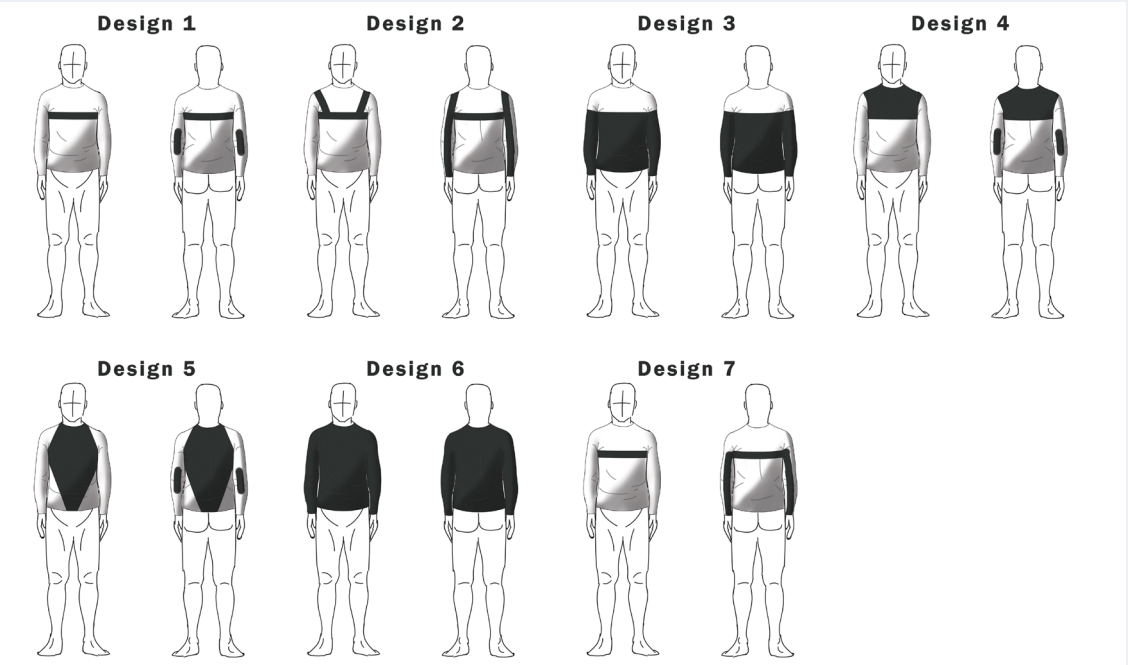


Figure 110. Revalidation shirt designs

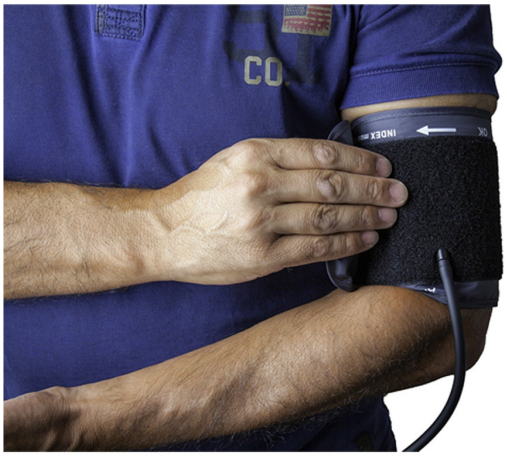
















Figure 111. Mind map for the revalidation target group.

Chapter 5.6

Sports

When athletes want to measure their performance, they also train with gear that can measure their performance. Having hard sensors integrated into their clothing can be uncomfortable, but also cause a phenomenon called the observer effect (McGrath et al., 2013). When there is awareness of the sensor by the athlete, the performance is impacted. This can be avoided when sensors are fully integrated into their apparel. In this chapter a possible design for this target group is proposed for inspiration purposes.

Interaction

The shirt that is targeted to sports people has a more sporty way of interacting with it. Touching the end of the sleeve or touching the chest fits more with this target group, as it is more fun, but also cooler way of interacting.

Data visualization

As with the interaction, the data visualization also needs to be more fitting with the sports target group. Popular data tracking devices mostly use apps to process and show different performance data. This might also be the most interesting choice for this target group.

Design

In figure 112 nine shirt designs are shown. As with the revalidation shirt, the focus of the designs is showing how the sensors can be blended in by creating a two tone design.

Colours are chosen based on a mind map (Figure 113) made for the revalidation target group.



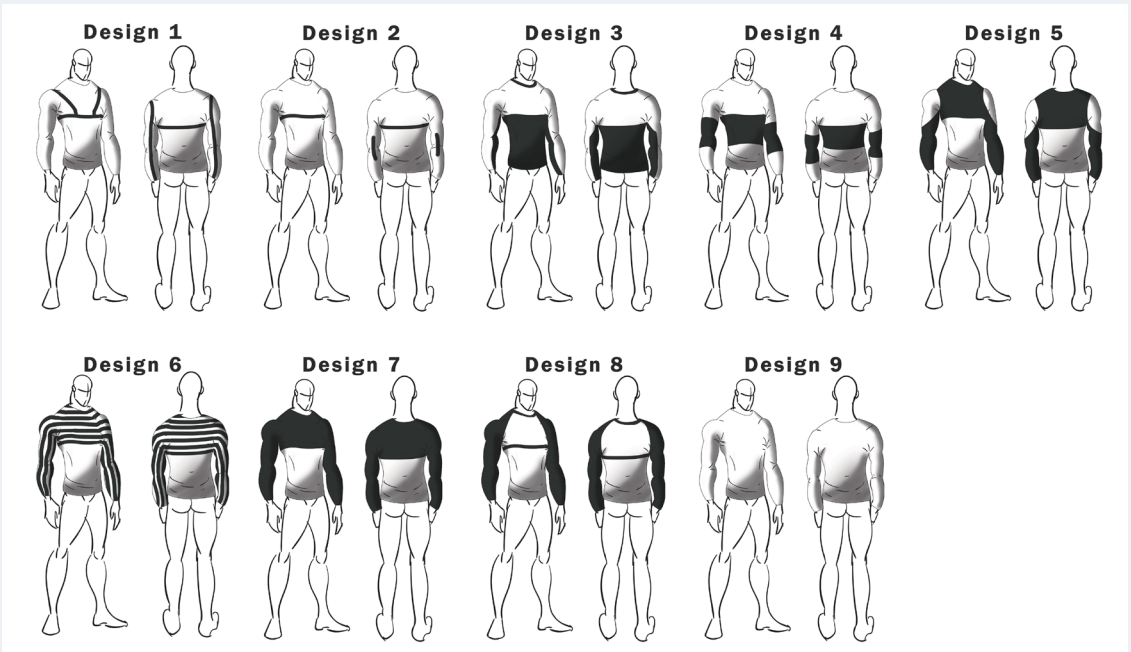


Figure 112. Sports shirt designs.















Figure 113. Mind map for the sports target group.

Colour study

To show how the possible shirt design would fit with the colour palette that was created for each target group, a small colour study is done. This colour study is done with a few selected designs from each target group.

Examples from the color study on both target groups can be seen in figure 114 and 115.
This colour study is a method to show what a final shirt design for each target group might look like. It can be used as an inspiration for designers on how these integrated sensors can be blended together with the design of the shirt. They create a starting point for future designers that will be working on smart garment designs.
The full colour study can be found in appendix K and L.

Discussion

The colour study is mainly done to show what a possible design might look like. They provide a look into the future of how a garment with the developed technology might work and look. It should be used as inspiration for follow up projects. A larger study into the design should be done to develop the garment further into a product that can be sold to consumers.

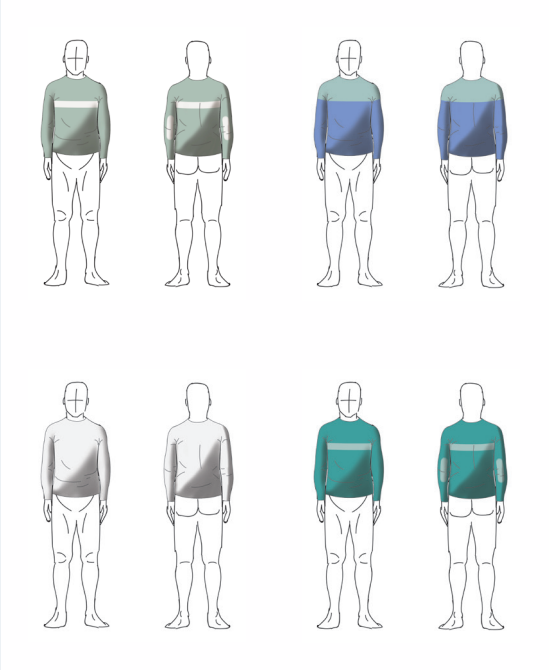


Figure 114. Examples from the color study of the revalidation shirt

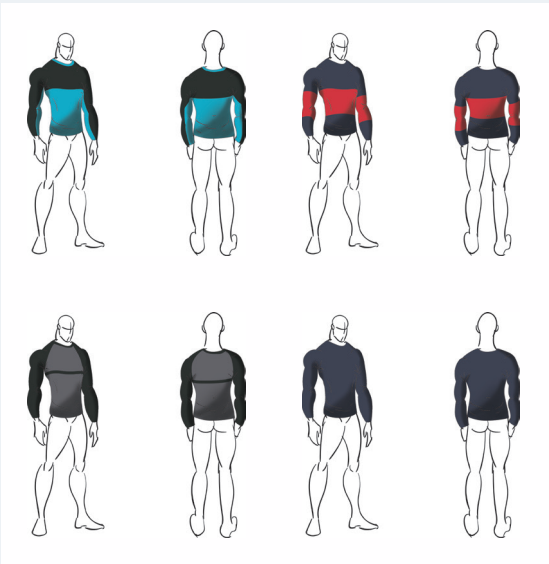


Figure 115. Examples from the color study of the sports shirt

Chapter 5.7

Sense wear

A final prototype called SenseWear is made as a showcase model to demonstrate how the sensor technology works, how it can be used and how it can be interacted with. Unfortunately, it was not possible to fully knit the final shirt due to circumstances. A revised prototype is made. The changes will be announced with the following word: **Revised**

Sensors

Both breathing and arm movement sensors are knitted into a garment that is also fully knitted.

Revised: Both arm and breathing sensor are knitted and attached together to create a tube with a sewing machine. The sensors are then sewn onto a bought compression garment.

Interconnects

With the shirt being fully knitted, the interconnects will also be fully knitted or will be integrated into long pockets alongside the shirt. The challenge with knitting the interconnects is that the material needs to be strong enough to be used in a knitting machine and the machine needs to be able to handle the material.

Revised: The connections between the sensor and the processing unit is made with flexible copper cable (Figure 116) that is able to be stretched. This cable is sewn on the side of the garment.

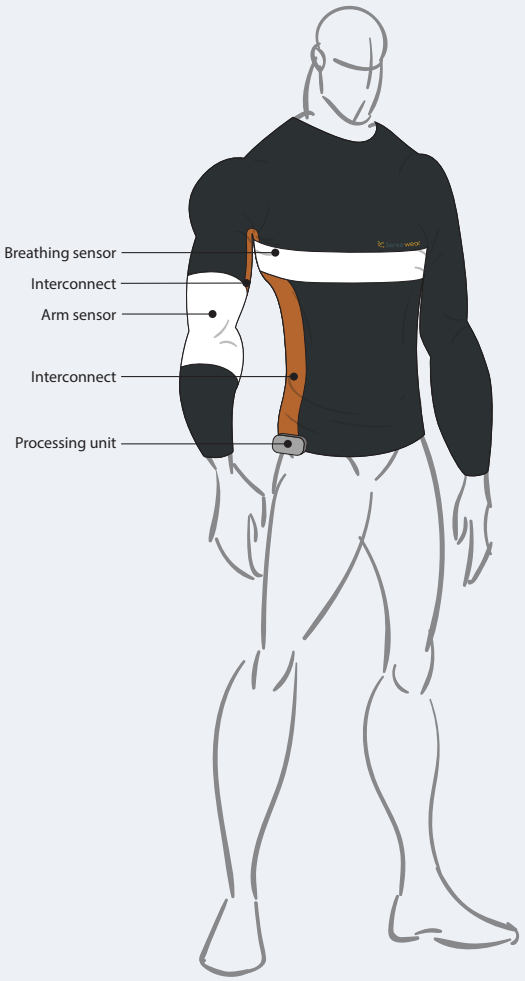


Figure 116. Schematic drawing of the final prototype

Processing unit

To store and process all the data that the sensors generate, a processing unit needs to be added to the garment. This will make use of on board storage and battery to make the device portable. A plug attachment connects the shirt to the processing unit.

Chapter 5.8

Prototype building

To test the breathing and arm sensor in an actual garment, a prototype shirt is created with both sensors integrated. The building process of the final shirt, the interconnects, processing unit and casing is described in this chapter.

Method

The created prototype has been built using Sewing machine (Brother Innovis) (Figure 117), locking machine (Janome) (Figure 119), 3D printing, hand sewing and soldering.

Shirt

The shirt is a compression shirt that is design to be mostly used for sports (Figure 118). Although the fabric that the compression shirt is made of does not have similar properties to the knitted sensors, it is the best option for now.



Figure 118. Chosen shirt to sew sensors on.



Figure 117. Brother Innovis sewing machine.



Figure 119. Janome locking machine.

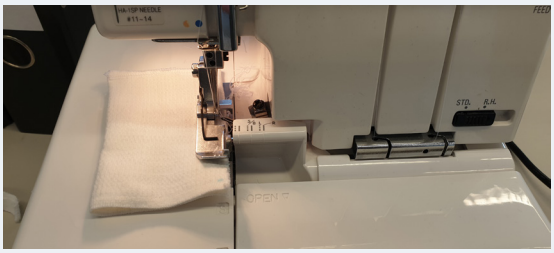


Figure 120. Locking the sensor into a tube.



Figure 121. Locking the sensor onto the shirt.

Shirt

Both breathing and arm sensor are knitted on the Stoll knitting machine, where they eventually get sewn together on a sewing machine to make the parts tubular (Figure 120).

The placement of the sensors is marked and then cut. The sensors are then aligned, pinned in place and sewn together on a locking machine (Figure 121). This machine creates a stretchable sewn seem, which is necessary for this garment, because it needs to be able to stretch to detect resistance changes in the sensor.

The interconnects are insulated flat stretchable copper cables. These are sewn onto the shirt with a sewing machine. The ends of the copper cable are stripped of their insulation to be soldered and crimped to thin copper wires (Figure 122). Those are then crimped onto metal plugs (Figure 123) that can be slotted into a plastic plug that fits onto the electronics housing (Figure 124).

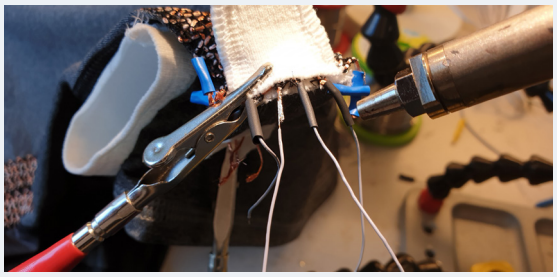


Figure 122. Soldering wires and applying heat shrink tubing.



Figure 123. Wire connections for in plugs.



Figure 124. Final plug to connect shirt to processing unit.

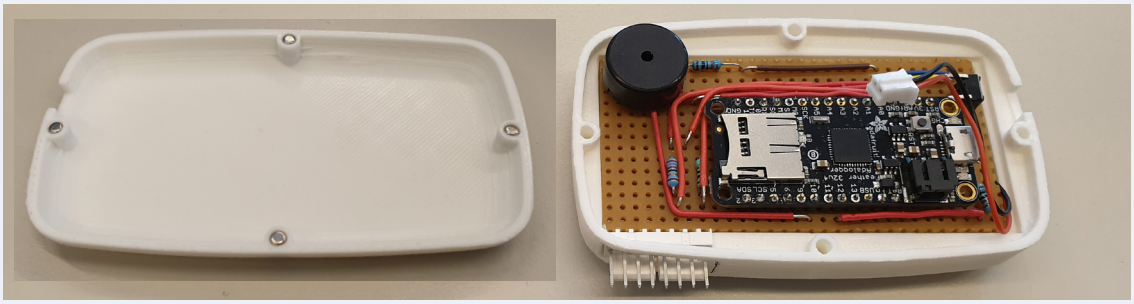


Figure 125. 3D printed housing for electronics.

Electronics

The electronics exist of an Adafruit feather Mo Adalogger that is soldered onto a prototyping PCB. The Adafruit board has an inbuilt micro SD card reader and a plug connection to attach a LiPo battery.

A connection is soldered on to the prototyping PCB where a connection can be made with the shirt by plugging in a cable from the shirt. A button and a small speaker are soldered on as well. The button is used to start and stop recording data from the sensors. The speaker beeps once when the button is pressed to start the device and it beeps twice when the user stops the data recording (Figure 126). The circuit schematic can be seen on figure 127 and the Arduino code in appendix H.

A case to house the electronics is 3D printed, sanded and painted (Figure 125). Small magnets are attached so that the casing can easily be opened to check the electronics, remove the micro SD card or to charge the battery. The casing can be put in a pocket on the shirt (Figure 128).

More detail shots of the final prototype can seen on the right (Figure 129) and Appendix M.

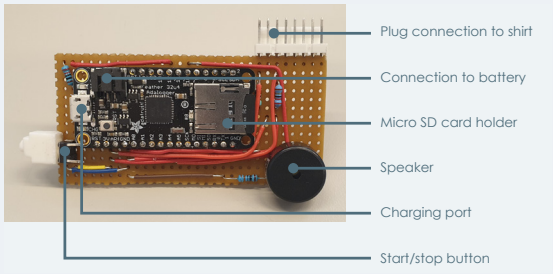


Figure 126. Processing unit.

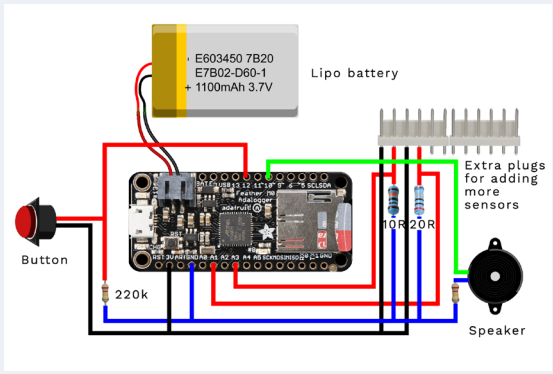


Figure 127. Adding magnets to easily open and close electronics housing.



Figure 128. Plug attaching shirt wiring to electronics.



Figure 129. Electronics housing in pocket attached to shirt.



Chapter 6

Evaluating knitted strain sensors

The goal of this chapter is to evaluate, discuss, reflect and make recommendations based on the final prototype.

Chapter 6.1

Evaluation of the final prototype

This chapter describes the evaluation of the final prototype shirt. The final prototype is compared to previous prototypes and examined literature. An educated guess can be made from these results.

Method

To evaluate the final prototype a video is made that shows and records different predetermined movements to see how both arm and breathing sensors react. A graph is created from both sensor outputs to clearly see which movements cause a certain sensor output. Next to that, unwanted registration of movements is also checked. The predetermined movements are described in Appendix N. Screenshots of the video can be seen in figure 130.

Result

In the beginning part of the analyses video it can be seen that the breathing sensor works as intended. During the raising of the lower arm the shoulders stays in a stable position, which helps with tracking the breathing. The signal of the arm sensor starts to gain more noise as the arm is moved. When moving the arm from a small angle to a more steep angle, the signal from the arm sensor becomes larger and consequently more clear, which makes sense, as the resistance increase is larger.

Here the arm movements are the largest and the peaks that the arm sensor produce are clearly distinguishable. The breathing sensor still continues to produce a clear signal.

When the rotation of the arm from the shoulder starts, a different sensor behaviour can be seen in the breathing sensor graph. When the arm is in the highest position above the body, the breathing sensor gets stretched, creating a peak in the graph. The same happens at 36 seconds, with the clearest peak at 39 seconds. At 39 seconds, exhaling happens, which lowers the resistance in the breathing sensor. Stretching the breathing sensor when moving the arm gives it a more visible peak.

The interesting thing is that the arm sensor also shows a peak, while the elbow stays in the same angle. This might be caused by fabric of the shirt pulling on the arm sensor, causing the resistance to increase a little.

The overall signal of the breathing can still be observed. It has more noise due to the arm interfering with the breathing signal, but most peaks and lows can be interpreted as inhaling and exhaling.

Moving the arm to the right causes the breathing sensor to move up a bit, which can be seen in screenshot at 55 seconds. This causes the breathing sensor to have a clear peak. This also happens when the arm is moved up as can be seen in the screenshot at 1:03.

Again the arm sensor shows an increased

signal when moved up, while the elbow stays in at the same angle. As this happens more than once, it most likely is caused by the stretching of the fabric around the armpit.

Overall, both sensors seem to perform well. Some minor unwanted interactions are detectable in the breathing sensor due to arm movements, but this is logical. Both graph can be found in appendix O.



Figure 130. Analyses of shirt movements with sensor data in graph combined

Literature comparison

What is stated at the beginning of this report is that the sensors must be able to be made with off-the-shelf materials: stainless steel and silver coated yarns. This is done to keep production time and price low.

Similar results were had with stainless steel yarns in the creation of strain sensors. Wang (2019) was also not able to calculate gauge factors from the signals with stainless steel yarns. It seems that silver coated yarn provides the best results when making knitted strain sensors.

This research is a start to future research to improve this technology. As Wang (2019) stated that the next challenge is to develop the power source, signal processing and communication with for example a phone.

With the conductive yarn looking and feeling more and more like normal yarn, a fabric sensor provides a way to integrate electronic functionality in a truly unobtrusive way (McKnight et al., 2018). The silver coated yarn is flexible and feels soft enough to the skin. Integrating the sensor in such a way that is not visible anymore can increase comfort further.

Another challenge is the wear and tear of the sensors. As Seyedin (2019) describes, the sensors must be able to handle 100.000 stretches in its lifetime and still output usable data to be classified as a reliable sensor. In my research this has not been tested because of a lack of time, but is definitely something that needs to be tested in future research.

The proposition for the strain sensors to be used for gait analysis and respiration monitoring was done by Atalay (2015). In this research both gait and respiration are measured with different sensors. Showing results for both large (40%) strain and smaller (10%) strains (Seyedin et al., 2019). Both outputting usable data.

Research on knitted interconnections shows that these could be useful for soft robotics (Pei at al., 2019). Knitting these in a fabric makes them flexible while the interconnect itself is not. The knitted structure gives it its flexibility. This research is only focussed on the interconnections, but shows that knitting is useful technique when creating smart fabrics.

All in all, this development of fabric sensors shows great potential for continuous monitoring of body kinematics and vital signs (Seyedin et al., 2019) for applications in sports and medical monitoring. Even monitoring people in harsh or risky conditions such as firefighters or soldiers could be done in the future (Paradiso et al., 2005).

Washing the sensor

When exercising, the body generates sweat. This can cause electronics to deteriorate and garments to smell, which is unwanted. To keep the sensors clean, a small washing test is done with one of the sensor samples. Outputs of before and after washing are compared.

Method

The sensor with 4 lines of silver conductive yarn is used as washing sample. The sensor is washed two times at 30°C with detergent together with other clothing.

Result

In figure 131 and 132 both sensor outputs can be seen. Comparing both graphs it can also be noticed that the washed sample has a higher overall resistance. The overall resistance is increased with around 100cΩ. This is most likely caused by the washing machine wearing out the silver conductive coating.

In the washed sample, after the sensor is stretched the fabric takes longer to reach their resting resistance. This might be caused by the fabric being more stiff after washing and experiencing more friction when returning to its resting state.

Before the sensor sample is washed, the graph shows more extreme peaks in both 30 and 40 percent strain. These extreme peaks are not visible anymore on the washed sample. Why this happens is not clear, but could be because of increased friction in the fabric, which makes the sensor get more slowly into a resting state.

Overall, the different strains can still be clearly distinguished, which is a positive point. Washing the sensor more times will most likely end up making the sensor perform more poorly, but more research into the effects of washing knitted strain sensor is needed to make a clear statement about this.

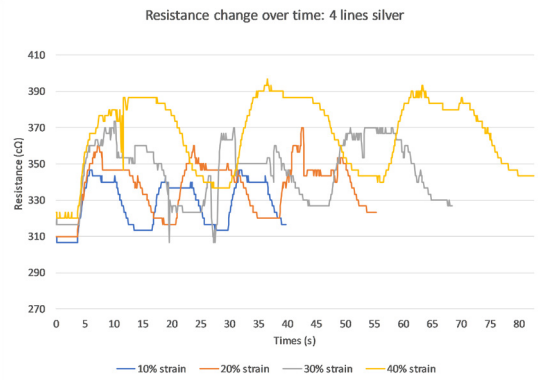


Figure 131. Graph of sensor with 4 lines conductive silver yarn, before washing.

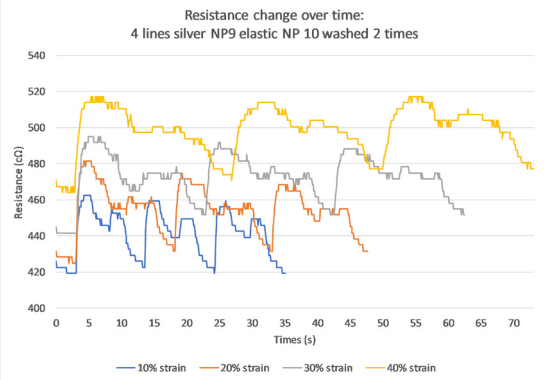


Figure 132. Graph of sensor with 4 lines conductive silver yarn, washed 2 times.

Chapter 6.2

Discussion

In this chapter the results of the project and future research possibilities with their importance and shortcomings will be discussed.

Yarn selection

Two yarn types were tested and it was concluded that silver coated gave the best results. Further experiments with different types of silver coated yarn could have been done, but the focus was on creating a well working knitted strain sensor. When results showed that silver coated worked well, it was a matter of fine tuning the knitting process to improve the sensor.

For this research a silver coated yarn with a resistance of 80 Ω/m was used to create a strain sensor. Atalay (2014) uses a silver coated yarn with a resistance of 200 Ω/m, which is much higher. Ou (2019) even uses a higher resistance conductive yarn; 1000 Ω/m to create conductive pleads. It might be beneficial to use a higher resistance yarn, because this makes the resistance differences from stretched to unstretched also larger, increasing the sensor resolution. For this project the yarn with a resistance of 80 Ω/m worked well enough, but for future research it might be interesting to experiment with higher resistance yarns and see which type works even better.

Knitting

The knitting process was chosen as its unique structural properties provide the possibility to create strain sensors with.

As I was the first student to have worked on the knitting machine, there was a lot knowledge that had to be gained. This was done with a week of knitting lessons. This was very helpful to start off the project, but the possibilities of an industrial knitting machine are so vast that it cannot be learned in a week.

Shirts like X-bionic (X-BIONIC, n.d.), which are fully knitted pressure shirts are great examples of what is possible with an industrial knitting machine. For future projects it would be very beneficial to have a lot more knowledge in house on using this machine. Even people who know a lot about industrial knitting machines, often are not familiar with the even more detailed ways the knitting software can be used (Rudi, 2019).

Sensor samples

In this research, tests are done which are similar to what existing papers have written about. To confirm their results and to see how these experiments would work on the Stoll knitting machine of the Technical University of Delft they are repeated. The available Stoll knitting machine works with settings that are sometimes different from what other papers talk about. Correctly reproducing these was therefore necessary.

After successfully recreating these sensors they are further improved, mainly optimising NP value. These improvements could only be made on the machine that was available.

Because this project direction is still in its infancy for the Technical University of Delft and me having been the first to work with this machine, made it difficult to determine what the possibilities were for this project. The focus for this project was to develop working strain sensors and the working final prototypes show how, for whom and how well these could work.

Measuring setup

The main problem with the tensile tester, was the connection to the conductive parts in the fabric that resulted in a consistent output for every test. To make the tensile tester working properly took more time than first calculated, but was necessary to be finished first to eventually do proper tests with that could be compared to each other.

The connection from conductive fabric to normal wiring inside the clamps was what made it difficult. First some conductive glues were tested (Sample map), but these were unsuccessful. Eventually, this was resolved by using clamps with conductive parts. Although, these clamps were not high grade, they provided consistent and clear results without much noise. For future research this clamping mechanism can be taken as a starting point to be further improved, as it has shown to deliver consistent results.
The measuring was done with a 4-point or Kelvin measuring setup. This worked well and removes all extra resistance created by wiring and connection.

Atalay (2017) uses wheatstone bridge to measure the resistance in the knitted strain sensor. This is also a good option to measure small resistance changes, but is much more difficult to build and calculate. For this research, a 4-point measurement worked well enough to clearly identify the different strains.

Washing

Although washing was only done two times with a sensor sample, it still provided a good result. It showed that there is a clear signal deterioration, but the different strain peaks could still be identified. For future research into yarn selection it might be good to also take washability into account.

Prototype arm sensor

Two sensor types were used to test the arm sensor. A sensor in course and in wale direction. This showed how the different sensors would perform in the same scenario.
Also, the arm sensor was a good showcase to test the full motion range to around 40 percent strain with inconsistent movement patterns.
The sensor in wale direction was sewn onto two separate tubes, while the

sensor in course direction was one fully knitted tube.

- To crumpling of the fabric around the elbow, as there is none
- Crumpling in the course knitted sensor could influence sensor data
- The tubes on the sensor in wale direction could slide after a certain amount of arm movements. This could result in the sensor being too loose in the resting position (arm fully stretched). This was less the case with the sensor in course direction, as this was a full tube instead of two separate ones. In future research this tube shape could be more moulded to fit the shape of the arm more, gaining a more constant pressure on every part of the tube and decrease crumpling.

Prototype breathing sensor

The breathing measuring prototype is a good example of strain around the 10 percent strain range. The consistent movement of the chest expanding and contracting made it a good prototype to measure continuously repeating patterns. This sensor was created using the full width of the Stoll knitting machine. In future research it might be interesting to see what length works well when stretching only to 10 percent strain. Maybe having the sensor already stretched around the body might improve sensor response and decrease influence from arm and chest movements that are not related to breathing.

Final prototype

The final prototype is different from what it was supposed to be, as it was supposed to be fully knitted. The final prototype now is partially knitted and partially sewn. Nonetheless, this prototype was able to be tested. The results can be found in chapter 6.1. Due to the prototype not being fully knitted, the results of the testing the final prototype are most likely different from tests from a fully knitted prototype.

The type of fabric that the shirt has is different from the knitted fabric. It is less stiff, thinner and less stretchy. It fits less tight around the body, making it move more.

If the final prototype was fully knitted, the influence of the arm on the breathing sensor would probably be much higher, because the knitted fabric is a lot stiffer. The wiring sits outside of the shirt with the current final prototype. If the final prototype was fully knitted, the wiring would have been placed in small tubular parts to hide it.

The pocket that holds the housing with all the electronics would have also been more integrated if the final prototype would have been knitted.

If the final prototype would have been fully knitted, the following parts would be different:

- The pocket holding the electronics
- The fitting of the shirt

- The sensor influence from body movements
- The interconnects

Shirt design

The shirt design in this research shows how the placement of the sensors can be combined with the design. By not hiding the sensors but embracing them in the design, they become more of a statement. Although the design of the shirt is looked at, it is done in a very minimal way and should be more expanded in further research.

Together with the colour palette, the shirt design should be worked out further to make a complete package people want to have. Further research should look more into shirt design and see what different target groups would want.

Being the first to have worked with the industrial knitting machine showed that it is not as easy as it looks using it. This became apparent when working on this project, as there were quite some times when the project slowed down due to knowledge gaps or problems. Overall the this research has been a big contribution to the technology development of smart fabrics and the smart material department of the Technical University of Delft.

Chapter 6.3

Conclusion

In the beginning of this paper the following question was set to be answered: How to make smart textiles with a knitting machine? With this paper a starting point has been made to eventually further develop this technology. Although smart clothing is still in its infancy, there is a big opportunity to improve this technology further. A future of smart devices integrated into our everyday clothing could be a way to get rid of all the extras we now carry around with us like smartphones, smartwatches and even things like credit cards. This paper has shown the first steps of a way to track certain bodily features with a sensor that is able to be integrated directly into the fabric during production.

The knitted strain sensor created with off-the-shelf yarns such as lycra and conductive yarn that is discussed in this paper has been shown to track strain from 10 up to 40 percent successfully. The best results were produced with sensors created with six lines of silver coated conductive yarn with the Lycra and silver coated yarn having an NP value of 9 and 10 respectively. It has also been shown that a strain sensor in both course and wale direction can be created, which provides an extra measurement direction in fully knitted garments and could even be combined to measure diagonal strain.

Two example prototypes were produced which could measure the breathing pattern and arm movement of the wearer. Both showed promising results and could measure well in different settings. The breathing measurement device has been tested while sitting still, with walking up and down the stairs and while cycling.

Final showcase models have been created showing the potential of the two applied strain sensors. One shirt for sports that can measure the breathing pattern and show arm movements when for example lifting weights. The other being for revalidation patients that need to train their arm movement and keep track of their exercises. Having a way to measure body performance is also useful for the doctors that guide the revalidation to keep track of their patient, while they are not together.

While this technology is improving and showing promising results, there are still things that need to be further improved and tested, such as consistency over longer periods, the comfort of a knitted sensor garment, what washing will do to the sensors and the shirt, the processing of data to use less power, the portability and wearability. Connecting the garment via bluetooth or wifi to a smartphone to show the gathered data in a clear overview might also be an improvement. Most tracking devices nowadays can connect to a smartphone which can provide more than just a clear overview of data and give the user recommendations on how to further improve.

Chapter 6.4

Recommendations

This chapter provides recommendations for future research and development into knitted sensors and smart garments.

Yarn selection

In this research, two conductive yarn types are tested. The silver coated yarn showed the most promising results. For future research it might be beneficial to test more yarn types. This includes yarns with different resistances, different dtex values and different structures (coated, multi-fibre etc.). This can lead to better signal results and better signal output after wear and tear from wearing or washing.

The base yarn used in this research is a Lycra yarn with a dtex value of 800. Although, this is based on existing research it might still be beneficial to test different Lycra yarn thicknesses.

Knitting

Because this is the first project the Technical University of Delft did with their newly acquired knitting machine, the amount of knowledge is still quite limited. For future research it is highly beneficial to have someone in-house with a lot of knitting knowledge, as working with this machine can be done in extreme detail and can have a steep learning curve for anyone starting work with this machine.

Measuring setup

A tensile tester was modified to accompany the fabric tests that needed to be made. This was done by using food clamps with in conductive part on the inside that could connect with conductive yarn in the knitted sensors. Creating a clamp that can hold multiple sizes of fabrics and has conductive parts on the inside that can be wired and synced with the tensile tester would help tremendously in producing higher quality results. This way signal interference could be lowered, measuring results would always be consistent, multiple measurements could be combined more easily and a more precise resistance sensor could increase sensor resolution.

A modified jaw on the Zwick tensile tester (Atalay et al., 2017) with an added channel for electrical properties could be an option.

Sensor creation

In this report sensors in course and wale direction are researched. An interesting option for future research is the combination of sensor types. Combining course and wale direction sensors into multi-directional sensor. A sensor that can also measure diagonally.

Shirt interaction

A beginning is made with how the wearer could interact with and how data is visualized by the shirt.

To get a better understanding of the user and what method works best for what target group should be further researched with user tests. Visualisation of data might be done with an application for a smartphone, but this also needs to be tested.

Electronics

The electronic board used in the final prototype is a basic Arduino that easily can be made portable through its lipo battery port and micro SD card slot. This chip has a 12 bit analogue input. To total package is quite big to implement in a shirt.

A custom version could be smaller and transfer its data to a smartphone wirelessly. Its battery would be smaller and its power usage would also be a lot lower. Making a custom processing unit would also be the cheaper option if the production rate is higher.

For interconnections, stretchable copper wires are used. When fully knitting a garment the interconnections might best be knitted together with the shirt or be inserted into knitted tubular parts on the shirt.

The connection from the conductive yarn to the processing unit was difficult and time consuming to make. This can also benefit from a faster and more reliable connection to increase conductivity and decrease the amount of noise. Noise is a big problem when measuring the sensors, especially when a more sensitive measuring device is used. Connections need to be attached well, be uninsulated and have little to no resistance.

Data processing

Processing the data the sensor creates is now done by hand on the computer. The best option for this might be the smartphone, as this is something most people have on hand at all times. The data needs to be sent wirelessly via bluetooth or wifi and a app can take care of processing the data and visualizing it into something the user can understand clearly.

Testing

In this research only the technical side of the shirt is tested. Seeing what the sensor outputs and how certain movements trigger certain sensors in unwanted ways. In future research it might be beneficial to produce a fully knitted shirt where this influence can be researched further. Also, due to circumstances the final prototype has only been tested by me, which might give biased results.

Wearability

There are a few things that can be improved when it comes to wearability. Firstly, the sensors are very tight on the body and are hard to put on and off. Pulling the shirt too hard might also damage it, which is unwanted. More research needs to be done into the combination of wearability and sensor output quality.

Secondly, the comfort also decreases due to the sensors being tight around the body. The sensors are sewn onto an existing shirt where the seems are on the inside of the shirt. This also increases discomfort. With a fully knitted shirt, this problem can be solved.

When the shirt is fully knitted, the tightness might even more be a problem for comfort and wearability. A good balance between sensor output quality and how tight the sensors are on the body is therefore crucial.

Washability

Washing has been tested with one sensor only and must be researched further in future projects as this is a very important aspect for garments. People tend to wash their clothes a lot of times and when technology is integrated, washing will lower garments lifetime. Researching ways to make the fabric sensors, interconnections and plugs more durable and washer friendly will help with that.

Chapter 6.5

Reflection

In this chapter a reflection is given on the project as a whole. The reflection exists of three parts. An overall and a personal growth reflection are given.

Project

The main method used for this project is the basic design cycle in a triple diamond setup. This was combined with fast iteration and a lot of prototyping.

In the beginning of the project a lot of knitted samples were created. This helped a lot with learning the knitting machine and the software that operates it. Although the creating the samples really helped and I learned a lot, it took longer than expected. This was maybe due to the fact that I was a bit too fascinated with working with a new machine. My fascination sometimes let the focus of the project drift off a bit.

As I am someone who works the best by making, fast prototyping was really helpful in the project. Making small knitted samples increased my knowledge of knitting and its possibilities and moved the project forward at the same time. This is the part that made project interesting to me, creating, learning and having fun at the same time.

The tensile tester was also something that took more time than I expected. Especially due to the fact that the contact between the conductive part in the sensor and the clamp took a lot of iterating to get right. A lot of ideas were tested, but most of them failed or gave inconsistent results. The sensors could only be tested when the tensile tester worked correctly, so this had to be finished first. In the end, I am very pleased with the solution I came up with to get good electrical contact with the knitted sensor every measurement and get consistent results.

When it was time to move to creating actual sensors, it went a little slower. Creating a working sensor was difficult and trying to replicate work from literature was something that I switched maybe a bit too late to. In the end I created working sensors, improved those and integrated them into a final garment, which I am very pleased with.

The last phase of the project a second teaching lesson for the knitting machine was planned. Unfortunately due to Covid-19, this was cancelled. This made me change my plan for the final prototype from fully trying to knit it, to sewing it onto an existing shirt. This is something I was a bit upset about, but there was nothing that could be done about it. The final prototype still turned out good I think.

Due to Covid-19, I also could not do user testing, which was unfortunate. I think if I would be able to have done it I would have found more things that could be improved than I have already described in the recommendations chapter.

Personal

At the start of the project I focussed too much on working with the machine and making samples, than I was on the project itself. I focussed too much on getting more information on how to make certain patterns and use all kinds of yarns. Even though, I learned a lot, not all information was used in the end. This could have been better if I would have defined more beforehand what was needed.
It was the first project I have done that incorporated working with fabrics and knitting. I would have never thought beforehand that I would do such a project, but I found it really fun to do and I learned a lot. The end result is also not something I would have expected to have done, as it was quite technical and not something I had done before.

Something else I had difficulties with is doing a project on your own. Having to plan, decide and do everything yourself is sometimes really difficult. I prefer working in a team, that way you have some sparring partners, you can discuss important decisions etc. Also doing a more research focussed project is something I had not done before. Having the freedom to do tests and work in a lab was really eye opening.

Another interesting part of this project is that it did not include a company. This gave a lot more freedom as company usually steers you in a certain direction, which is not always the direction you want to go to.

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When I first started studying in Delft, I started with mechanical engineering. I had a visiting day with a student from Industrial design before studying, but the project was cancelled and the lecture was boring. So I started mechanical design, when quickly knowing this was too technical for me. So I switched to Industrial Design Engineering. The best choice I have made in my life. The perfect place to combine technology with design and solve complex problems.

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