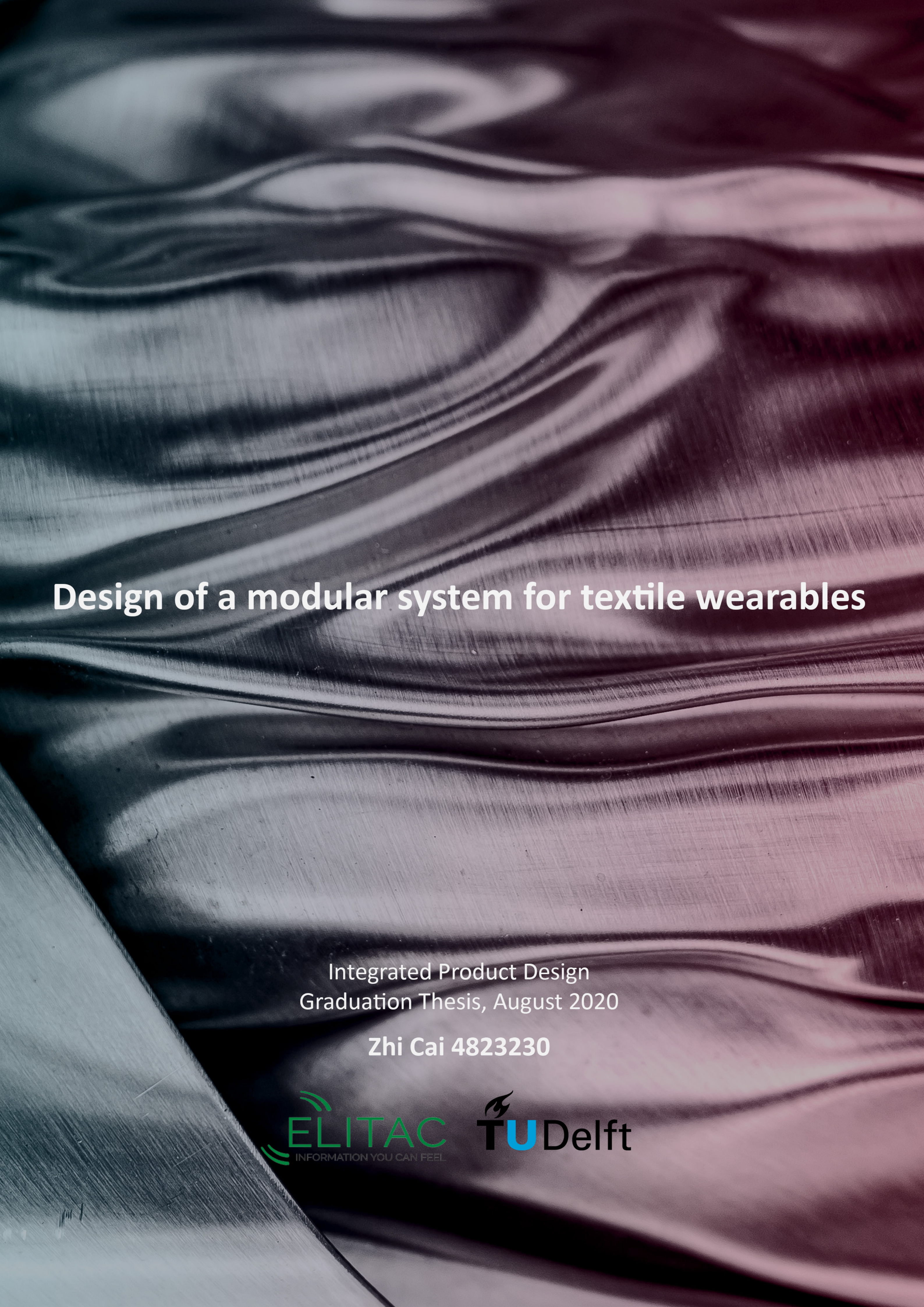

Design of a modular system for textile wearables

Integrated Product Design
Graduation Thesis, August 2020

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ELITAC — INFORMATION YOU CAN FEEL
TU Delft

Parties involved

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Summary

The thesis clarifies the graduation project for the master program of Integrated Product Design at the Delft University of Technology. It describes an interconnection method to connect electronics onto the smart textiles that differs from any solutions existing in the market. Smart textiles are considered as the future of the clothes and are predicted to have a large potential market. However, there is no standard interconnection technique that is applicable to the wide variety of smart systems. Problems on the wearability, reliability, size, comfort and cost severely limit the development of smart textile. Thus related products are still in a preliminary stage.

In this thesis, it is first explored the previous work in the field of smart textiles. User research and using context analysis helps to form the design requirements. A thorough exploration of the existing interconnection techniques and wirings help to form the first ideas to start. Then it is made into several rounds of ideations. Design decisions are made based on the design goal and the list of requirements. Practical tests are set up to evaluate and compare the different concepts as well. Finally, the work of detailing, user experience design, aesthetics, manufacturing is also carefully considered and elaborated for the chosen concept.

The result of this study is a product with a highly-finished level. Elitac, the corporate company, should be able to start manufacturing after the electronics are finished. From the academic aspect, this new interconnection solution gives a promising direction for the development of smart textiles. It solves the most difficult part of this field, which is the integration of electronics into the textiles. In general, the result of this thesis should be helpful to the researchers, designers and companies in this field.

My thanks

So many people helped me along with the project. Without their supports, I can never achieve today's result. I would like to say thanks to:

Kaspar Jansen: for giving me the chance to do the project, thinking and nice recommendation along the design process, kind support during the project.

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Guus De Goog: for letting me quickly adapt to the company work, introducing me to the colleague, very practical and useful recommendation from a designers point of view. I am very appreciated for your patience, kindness and encouragement.

All my colleagues in Elitac: thanks so much for your help during each step of my graduation project.

Linda Plaude: My special thanks for Linda. Thank you for sharing so much knowledge of the textiles and helping me make an excellent finished shirt. I could not expect someone else to help me so much and spare that much effort on me besides my supervision team.

All my friends who participated in my user tests and interviews.

All the staff in Tu Delft who helped me along with the project.

My dear girlfriend Yinyin: For always supporting and inspiring me.

Content

Introduction

Backgrounds

Smart textiles, which are intelligent textile structures or fabrics that can sense and react to environmental stimuli(Tao, 2015), have a very promising realm in science and technology nowadays because of commercial viability and public interests(Koncar, 2016). The market of “Internet of Things” is predicted to contain 30 billion devices connected in 2020, and 10% of those things will be the clothes(Koncar, 2019). It means in 2020, there will be 3 billion clothes that will use some aspects of smart textiles such as sensors, or actuators together with emitters, receivers, and units of computation(Koncar, 2019). Then the potential market will be even greater than forecasted.

Unfortunately, most conventional sensing and actuating systems are not compatible with textile production progress(Koncar, 2019). The systems implemented in most of the existing smart textiles available in the market have many limitations regarding the size, production methods and compatibility. There is generally no conventional solution that is suitable for the common sensing and actuating system, which results in a high price and low durability. As the companies have to design the system specifically for one product, it is also not economically efficient. Coming up with an interconnection solution that could be compatible with both textiles production processes and the common sensing and actuating system will be a new task for the designers and engineers.

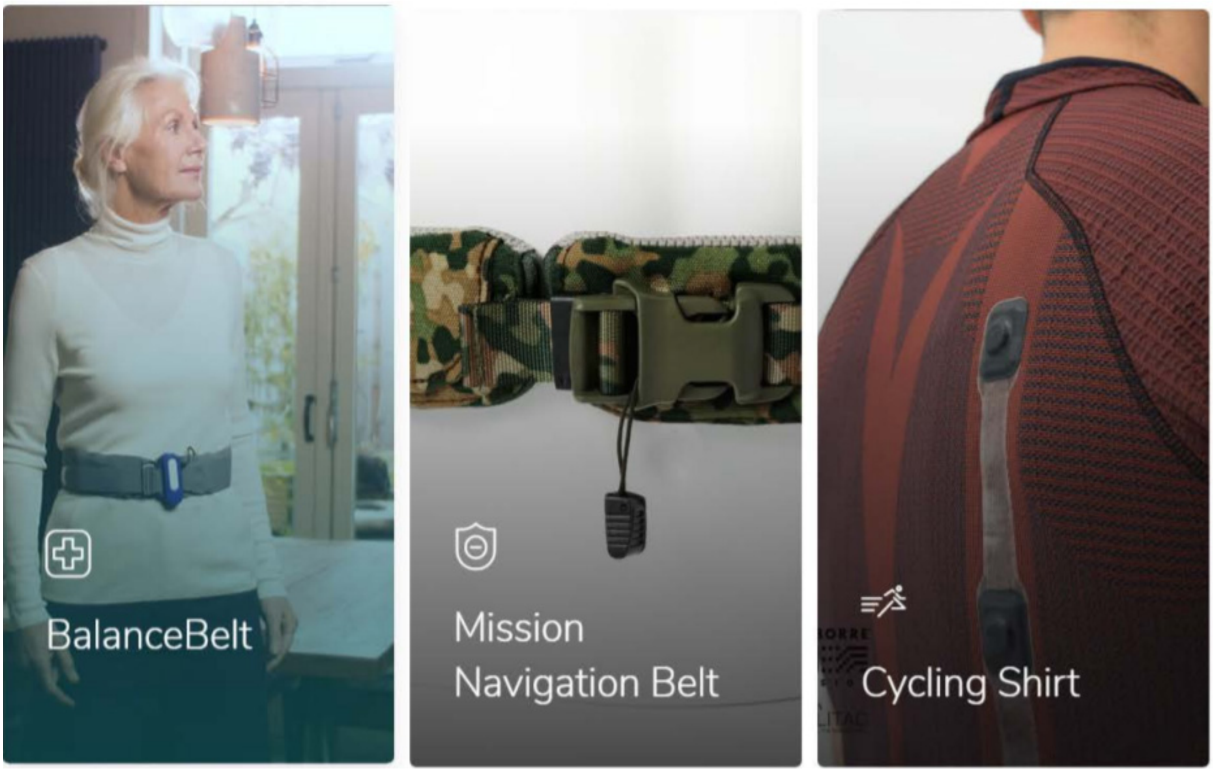


Figure 1: Current products of Elitac

Company

In this project, it has cooperated with Elitac Wearables, a Dutch company specialised in flexible electronics integration. Elitac is currently focusing on integrating haptic technology into textiles. These smart textiles will end up as wearable products for professionals and consumers in the health, safety and sports fields. Examples of their current products(Figure 1) are: "Balance Belt", the belt gives haptic feedback to help patients control their body; "Mission navigation Belt", using haptic navigation to free soldiers' hands; "Cycling shirt", using haptic feedback to do navigation and give the recommendation to adjust the cycling speed.

Assignment

The assignment is to improve the current interconnection system of "Elitac cycling shirt". The cycling shirt, as explained previously, gives feedbackon heart rate for interval training purposes and navigation via seven tactile motors. These tactile motors, together with their respective haptic drivers, are placed in a horizontal and a vertical trace on top of the shirt(-Figure 2). The whole system is using I2c protocol for data transfer.

The interconnection system means the technique of connecting the electronics on to the textiles in this project. The current solution is using the flexible PCB technology as the wiring (multi-layers PU with the thin copper conductor in between, chapter 1.4.6 shows more information), while soldering the printed circular board(PCB) with tactile sensors on. Afterwards, the epoxy housing seals all the electronics on top of the wiring(Figure 3).

However, this design is not perfect. The flexible PCB wirings and all the electrical components are mounted on the shirt, so they go into the washing machine together with the shirt when being washed. This causes several problems:

1. Compared to the thin PU film, the epoxy housing can be considered "more rigid". This results in a tension concentration area, which easily breaks the inner copper conductor when being washed, as the whole shirt structure will suffer the high and overall stretching and twisting.
2. The waterproof is also a problem. The PU film hardly bonds to most other materials(including the epoxy used for housing), which leads a failure for protecting the inner circuit.

Except for the two severe difficulties mentioned above, the high cost and the aesthetic feel of the PU wiring are also the unignorable limitations. Till now, this kind of structure seems to reach its limit and is not able to achieve a consumer product level. Thus Elitac decides to develop a new technique to connect electronics into smart textiles. A modular design could be the core of the project.

The project requirement published by Elitac is designing a modular interconnection system enabling part of the electronic system to be removed. Meanwhile, the fixed parts can resist at least 30 times washing cycles for cleaning. However, there is something more that needs to be considered.

Figure 2: Layout of the electronics

Problem definition

Thinking from a whole picture, the ambition of Elitac for the smart cycling shirt is obviously to the market end. Unlike the research-based project, coming up with a reliable, with good user experience and low-cost mass-production modular design has a meaningful influence on the company's strategy. Apparently, it is necessary to keep the fabric-like characteristics of the modular system while improving the drawbacks of the current solution. So here is defined four design levels:

Level1: The modular solution should be washable, durable enough for cycling exercise, and be able to drive the electrical system of the Elitac cycling shirt.

Level2: The modular solution could be possible to be implemented in other systems or products in the field of smart textiles.

Level3: The modular solution should be aesthetically fitting to the style of the cycling shirt, regarding the size and feel. It should also have a good user experience considering the comforts while wearing and the simplicity while detaching or attaching some parts of the system(if needed).

Level4: The modular solution should be applicable for the mass-production process, and possible to gain profit for Elitac(low-cost solution).

Figure 3: Moulding on the strechable PCB

The least requirement for this project is achieving level 1, according to the assignment published by Elitac. It is also expected to go as far as possible. After the discussion with the supervision team, a design goal is formed as follows:

Design of a reliable and washable technique to connect actuator nodes with control unit and power on the surface of a smart garment with 20% stretchability

Chapter 1
Analysis

In this chapter, results of user research, market research and technical research are presented. An interview is made with an experienced cyclist for a good understanding of the working environment of this design project. The market research introduces the development level of the current products. The technical research consists of a thorough comparison of the existing interconnection techniques and the interconnection wirings. These research outcomes help to form the design list of requirements and generate a starting point for the design ideation.

1.1 Using context analysis

This system is built for supporting the professional cyclists for a long and safe cycling exercise. The user study is important for forming the design requirements. The cycling environment and using context description also poses challenges for the design. To get this knowledge, it is made a consultation with Martin, the Head of Operation in Elitac, who is also an experienced cyclist.

An user model of cyclists in the Netherlands is built based on the consultation:

Age: from 18 to 80
Gender: Most are male
Education: High
Job: White-collar
Level: Professional cyclists
Cycling speed: 25km/h
Time duration of each cycling: around 2 hours

User journey map

As one of the outcome of the interview, the user journey map is formed. It helps to find design opportunities and pose design challenges.

Preparation	*1. Make sure you have eaten enough food to have enough energy for cycling training.* *2. Check the battery of the bike computer.* *3. Check the tyre.* *4. Tend to cycle in a new route every time.*
Warm-up	*The warm-up is also cycling, but with the bigger gears. The phase will last for around 20 minutes.*
Training	*1. During the common training, it is trained in a way of circle: 6 minutes fast riding and 4 minutes of slow riding. This slow riding is for resting. Normally there are 6 circles during one time training.* *2. He drinks water on the bike. He never stops drinking water. The water bottle is just placed on the bike.* *3. There is sometimes an accidental fall. The reason could be the oil, thus the road is slippery. The sudden break of the chain could also lead to a fall.*
Finishing	*1. He will use Strava, an online social media for the cyclists, to upload the training data. This website can also generate the cycling route for the user, and it can be connected to the bike computer.* *2. He will clean the mud out off the bike because he does not want to cycle with a strange noise caused by friction.* *3. He will wash the cycling shirt.*

Using and environment context

The following list summarizes the key findings of the possible working environment for the smart system. The important facts of cyclists habits are also mentioned here:

1. In the Netherlands, there is always a cycling track built for cycling, which has a flat and good road condition. However, there could be some difficulties: slippery, muddy and tree branches on the road.

2. The unexpected and sudden rain is quite common in the Netherlands, which could also come together with strong winds. The wind could blow up the dust as well. The cyclists will not do cycling when there is extreme weather like hail, snow and thunderstorm.

3. There is a chance that the cyclists will fall when accidents happen, e.g. the chain broke, slippery road or unexpected obstacles on the cycling track.

4. The shirt will become sweaty during cycling.

5. Normally the cyclists will not ride when it is dark.

6. Cyclists like to have steady cycling speed within a certain time duration(average 25 km/h), they do not want to stop in the middle of the cycling exercise.

7. Most of the cyclists are high-educated people.

8. Cyclists have a bike computer and water bottles on the bike. In their back pocket of the cycling shirt, they have some other stuff: e.g. mobile phone, multitool, CO2 pump. The cyclists only use the pocket stuff when it is really necessary, and they expect to never use them during cycling.

9. Cyclists like to ride in the countryside because there are fewer people and traffic. So they will not have to stop during cycling.

10. Though the cyclists have club activities, they prefer to cycle alone for training. Because they can ride at their own speed.

11. Most of the cyclists are men. For racing training, women are even less.

12. The cyclists would like to finish the preparation phase quickly. (According to Martin, the set up of the system should be finished in 2 minutes)

1.2 Market research

Market research section shows some representative smart textile products existing in the market, the respective pros and cons are analyzed(Table 1). Based on the current developing status in this field, a trend analysis is done to have a vision for design direction for this project.

1.2.1 State of the art

There are many smart textile products available in the market. However, the main interconnection techniques used in these products do not vary that much. Here is selected the products using the most representative interconnection techniques:

Wearic

Wearic is a company that focuses on modularizing the smart system. They use the quick snapping connection(Figure 4) for making the do-it-yourself electronic kits.

The smart jacket developed by Google(Figure 5)

This is a highly integrated system by using the woven-in Jacquard conductive yarn. A small snap tag connecting the Jacquard yarns is holding tiny electronics. The snap tag on the inner cuff lets a user know about incoming information, such as a phone call, by flashing a light on the tag and by using haptic feedback to make it vibrate. As there are no cables outside, this jacket has an ordinary jacket looking.

Athos shirt(Figure 6)

It is using the garment sensor and an external processing module for analysing and transferring data with a snap connection.

Hexoskin

The Hexoskin training shirt(Figure 7) includes the internal sensor, a cable and an external device with bluetooth and data-recording unit.

Sensoria Fitness Socks(Figure 8)

The external chip contains the processor. The sensors are already woven in the socks. It can monitor health and sports-related data.

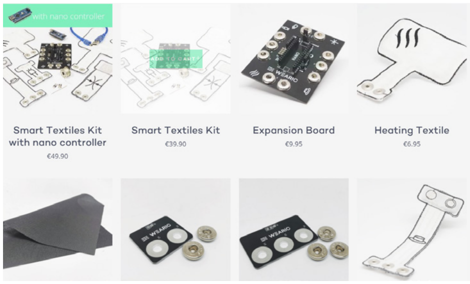


Figure 4: Wearic products

Figure 5: Smart jacket

Figure 6: Athos shirt

Figure 7: Hexoskin shirt

Figure 8: Sensoria Socks

Table 1: Smart textile products in the market

Product	Pros	Cons
Wearic	1. Quick attachment and detachment 2. Snap button is commonly used in the field of textile, thus it is easier to make the interconnection fit the style of clothes.	1. The size of the electronics will be too big especially when multiple snap buttons are needed.
The smart jacket developed by Levis and Google	1. The system is highly integrated into textiles and reliable. The electronics are well hidden in the cloth. 2. The jacket does not need complex operation by users.	1. This technique makes the system really expensive. 2. The proposed connection system is less compatible with other smart textile products and smart systems, which means designers have to redesign the connection when dealing with a different product. 3. The core of this product, Jacquard yarn, is not commercially available.
Athos shirt	1. The sensors are well integrated into the textiles. 2. The snap interconnection is quick and easy for the user.	1. The external module is too large. 2. For now, the actuators are not integrating into textiles. All the actuators in this product are in the centre module, and they can not be integrated into the textile as the way of sensors.
Hexoskin	1. The sensors are well integrated into the textiles.	1. The external module is too large and does not match the shirt. 2. It is still using the standard cable that is less fitting in the aesthetic style of the shirt. 3. For now, the actuators are not integrating into textiles. All the actuators in this product are in the centre module, and they can not be integrated into the textile as the way of sensors.
Sensoria Fitness Socks	1. The sensors are well integrated into the textiles. 2. The snap connection is quick and easy for the user.	1. For now, the actuators are not integrating into textiles. All the actuators in this product are in the centre module, and they can not be integrated into the textile as the way of sensors.

1.2.2 Conclusion

Taking a look in the outside world, there are many products and prototypes in the field of smart textile. For the products already in the market, the function of their smart system still has a lot of limitations. The tension sensor can be already well integrated into the textile, while a lot of actuators can not with the same technique. This directly leads to the functional limitation of smart textile products. There are some research projects shown in Chapter 1.3.2 as well, most of them focus on the development of the interconnection techniques while having less consideration on the comfort, aesthetics and wearability. That makes the field of smart textile still in the preliminary phase.

Thus, there seems to be no overall solution for the different smart systems. Because smart textile is the mixed product of multiple disciplines, its special nature makes it necessary to break through traditional manufacturing processes and balance all the attributes that both cloth and the smart system should have. Research in these fields will provide a guarantee for the commercialization of smart textiles and enable it to adapt to the mass market.

1.2.3 Trends analysis

Trend analysis is an important tool for the ideation of new products. Analysing and comparing the existing solutions will give designers insight on what the future would be, as a guideline for the new products generation. The following guidelines are the result of market research:

More diversified application and using scenario -- Applicity and producibility

It could be seen from the current products that the function of the most existing smart textiles are similar: monitoring health-related data. Compared to the field of electronic hardware, the development of smart textile is obviously at a very early stage. It is not hard to imagine that smart textiles will play a more important role in the field of sports and healthcare management, leisure and education(Innovation in Textiles, 2016.). However, the interconnection and mass-production difficulties severely restrict the variety and complexity of the smart system in the textile. For designers, how to make the interconnection technique be applicable to a range of different systems will be an inevitable task for the future of smart textiles.

Miniaturization and comfort -- Size, flexibility

To be more compatible with the textiles, the trend of the smart textile circuit and components is to become smaller, more flexible and stretchable. It can be seen that there are more and more miniaturized and flexible batteries, sensors, chips, screens used in the smart textile field. In the ideal situation, users may not even feel the electronics and technologies in the cloth, while this raises an enormous challenge for the designers and engineers.

Aesthetics

The smart textile also has aesthetic attributes as the "non-smart" clothes. All the integrated electronics should have the least influence and limitations on the production of these textiles.

1.3 Interconnection techniques

As noted by a smart person, all the problems in the world seem to occur at the boundary between one entity and another. While this analogy might be slightly overkilling, it does catch people's attention on one of the most common problems in electro-mechanical design and the field of smart textiles: the interconnections.

Interconnection is a physical connection between two electronic devices, allowing the electricity to flow. In the field of smart textiles, electronic devices always refer to the electronic components in the smart systems, such as conductive wires/yarns, sensors and actuators, power supply and microcontrollers. To be implemented into wearable textiles, an easy, strong and reliable interconnection is a basic requirement. To get inspiration for the possible techniques suitable for implementation into textiles, some of the existing electronic interconnection methods are listed.

1.3.1 Standard interconnection techniques

1.3.1.1 Wire to wire connection --Clamping type interconnection

Crimping

Crimping is the method of joining two or more pieces of ductile material by deforming one or both of them to hold the other(Wikipedia, n.a.). For electronics, the stripped wire is inserted through the correctly sized opening of the connector, and a crimper is used to squeeze the opening against the wire tightly. The connector can be a soft deformable tube or a metal bus, see Figure 9. The auto-crimping machine is available in the market, which significantly saves labour. The crimping technique also works for some types of conductive yarn. In general, this is a reliable and robust interconnection technique that is also popular among the electrical field.

Figure 9: Crimping

Alligator Clip

The alligator clip(Figure 10) is a sprung metal clip with long, serrated jaws which is used for creating a temporary electrical connection(Wikipedia, 2020). The clip itself is conductive, so it only just needs to clip the wire that needs to be connected. It is often used in the lab for rapid testing and prototyping, while the connection itself is not reliable.

Figure 10: Alligator clip

Solder Sleeve/ Shrink sleeve

Solder/shrink sleeve(Figure 11) is a heat shrink material that, by shrinking down to the diameter of the cable, creates a primary environmental barrier. It is a robust, simple and effective connection method but does need an experienced worker.

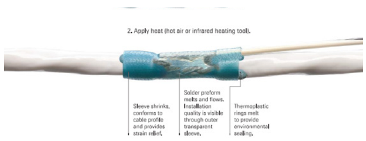


Figure 11: Shrink sleeve

Twist-on wire connector -- Electrical caps (Figure 12)

Twist-on wire connectors are a type of electrical connector used to fasten two or more low-voltage (or extra-low-voltage) electrical conductors(Wikipedia, 2020). When such a connector is twisted onto the stripped ends of wires, the wires are drawn into the connector's metal insert and squeezed together inside it. This connector has many different sizes available.

Figure 12: Electrical caps

1.3.1.2 Wire to wire connection--Soldering/Welding/Gluing

Soldering

Soldering(Figure 13) is using a fusible metal alloy to create a permanent bond between metal workpieces, while the tin alloy is the most commonly used for the electronics. Soldering iron or soldering stations are often used to melt the tin. There are only a few metals that can be soldered, e.g. copper, while stainless steel is not solderable. Soldering is the most traditional way to make connections for electronics, while the soldering bond is not flexible and is vulnerable, therefore needs protection.

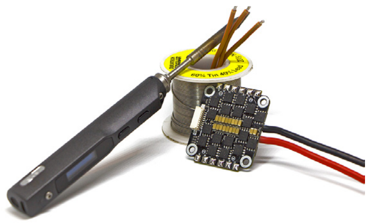


Figure 13: Soldering

Microspot-welding

Welding(Figure 14) is a connecting process that uses high temperature to melt the metal and join the materials. The difference from soldering is the temperature is much higher and welding melts the connected material, while soldering only melts the tin.

Figure 14: Microspot-welding

Glue

Glue is also an option. One is the non-conductive glue, such as the hot glue gun(Figure 15). The two exposed wires are twisted, the non-conductive glue could be used as a protective coating and fixing the wire. Another option is using conductive glue. Then the wire does not have to be twisted and connected carefully.

Figure 15: Hot glue gun connection

Ultrasonic Welding

The ultrasonic welding process(Figure 16) is to overlap two metal parts and rub them against each other using low pressure and high-frequency mechanical oscillation. Within several seconds, a permanent, solid and pure connection is created.

This technique is suitable for all non-ferrous metals, while copper, aluminium and their respective alloys are particularly well-suited.The method of Ultrasonic welding is the strongest and most reliable. However, it is also the most expensive, requiring the use of incredibly expensive machines.

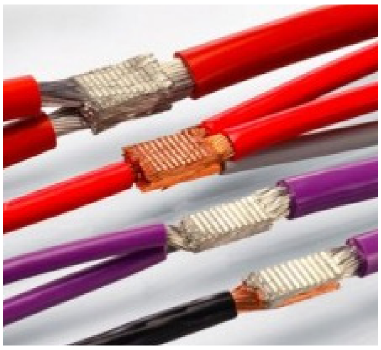


Figure 16: Ultrasonic welding

Insulation tape connection

Insulation tape(Figure 17) is used for wrapping around two exposed and twisted wires. It is adhesive and insulated. It can be made of many plastics, but vinyl is most popular, as it stretches well and gives effective and long-lasting insulation.

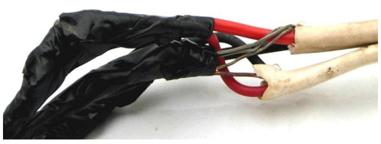


Figure 17: Insulation tape

1.3.1.3 Wire to board connection--Soldering/Welding/Gluing

Soldering

Having explained the principle in the wire-to-wire connection, soldering can also be used in the interconnection on printed circuit boards (PCB). Micro-electronics industry already has a variety of mass production soldering methods developed:

Through-hole technology (THT)

Through-hole technology(Figure 18) refers to the mounting scheme used for electronic components that involve the use of leads on the components that are inserted into holes drilled in PCB and soldered to pads on the opposite side either by the manual assembly or by the use of automated insertion mount machines. It offers strong mechanical strength and it is one of the most common techniques used in printed circuit boards assembly (PCBA) production. Wave soldering is the most popular mass production technique used in THT.

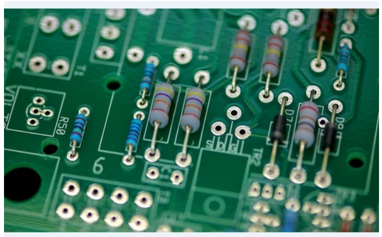


Figure 18: PCB made by through-hole technology

Surface mount technology(SMT)

Surface-mount technology (SMT) is a method in which the electrical components are mounted directly onto the surface of a PCB(Figure 19). Compared to THT, the SMT component is usually smaller because it has either smaller leads or no leads at all. Reflow soldering is the most commonly used mass production method for SMT.

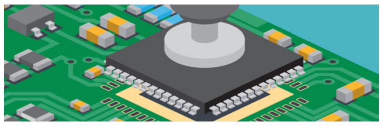


Figure 19: Illustration of Surface mount technology

Wire bonding

Wire bonding(Figure 20) is to make interconnections between an electrical circuit and microchips by using gold or aluminium wires(TWI, 2019). The connection is vulnerable and especially suitable for microcircuit interconnection. In the semiconductor industry, wire bonding speeds can reach 600-700 bonds per minute(James, 1998).

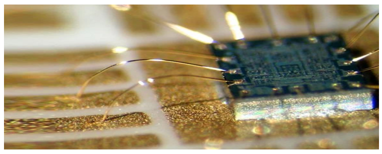


Figure 20: Wire bonding

Conductive epoxy(Figure 21)

Conductive epoxy(Figure 21) is just one of the many types of epoxy adhesives or glue available. The most common conductive adhesives are silver-filled thermosetting epoxies(ASI, n.a.).

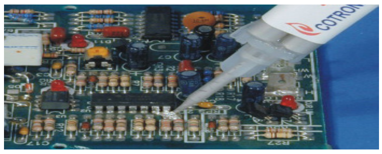


Figure 21: Conductive epoxy

1.3.1.4 Wire to board connection--Snaping/Wrapping/Jumper wire

Snaping

The direct contact is also a possible way of connecting electronics. There are various interconnection snaps(Figure 22) available in the market, both standard and specialized.

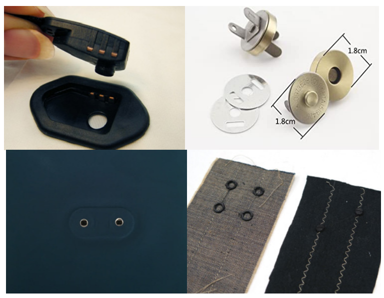


Figure 22: Various snapping interconnections

Wire wrapping

This connection is made by wrapping several turns of uninsulated wire sections around a component lead or a socket pin, as shown in Figure 23. Wire wrap construction can produce assemblies which are more reliable than printed circuits(Wikipedia, 2018).

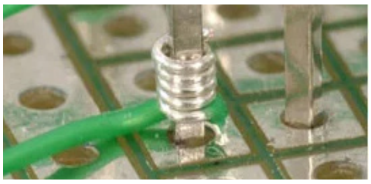


Figure 23: Wire wrapping

Jumper wires

Jumper wires(Figure 24) are quite commonly used for the quick prototypes in the electronic fields. One example is the Arduino, a well known open-source microcontroller. The jumper wires are using the crimping techniques to make quick interconnection at the terminals of the wires.

Figure 24: Jumper wires

1.3.1.5 Wire to board connection--Embroidering/Lamination

Embroidering

Embroidering conductive yarn through specially prepared conductive holes in a PCB is a unique technique for the yarn-based smart textile circuit (Figure 25). While this connection is vulnerable because of the friction with the PCB edge. This process happens in an embroidery machine.

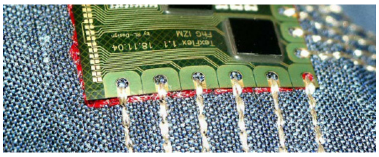


Figure 25: Embroider conductive yarns

Anisotropic conductive film(ACF) tape

The anisotropic conductive film(Figure 26) is a tape, or called Z tape, that makes mechanical and electrical connections in a vertical direction. There are millions of tiny conductive particles built in this tape. It is not conductive when the tiny conductive particles are not contacting each other. When being placed under pressure and heated, the conductive particles become squeezed to each other, which makes it anisotropic conductive. This technique is especially useful for making a row connection.

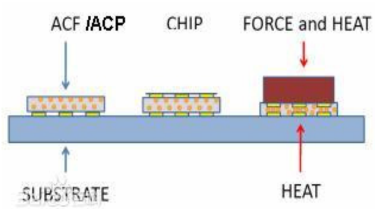


Figure 26: Illustration of the ACF tape

lamination

Lamination(Figure 27) is the technique/process of manufacturing a material in multiple layers so that the composite material achieves improved strength, stability, sound insulation, appearance, or other properties from the use of the differing materials. A laminate is a permanently assembled object created using heat, pressure, welding, or glueing. Lamination is the key technique for producing the flexible PCB(the one with horseshoe copper traces and PU cover), which will be explained in the Chapter 2.2.1.

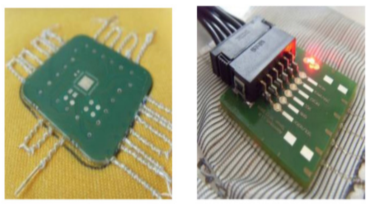


Figure 27: Lamination for the smart textile interconnection

1.3.1.6 Miniaturizednelectronic connectors

Miniaturized electronic connectors are highly specialized connection methods between wires or wires and PCB boards. There are thousands of different connectors available in the market. Some even have a locking mechanism which enables quick attachment and detachment. After a preliminary research, some possible electrical connectors for the implementation in the smart textiles are selected considering the size, connection strength, quick detachability and suitability to the I2c protocol. They can either be directly used in the project or as an inspiration.

Crimping type connector

JFA connector(Crimping type)(Figure 28)

This kind of connector is suitable for both wire-to-board and wire-to-wire connection and can be used on a wide range of applications. It has two springs in its structure and a locking system. Here is one example from the JFA connector family.

Figure 28: JFA connector

ACHF connector(Figure 29)

This is a disconnectable connector with 1.2mm pitch. The height is 1.43mm.

Figure 29: ACHF connector

IDC Type connectors

An insulation-displacement contact (IDC) is an electrical connector designed to be connected to the conductor(s) of an insulated cable by a connection process which forces a selectively sharpened bladethrough the insulation, bypassing the need to strip the conductors of insulation before connecting(Wikipedia, 2020). Figure 30 shows the standard ribbon cable connector.

Figure 30: Ribbon cable connector

XFR connector(Figure 31)

Mentioned by the company, this is one of the smallest IDC connectors in the world. It needs 1.45mm high and 3.00mm deep space on the PCB for a strong connection. It is specially designed for wearables and medical applications. It has a strain relief system.

Figure 31: XFR connector

FFC/FPC connector(Figure 32)

FFC(Flexible flat cable) refers to the category of the ribbon cable that is both flat and flexible. FPC(Flexible printed circuit) is the flexible PCB(Figure 33). There are a variety of terminations for FPC, divided into three types: connector, finger and pin(Figure 34).

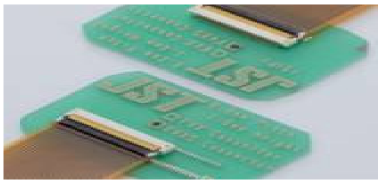


Figure 32: FFC/FPC connector

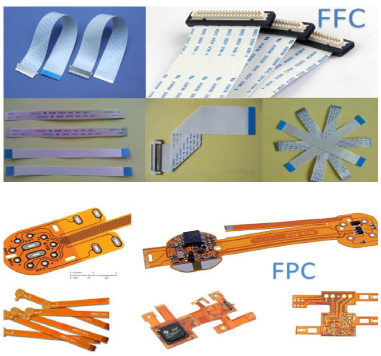


Figure 33: FFC and FPC

Pogo pin connector

Typical pogo pin connector

A pogo pin connector(Figure 35) is a standard connector that one side is flat and the other side has a spring mechanism to make proper contact.

Pogo pin magnetic connector(Figure 36)

It is the pogo pin connector with a specially designed magnetic structure. This magnetic structure enables quick connecting and prevents accidental contact failure. It can only be taken off by a few directions. It can also be customized.

Figure 35: 4-pins pogo pin

Figure 36: Various customized magnetic pogo pin

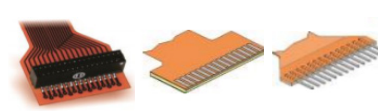


Figure 34: From left to right: Vertical or horizontal mounting to fit your designs, supported fingers, endpins.

1.3.2 Interconnection techniques in the research phase

Double-sided conductive textile

Here is a research project by Akihito Noda and Hiroyuki Shinoda(2019). They propose to use a two-side and isolated in between conductive mesh(Figure 37). The conductive yarns are electrically connected on the one side and insulated from the conductive mesh on the other side(Figure 38). The electronics will connect to both sides of the conductive mesh respectively to have a close circuit. In principle, Inter-Integrated Circuit (I 2 C) data can be transferred along with the dc power supply based on frequency division multiplexing. Thus I2C communication applies to any two-conductor transmission with the help of a specially designed filter(Figure 39). Chapter 2.2.3 gives more information on this technique.

The biggest advantage is that this mesh system can be widely used among different smart textile products and can be applied for different sensing and actuating systems. However, the current prototype still have some drawbacks: The 3 layers' mesh is too thick compared to the common cloth; the PCB needs an extra module, which enlarges the size of this system; the shown example is not waterproof.

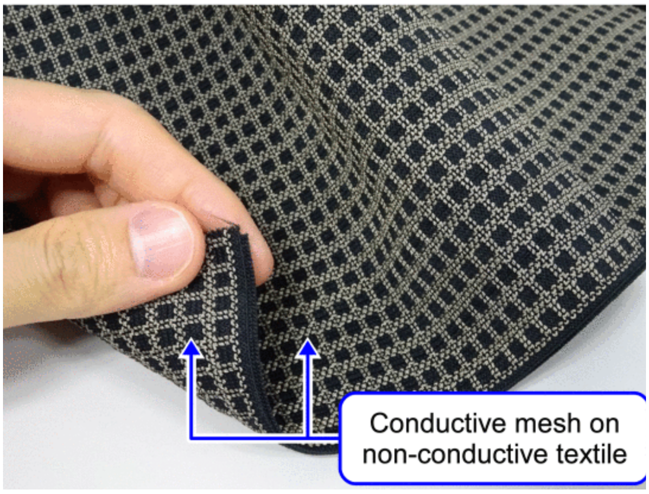


Figure 37: Example of double-sided conductive mesh

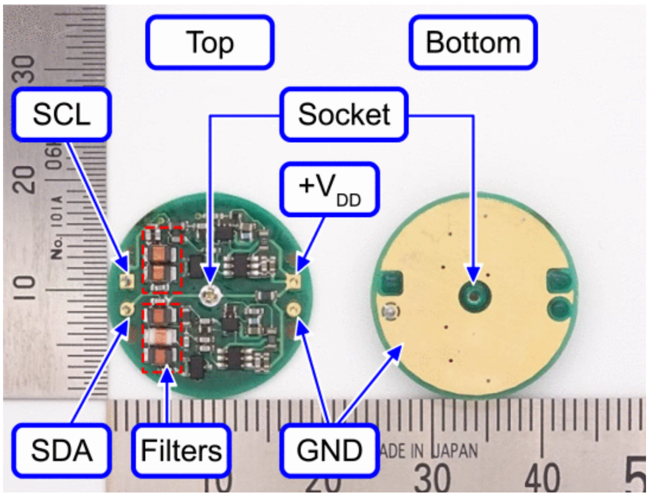


Figure 39: Fabricated modem module PCB

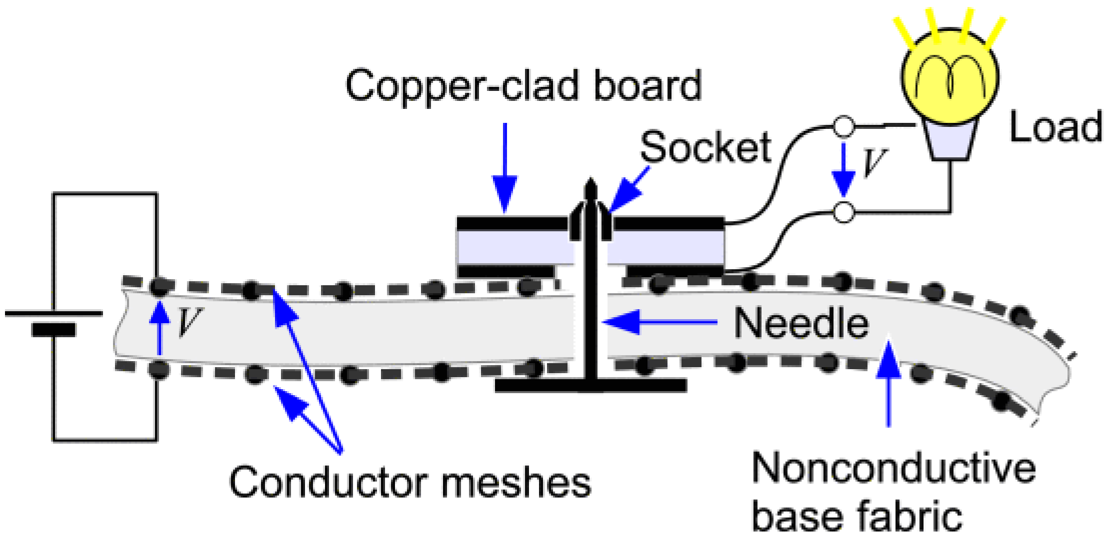


Figure 38: Cross-sectional view of a wearable signal/power transfer sheet and a tack connector

Diabolo chips

The “Diabolo” process(Figure 40) aims at a direct connection from a chip assembly to external wires without using the traditional bonding/packaging stage(Brun, et al., 2009). Through a very limited set of wafer-scale operations, chip dies can be assembled and connected to conductive wires directly from the chip surface.

Diabolo chips are already widely used in the integration of the Radio-frequency identification(RFID) system. Compared to other interconnection techniques, advantages can be seen on the well integration into textiles and the do not need traditional bonding and packaging processes. However, this technique is more suitable for a tiny chip connection, while less compatible with a more complex electronic system with bigger electronic components.

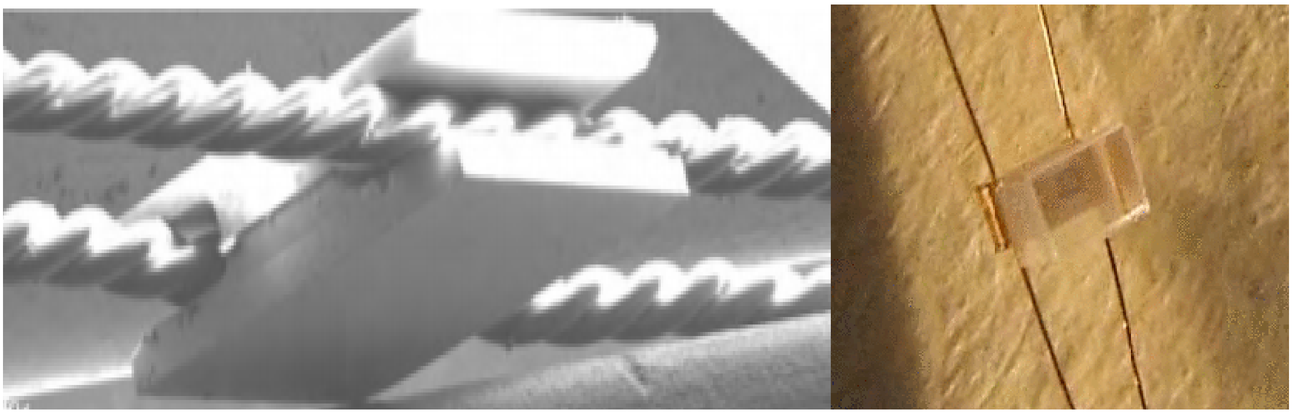


Figure 40: Diabolo assembly

Skin display

This is a prototype developed by Dai Nippon Printing (DNP), shown in Figure 41. The screen-printed stretchable silver wiring is mounted onto a rubber sheet. This skin display is only 1mm thick, it can be stretched to 45% of its original size.

The advantages are the well integration with textiles and the thin assembly. However, the micro electronics are not always available. With larger components, it is hard to seal the assembly on top of the electronics to make it waterproof.

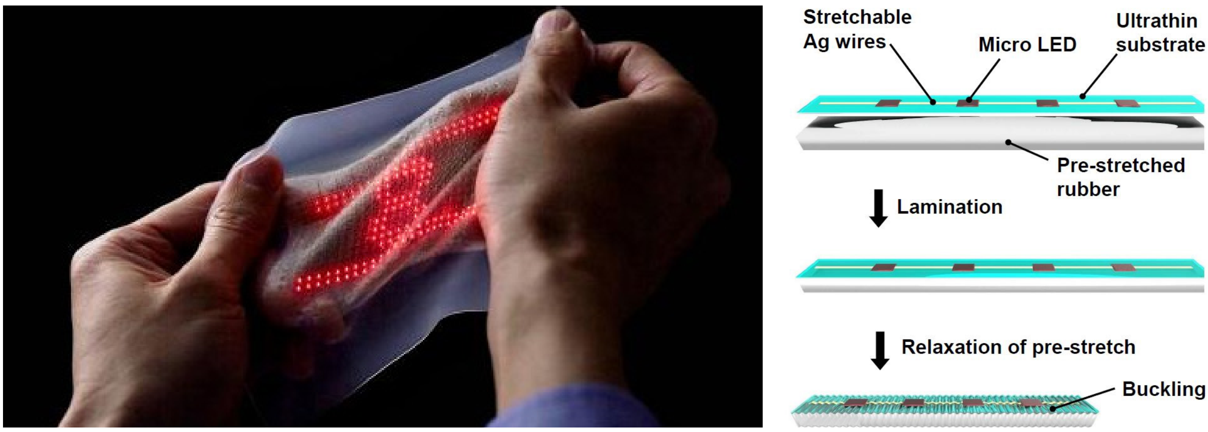


Figure 41: Skin display

Polyurethane mechanical connector for EMG sensor.

It laminates the non conductive film on the textile ribbon cable to make an adhesive connection and direct contact with the conductors, as shown in Figure 42. For details, look at chapter 2.2.1.

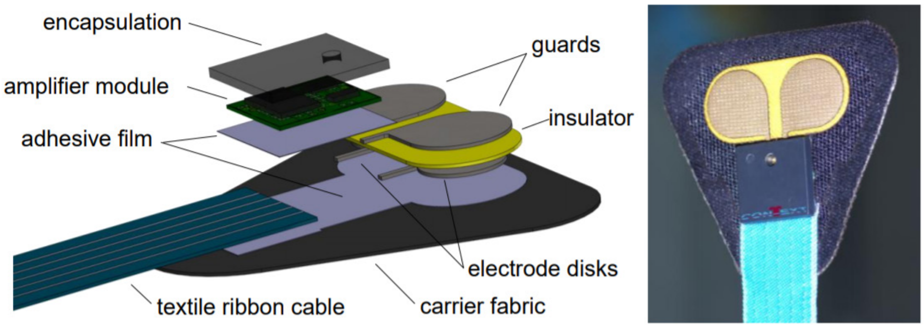


Figure 42: Polyurethane mechanical connector

1.3.3 Analysis

Considering the selection of proper connection techniques, it is important to distinguish their characteristics. To have an overview, it is listed and classified in the Table 2 by "temporary connection", "semi-permanent connection", "permanent connection".

"Temporary connection" means the connection is only designed for a short time using, only used in the lab. Long-time using may result in connection failure. "Semi-permanent connection" refers to the detachable connection. They can provide a reliable and lasting connection while also being able to be detached and re-assembled while not destroying the interconnection structure. "Permanent connection" is not detachable.

Table 2: Classification of interconnection techniques

Temporary connection	Alligator grip, jumper wire, insulation tape
Semi-permanent connection	Crimp type connector, crimping, snaps, pogo pin connector, electrical caps, wire wrapping, double-sided conductive textile
Permanent connection	Soldering, micro spot welding, glue, shrink sleeve, insulation tape, ultrasonic welding, embroidering, wire bonding, conductive epoxy, anisotropic film, lamination, skin display, diabolo chips, polyurethane mechanical connector

In general, the temporary connection is not suitable for this project. The semi-permanent connection seems to be the most promising interconnection category for the modular system. However, the system could consist of multiple interconnection techniques. A good example is the pogo pin, which needs first to be soldered to the cable or circuit board. It is necessary to use the semi-permanent connection as a starting point of ideation while using other possible techniques for completing the connection system.

Regarding the simplicity of assembling the interconnection, strength, size and compatibility to the fabrics, nearly all the techniques under "semi-permanent connection" worth exploration except for the electrical caps, as it is mainly suitable for wire-to-wire connection. There are also some should be looked into under the category "permanent connection" for some distinctive characteristic:

Soldering(the primary and widely used technique)
Embroidering(especially suitable for the conductive yarns)
Anisotropic film(having the potential to replace soldering)
Polyurethane mechanical connector(has been proven to be a reliable connection for smart textile)

1.4 Interconnection wiring

There are uncounted interconnection wiring choices for the smart textiles. Having an overview with clear classification of these wirings will help choose the most suitable ones as a starting point of generating ideas.

1.4.1 Conductive yarn

Textiles, as one of the essential parts of composite clothes, always begin with yarns. Of course, a specialized yarn could also play an inneglectable role in the development of smart textiles. To integrate electronic circuits into the clothes, scientists and designers have developed hundreds of conductive yarns, which use conductive material to enable electricity to pass through. They have a relatively large difference regarding different aspects of mechanical properties and electrical performance. According to their structure, nearly all the yarns in the market could be classified as follows:

Multifilament core yarns with metal coating(Figure 43)

One example could be given as Detx 117. Its resistivity is between 10-500 ohm/cm, breaking strength 1-8N, and elongation 25% to 40%(Ivan Poupyrev et al., 2016). This yarn has great flexibility, which enables it to be woven. However, the resistivity is a bit higher. Statex, a German company that is focusing on developing these metal coating yarns, the minimum resistance they can achieve is around 30 ohm/m. What is more, the resistivity is not consistent along the yarn, and it also changes during wearing and tearing(Ivan Poupyrev et al., 2016). This instability could make it less reliable for data transfer and power supply for some actuators in the wearables. The solderability is also questionable.

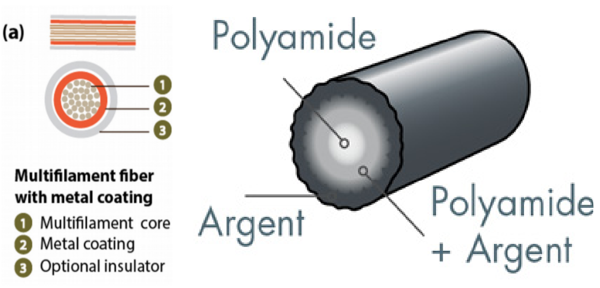


Figure 43: Multifilament core yarns with metal coating

Multifilament metal fibre yarns(Figure 44)

This kind of yarn can use copper, silver or stainless steel for the multifilament material. One typical yarn developed by Elektrisola is using copper filaments and covered by silver to prevent corrosion. It has high conductivity(around 0.09 ohm/m) and excellent mechanical strength. However, this metal filament makes it not so easy to sew. To solve this problem, the stainless steel yarn developed by Bekaert has an extra layer for lubricating. It is worth trying the compatibility with the sewing machine with this yarn.

Figure 44: Multifilament metal fibre yarns

Multifilament yarn with wrapped metal fibre

This yarn has a non-conductive multifilament core and a conductor twisted around it(Figure 45). The conductivity could be high, depending on the conductor material. This yarn is also very flexible because of the core material. The drawback is, compared to other yarn types, the conductor in this yarn could be easily broken during the manufacturing or under tearing. (Ivan Poupyrev et al., 2016)

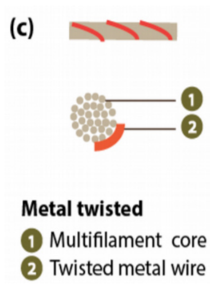


Figure 45: Multifilament yarn with wrapped metal fibre

Metalcore with braided yarn

The example is the Jacquard yarn(Figure 46) developed by Google(Ivan Poupyrev et al., 2016). This structure is using a core which is made of thin metal wire and twisted with silk. The core is then overbraided to protect the vulnerable metalcore. It is highly conductive, of good compatibility with fabrics, solderable and specially designed for mass-production. However, it is not commercially available now.

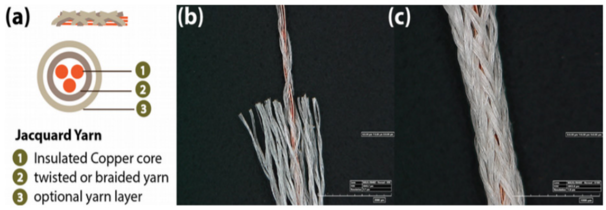


Figure 46: Jacquard yarn

Metal fibre

Conductive metal fibre is usually made of stainless steel or copper, which could be seen in FIgure 47. It could be considered as a thicker metal filament and usually made of between one to three strands. The copper fibre can be highly conductive, insulated and flexible. It is not stretchable and is hard to be implemented into textiles, because of the low compatibility to the fabric production process. The sewing machine can not be used for these fibres.

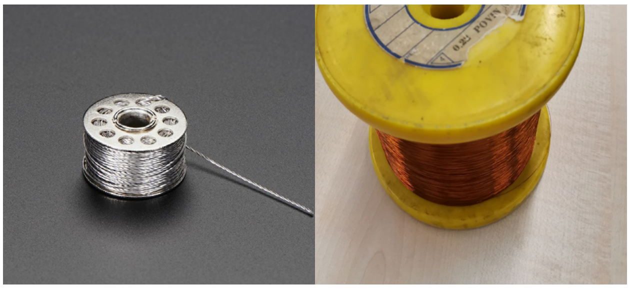


Figure 47: Stainless steel fibre and copper fibre

1.4.2 Standard cable

Single cable(Figure 48)

As a typical category of conductive wiring, these single wirings with insulation cover are the most commonly used in the electrical field. The conductor is usually copper, but there are also silver wires for even higher conductivity. The cross-section of these wiring can be various, as well as the insulation material. By enlarging the cross-section area, lower resistance and higher maximum current can be achieved. The insulation material can affect the mechanical strength and the maximum allowable voltage. It gives these classical wiring the possibility to be used for the smart textiles conductor. The cable using silicon rubber as the insulation material only has the cross-section of 1.2 mm. It is flexible, stretchable, robust and highly conductive.

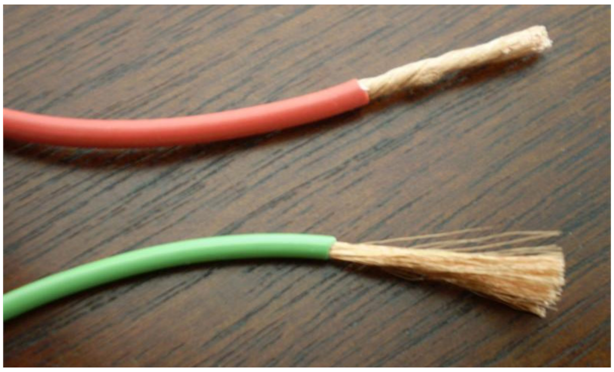


Figure 48: Single cable

Ribbon cable

A ribbon cable(Figure 49) is a cable with many conducting wires running parallel to each other on the same flat plane. There are standard ribbon cable connectors available in the market, which is simple to make a connection. However, the typical ribbon cable is not stretchable. The aesthetic feeling and its structure are not compatible with textiles

Figure 49: Ribbon cable

1.4.3 Conductive fabrics/sheets

Metal plated fabrics

This is a category of various fabrics coated by metal(Figure 50). The typical coating metal is silver, so it is not necessary to discuss all the interconnection wiring in this category respectively. The coated fabrics could be various depending on the requirements: velcro, knitted textiles and woven textiles. The conductive fabrics can be laser cut into different shapes, and stripes as well. The conductivity of metal plated fabrics is not as good as the metal yarns. It usually varies from dozens ohm/m to several thousand ohms/m. One example can be seen in Figure 51, the 99% silver-plated conductive fabric developed by Statex. It can be used for an application like flexible circuit line board, sensor technology, resistance heating and because of the lightweight and flexible, textile structure for RF(radio frequency) shielded enclosures, I/O panels, antimicrobial purposes, thermal applications and IR(infrared) reductions. (Statex, 2020)

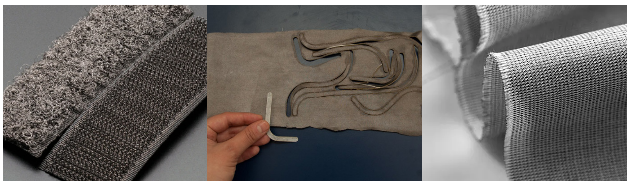


Figure 50: Various conductive fabrics

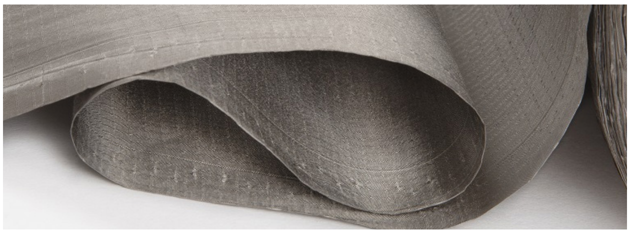


Figure 51: Shieldex®Nora

Metal sheets

A thin metal film can also be an option. Figure 52 shows an example of the thin copper sheet. It is flexible and highly conductive. However, it can hardly be stretched and can be broken when being folded.

Figure 52: Copper sheet

1.4.4 Textile ribbon cable

Apart from conductive yarns, designers and researchers also come up solutions with more integrated cables with textile feelings. Most of them have multiple conductive cores, whose conductive materials are usually copper or silver. They are then covered by a fabric coating or knitted into a type of textile.

Textile ribbon cable

Here is the product developed by Adafriut shown in Figure 53. It uses silver-plated nylon as the conductive core, then covered by Polyester woven. Pure textile material makes it highly flexible. However, this woven structure makes it hardly stretchable, which could be challenging to be implemented into elastic clothes like the cycling shirt or training clothes. Besides, silver-plated technology also has a limitation of conductivity. For most silver-plated conductive yarns or cables in the market, the resistance is higher than 10 ohms/m. The following example developed by Adafruit reaches 52.4 ohms/m.

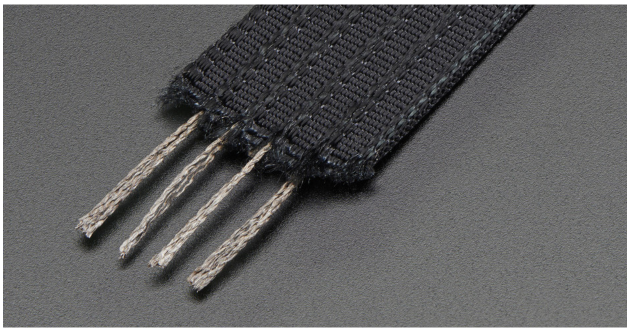


Figure 53: Adafruit cable

Textile ribbon cable with copper core

The majority of the textile ribbon cable in the market is still using the copper core. Here are listed some most representative products. Cables shown in Figure 54 the most typical structure: the twisted copper fibre covered by the textile coating. The mechanical properties are similar to the silver-plated nylon textile ribbon cable, while the conductivity is much higher. Since the conductor is copper, the resistance is lower than 1 ohm/m. However, the stretchability is quite low, as they are using the woven structure.

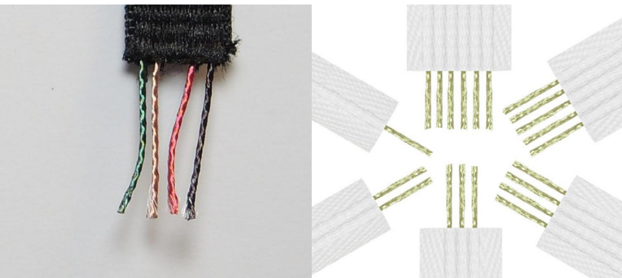


Figure 54: Textile ribbon cable with metal core conductor

The cable developed by LiTex(Figure 55) solved this problem. They use curved wire sewing on an elastic band, which gives the textile ribbon cable extra stretchability.

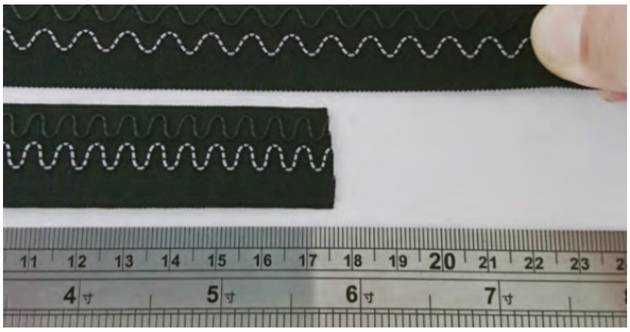


Figure 55: LiTex ribbon cable

Similar to the LiTex cable, Amohr integrated the copper-cotton yarn into fabric(Figure 56). It uses a knitting technique to ensure the stretchability and flexibility. It also has high conductivity and looks more compatible with textiles than other textile ribbon cables.

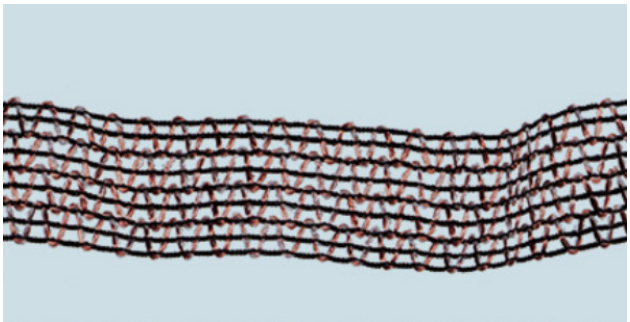


Figure 56: Amohr cable

1.4.5 Conductive prints

Apart from conductive yarns, designers and researchers also come up solutions with more integrated cables with textile feelings. Most of them have multiple conductive cores, whose conductive materials are usually copper or silver. They are then covered by a fabric coating or knitted into a type of textile.

Conductive ink

Conductive ink(Figure 57) is an ink that results in a printed object which conducts electricity. It is typically composed of silver, carbon nanotubes(not as conductive as silver particles) or other conductive particles embedded in a binder material linking to each other by solving agents. After drying, the solvents evaporate. For the inks based on silver particles, a conductivity of approximately 10 -5 ohm.m can be obtained (compared to 1.7 × 10 -8 ohm.m for the copper sheet(School science, n.a.)). For the 1mm wide and 0.1mm thick conductive printed trace, the resistance may be at least as high as 100 ohm/m for the silver conductive ink. An example shown below is called Babinks TC-C4001 silver ink. The ink can be screen printed on a stretchable substrate which allows mass production. In principle, any patterns are possible when fulfil the required resolution. However, the resistance may change significantly during stretching or bending.

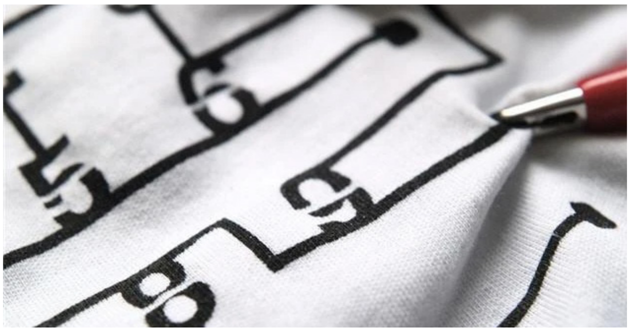


Figure 57: Conductive ink

3d printed conductive graphene filament

3d printed conductive graphene(Figure 58) is similar to conductive ink. It consists of conductive graphene particles into the typical PLA 3d printing material. The finished printing looks like standard 3d printing PLA while having conductivity. For a 1.75mm printed trace, the resistance is around 4,000 ohms/m.

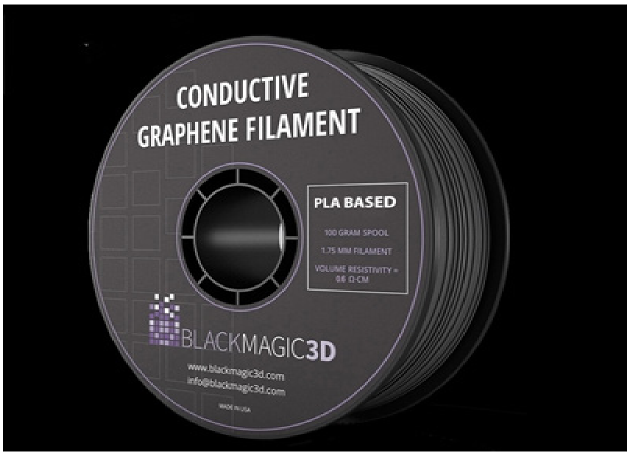


Figure 58: Conductive graphene

Conductive silicone rubber

By mixing conductive particles, silicone rubber can also be conductive. A company called Wacker has developed the conductive silicone rubber called ELASTOSIL® LR 3162 A/B(Figure 59). It has two two-component compounds. Like typical prototyping silicone rubber, it just needs to mix the two compounds and then it forms a soft solid silicone rubber. This silicone rubber material has great flexibility and stretchability.

Figure 59: Conductive silicone rubber

1.4.6 Flexible PCB circuit

Flexible circuit technology is a technology for assembling electronic circuits by mounting electronic devices on flexible plastic substrates, such as polyimide, PEEK or transparent conductive polyester film(Wikipedia, 2020). Figure 60 is one example of the flexible printed circular board using Kapton (thin polyimide film) as the substrates. One significant advantage is that it is compatible with the standard microelectronic bonding techniques, thus it can be mass-produced. It is flexible, bendable, while not stretchable.

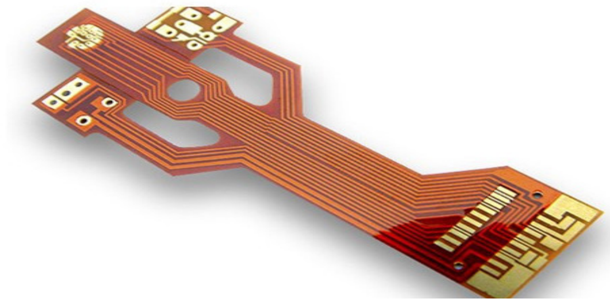


Figure 60: Flexible PCB

Besides, there is a new category of PCB technique called stretchable PCB(Figure 61 and 62). It uses two layers of soft and stretchable film as substrates, for example, polyurethane film to mount screen-printed copper traces and the electronic components in between. The copper traces are usually in a horseshoe shape to allow stretchability. All of these PCB techniques have excellent conductivity, and these flexible and stretchable characteristics make it a promising future for the field of smart textile. This is also the wiring used in the current design of “Elitac cycling shirt”.

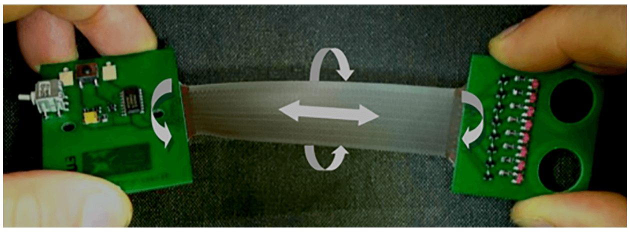


Figure 61: Stretchable PCB

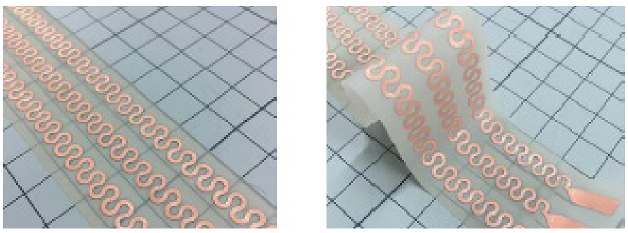


Figure 62: Details of the stretchable PCB

1.4.7 Criteria

Having a proper interconnection wiring could be the base and the first step of designing the modular electrical system. All of these techniques could be suitable for being the wiring for this project. Due to the time limit and efficiency, it is not decided to do the prototyping one by one using these techniques. Alternatively, defining specific criteria and having an overview of the pros and cons of these techniques will be helpful to have the first-round selection. As a careful consideration, there are four main criteria listed as the consideration of the "nature" of these techniques which designers have less affection for.

Here are the four criteria for selecting the wiring:

1. **Interconnection techniques**
2. **Cost**
3. **Electrical properties**
4. **Mechanical properties.**

Interconnection techniques

Interconnection is a half-subjective category. It contains the possible interconnection techniques, the reliability of these interconnections and the simplicity of making these interconnections. Some connections will be more robust while some are not that reliable. To simplify the decision matrix, it is decided to not give the score on reliability and simplicity respectively, but give an overall score to have a quick and general feeling.

Cost

The cost is concerned by the manufacturer. In this matrix, it will be indicated by the number of "€" marks to have a feeling of cost. In general, € means this wiring costs less than 1 euro per meter, and €€€ means the manufacturer may need hundreds of euros on the wiring of the end products.

Electrical properties

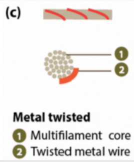
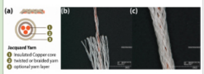
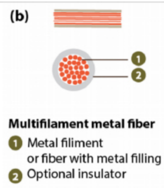
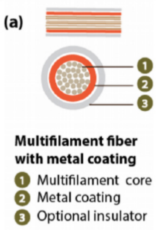
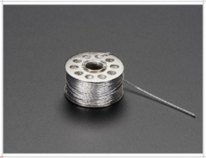
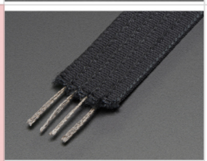
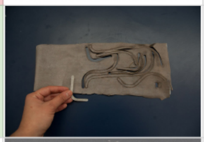
Electrical properties normally have a lot of parameters, such as resistance, maximum current and temperature coefficient of resistance. However, it is decided to only focus on the resistance for this project, as it is way more important than others. The unit will be ohm/m for the yarns and cable while ohm.m for the conductive prints. Based on the calculation of the resistance of power traces, the wiring resistance should be lower than 4.46 ohm/m. The calculation can be seen in Appendix A.

Mechanical properties

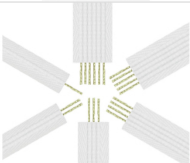
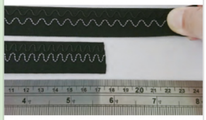
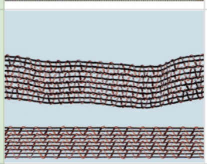
Tensile strength, elongation and density are the main three values to describe a conductive yarn or thread, while this information is not always available. To have a quick feeling of the compatibility of fabrics, flexibility and stretchability are also used in this matrix. Besides, the melting point is introduced here to have a feeling of solderability. Life span is also an important term to describe how vulnerable this wiring is. For some of the mechanical properties, "low", "medium", "high" are used to describe these terms to keep the matrix intuitive and straightforward.

1.4.8 Analysis

Not all terms are used to make a decision. Some exact terms are to give some extra information, which could be convenient to search during the later design phase. In general, the simplicity and reliability of the interconnection techniques, cost, resistance, stretchability, flexibility and the lifespan under the mechanical properties column are used to make a decision. The green colour is marked to indicate that one wiring solution has better performance in one aspect compared to other wiring candidates. The red marking is to the contrary. White colour means the performance is medium.

			Conductive material	Connection			Cost
				Possible connection techniques	Reliabilities of the connection techniques (1~5)	Simplicity of the connection techniques	cost
Conductive yarns	metal threads wrapped around a non-conductive core fiber		copper	solder, glue, embroider, crimping, welding, clip, shrink sleeve, contact & pressure, lamination	3	3	€€
	metal core covered by non-conducting yarns (not commercial available)		copper	solder, glue, embroider, crimping, welding, clip, shrink sleeve, contact & pressure, lamination	3	3	€€
	fibers made from intrinscially conductive materials Elektisola Cu/Ag20		copper	solder, glue, embroider, (crimping), welding, clip, shrink sleeve, contact & pressure, lamination	3	3	€€
	non-conductive core with metal coating Shieldex® 235/36 dtex 6 ply HC		silver plated	glue, crimping, embroider, (solder), clip, shrink sleeve, contact & pressure, lamination	2	2	€€
	Stainless fiber		stainless steel	glue, embroider clip, welding, shrink sleeve, contact & pressure	3	2	€
Conductive fabrics/ sheets	silver-plated wire with coating		silver plate	connector, solder, glue, clip, contact & pressure	3	3	$5.25/ yard €€
	conductive fabric stripes silver plated nylon		silver plate	(solder), glue, clip contact & pressure	3	3	€€
	conductive velcro		silver plate	(solder), glue, clip velcro sticking, contact & pressure	3	4	$6.95 for 3" long €€
	pure copper POLYESTER TAFFETA FABRIC		copper(35%)	solder, glue, clip, contact & pressure	3	4	€

Electrical properties				Mechanical properties						
Resistance per unit length	Volume resistance	Solutions to fullfil the requirements of less than 4.46 ohm/m	Whether the resistance is less than 4.46 ohm/m	Tensile strength	Percentage of elongation at the breakpoint	Strethability	Flexibility	Linea density /Density	Melting point ℃	Lifespan
Ranging from 5 Ω/m to several several kΩ/m This one: less than 12 ohm/m		multiple strands	possible	/	/	could be strethable	high	/	/	short
Not clear, it should be really low				/	/	could be strethable	high	/	/	medium
ranging, lowest: 0.087ohm/m when diameter is 0.5m 2.17ohm/m when diameter is 0.1m		thicker wire or multiple strands	yes	260N/mm2	22.50%	could be strethable	high	/	/	medium
30 ± 10 ohm/m		More threads together	possible	5200 m/kg	27% ± 6	could be strethable	high	/	223°C (based on polyamide)	short
3 Ω/m		Use threads with larger cross-section area, or use copper	Yes	215 MPa(Yield)	70 %	not strechable	medium	0.481kg/m	1400-1450 ° C	long
52.4 Ω / m		Not possible	no	unknown	unknown	Not strechable	high	3.99g/yd	260°C(nylon based)	lomg
various minimum is less than 1 Ohm per sq		With proper aspect ratio: wider fabric	Yes	82.7 MPa (based on Nylon 101)	50 % (Based on Nylon 101)	depends on shape	high	1.15 g/cm3 (Nylon101 based)	260 °C(Nylon 101 based)	short
Hook: 1.8 Ohm per sq, Loop: 1.4 Ohm per sq, 0.8 Ohm through mated closure		With proper aspect ratio: wider fabric	possible	various	various	Not strechable	low	0.15 oz/in²		5000 openings/closings medium
0.05 Ohm/sq		wider strips	possible	unknown	unknown	Not strechable	high	unknown	150°C, up to 200°C short term	medium

Conductive prints	conductive ink: Babinks TC-C4001 silver ink		silver ink	glue, clip, contact & pressure	3	4	around €29.95/ 50ml €€
	3d printed conductive graphene filament(PLA based)		conductive graphene	glue, mechanical gripping,	3	4	**€100/ 100g €€**
	Conductive silicon ELASTOSIL® LR 3162 A/B			glue, contact & pressure	**3**	**3**	**€€**
Textile ribbon cable	WEEL Technology data wire		the copper core	connector, solder, glue, crimping contact & pressure	5	4	€
	4 strand conductive ribbon – OHM-R-7-4L-1		the copper core	connector, solder, glue, crimping contact & pressure	5	4	**€** €100/ 10m
	Elastic conductive tape (LiTex, 24AWG)		the copper core	connector, solder, glue, crimping contact & pressure	**5**	**4**	**€**
	AMOTAPES®Conduct		the copper core	connector, solder, glue, crimping contact & pressure	**5**	**3**	**€€**
Flexible PCB technology			copper	solder, glue, (connector), contact & pressure	**4**	**2**	**€€€**

	3.81 E-07 ohmm	use flat and smooth substrate: for example, Kapton, to decrease the resistance	Yes	/	/	could be strethable	Depends on the substrate	/	120°C	Short
4 kOhm/m for a 1.75mm filament	0.006 ohmm	Not possible	No	37 MPa(PLA based)	6%(PLA based)	Not strechable	Depends on the substrate	1.3 g/cm3 (PLA based)	50°C	Medium
	0.11 Ohmm, too high	Not possible	No	5.3 N/mm²	340 %	medium	Medium	1.12 g/cm³	200-450°C	Long
0.15 ohm /m		Fulfilled	Fulfilled	/	/	Not strechable (by weaving)	medium	/	295°C(polyester based)	Long
0.4 Ω / m		Fulfilled	Fulfilled	490 N	Around 10%	Not strechable (by weaving)	High	/	295°C(polyester based)	Long
0.089Ω / m		Fulfilled	Fulfilled	Around 25Mpa	Various from 70% to 140%	High	High	/	between 190 and 220°C (TPU)	Long
0.5 Ω / m		Fulfilled	Fulfilled	/	around 70%	High	High	/		medium
	1.72 E-08 (Copper based)	Fulfilled		/	at least 30%(just PU, also depends on the structure of copper trace)	medium	High	copper traces plus PU	240°C(PU)	Long

For decision making, conductivity is the most important criteria. If one wiring can not fulfil the required resistance by any chance, the whole system simply becomes a failure. That is why the conductive fabrics and the conductive particles are first filtered out. One thing worth to point out is that, for some of the conductive yarns, there are methods to sew several traces for one circuit to reduce the resistance, which makes it possible to reach the required conductivity.

The stretchability, flexibility and connection techniques are the second priority. If one wiring has remarkable performance on all of these aspects, that will be undoubtedly perfect. Compared to the solid requirement like resistance, these properties have more "design space", which means some values can be promoted by design. For example, it could use an extra housing to relieve the strain and improve the connection reliability; the stretchability can be promoted by having a horseshoe design on an elastic substrate for the conductive yarns.

The rest criteria are also important for detailed design and marketing. While for the current design phase, they are the least priority.

Result:
As a result, the category of the conductive yarn and conductive fabric has a neutral scoring. These yarns somehow could be working, while there are still some apparent limitations: The metal multifilaments yarn and metal fibres can be difficult for sewing or knitting; the conductivity of the silver-plated yarns is possible to fulfil the requirements, but needs extra design work; Jacquard yarns are not commercially available now.

The category "insulated cable" has a neutral scoring. They have good conductivity and are compatible with the standard interconnection techniques, but they are less suitable to be integrated into textiles due to the looking and flexibility.

Most interconnection wiring in the category "printing and moulding material with conductive particles", and the conductive fabrics get a negative scoring. Their conductivities are not enough for driving that many motors(except copper sheets), the flexibility and stretchability are also not as good as other wiring candidates.

Some of the conductive fabric can work, regards the good conductivity and the textile properties. How to use them to transfer power and data will be a challenge, as it needs multiple wirings. Using these fabrics to make a double-sided conductive mesh system might be an option.

The textile ribbon cable gets great performance after the evaluation. These ribbon cables are using copper as the conductive core, which has a low resistance and various connection options. The compatibility with textile is also good. The flexible PCB technique also has similar performance regarding all these criteria, even though the price is too high. In general, textile ribbon cable and the flexible PCB are the wirings that deserve more in-depth studies, especially the LiTex tape and the Amohr tape. The conductive yarn could also be looked into, but with less priority.

Conclusions and desicions:

The conductivity of the silver-plated conductor(including yarns and fabric) is possible to fulfil the required conductivity for this project but needs extra design work.

Conductive ink, conductive silicon and 3d printed graphene are not going to work either, because of the high resistance.

Some of the textile ribbon cable with good stretchability and flexibility worth to be developed further, such as Amhor and LiTex cable.

The conductive yarn with metal multifilaments seems to be the only yarn type wiring that can be directly used for this project, regarding the resistance, sewability and tenacity.

Unstretchable wirings (like the copper sheet) will not be taken into consideration for now.

In a nutshell, LiTex and Amohr cable(or other products have a similar performance) will be the top priority to develop. This is the conservative design direction for this project. Conductive yarn with metal filaments(Bekaert yarn), flexible PCB technology and the conductive fabric will be the second priority to explore more possibilities. These are more innovative and challenging design directions.

In the scope of the possible application of these wirings, textile ribbon cables and flexible PCB are considered to be mainly used as linear wires. Conductive yarns and the conductive fabric, owing to their flexibility, can be used as either linear wires or surface conductors. The surface conductor is the core of the conductive mesh mentioned in Chapter 1.3.2.

This result and selection are for the main wiring used in the system, while it can always be possible to use multiple wirings in one system as they all have their pros and cons.

1.5 Conclusion

In this chapter, useful insights are gained through the research on the current products, user and cycling context. These research outcomes make the design scope much more clear, and based on what, the list of requirements are formed in Chapter 2.1. On the other hand, the technical research including the interconnection techniques and wirings gives an excellent starting point for generating ideas. A comprehensive understanding in these fields leads to various combinations of the wirings and their possible interconnection techniques. With such a strategy, the possibilities will be explored as much as possible during the ideation phase. For the next step, various ideas will be generated based on the conductive yarns, conductive fabric, flexible PCB technology and the textile ribbon cable, as mentioned in the interconnection wiring analysis.

Chapter 2 Concepts Generation

In this chapter, the list of requirements are generated based on the research outcome from the previous chapter. Then some preliminary ideas are formed and four of them are detailed into concepts. The pros and cons of all the concepts are analyzed and evaluated. Finally the design direction for the next ideation is formed.

2.1 List of requirements

In the concepts generation phase, the list of requirements is essential for forming and evaluating concepts. Based on the studies in chapter 1, it leads to the following requirements:

1. **The undetachable part of the electronic system should be able to wash more than 30 washing cycles at low-speed cycling and under 30 degrees together with the shirt. (Problem definition)**

2. **The design should be able to drive the current seven haptic motors system(maximum 2 motors working at the same time). (Problem definition)**

3. **The design should not fail to work during the 2 hours cycling exercise. (Problem definition & context analysis)**

4. **The concept should differ from the existing solutions of integrating electronics in textiles. (Design goal)**

5. **The design should be possible for mass-production. (Problem definition)**

6. **The design should be applicable for other sensing and actuating systems other than only be used as an Elitac cycling shirt. (Trend analysis)**

7. **The design should fit into the aesthetic style of the textiles. (Trend analysis & interviews with fashion designers)**

8. **The design should not influence the wearing comfort(in terms of breathability, stretch-ability, flexibility and sharp corner) of the shirt when the user is cycling. (User analysis)**

9. **The design should have an IP44 enclosure. Protection againest solid objects larger than 1mm and water splashes from all directions. (Context analysis)**

10. **The whole system should be assembled in 2 minutes. (User analysis)**

11. **The modular mechanism should survive from a fall from 1.5 meters high. (Context)**

12. **The system should work when the shirt is being stretched, twisted and folded. (Context analysis)**

13. **The design should be anti-corrosion. (Context analysis)**

14. **The design should work on the stretchable garment. (Design goal)**

15. **The design should be percieved attractive for men. (User analysis)**

16. **The cost for each unit should be less than €5.7 excluding electronics. (Cost estimation)**

2.2 Concepts generation

As four interconnection wirings are selected based on the chapter 1.4, several ideas are generated based on these research outcomes. Table 3 is formed to have an overview of these ideas. It shows the description of different ideas and the conductors which they are based on.

Table 3: Classification of ideas

		Conductive yarn	Textile ribbon cable	Laminated wiring	Conductive mesh
Permanent interconnection	**Non-detach-able from shirt**	A1	B1	C1	D1
	Detachable	A2	B2	C2	D2
Semi-permanent interconnection	**Non-detach-able from shirt**	A3	B3	C3	D3
	Detachable	A4	B4	C4	D4

After a discussion meeting with the supervision team and Elitac, four ideas are chosen for detailing. These concepts can be seen as follows. Other ideas can be seen in Appendix B.

2.2.1 Laminate thermoplastic adhesive film between PCB and textile ribbon cable(A1)

This concept is to laminate a printed circular board on a conductive yarn embroidered fabric together with NCA for sealing, electrical connection and bonding.

Getting inspired by the flip-chip bonding process, a similar process is proposed by Torsten Linz(2012): Bond a substrate with electrical protruding contacts(i.e. a textile fabric with embroidered (insulated) conductive yarns) to a PCB by merely inserting a soft thermoplastic adhesive film (i.e. thermoplastic polyurethane film) between the substrate and PCB and then heat-press it, shown in Figure 63.

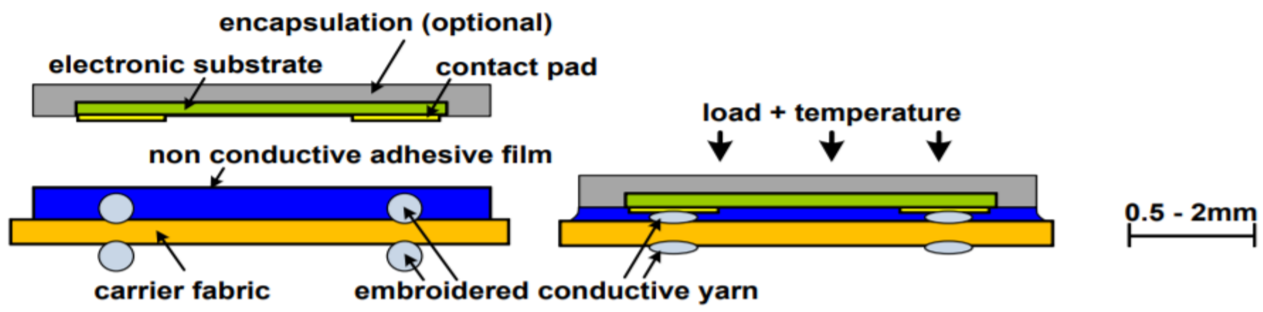


Figure 63: The concept of Torsten Linz

By raising the temperature and adding pressure, the yarn insulation (usually TPU or other thermoplastic material that will melt when being heated) together with the thermoplastic adhesive film will locally melt and be squeezed out of the contact area, which makes direct electrical contact with the PCB contact pad. When cooling down, the thermoplastic adhesive film will be fixed, which ensures a robust bonding.

This bonding process will both melt the insulation coating of the conductive yarn and make bonding in one step. From a manufacturing point of view, this is very simple and efficient – compared to having to remove the insulator in a separate step or having to apply the insulator after the contacting process. This finished bonding area is also waterproof.

Details:
As shown in Figure 64, the adhesive film (here is using TPU) was laminated on top and bottom side of the textile ribbon cable. The PCB is placed on top of the top film with the encapsulation. The encapsulation can be made by transfer moulding for protecting the electronics from water.

For protection, the bottom TPU layer is required as the yarn is heated to 195 °C during the bonding process which leads to a significant resistance rise during washing if the yarn is not protected with a polymer film.

For proper bonding to the PCB, the bonding pads should have a grid structure with open spaces of epoxy (rigid PCB) or polyimide (flex PCB) since copper or silver films do not bond well to the TPU adhesive film. In Figure 65, Torsten Linz proposed to use silver meshed contact pad and polyimide film to strengthen the bonding.

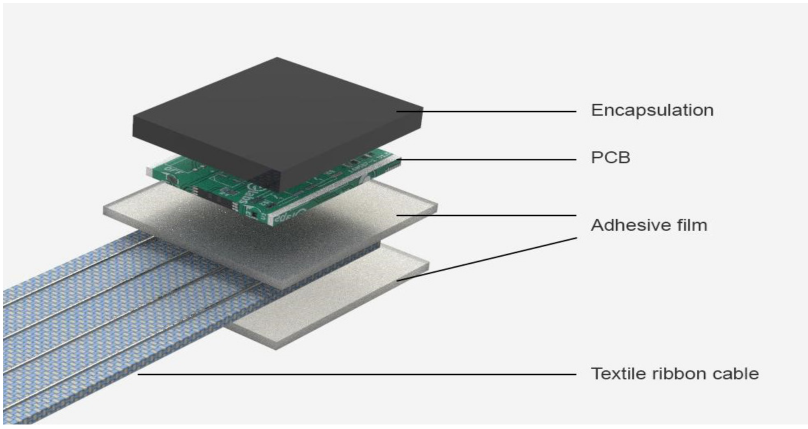


Figure 64: Lamination component

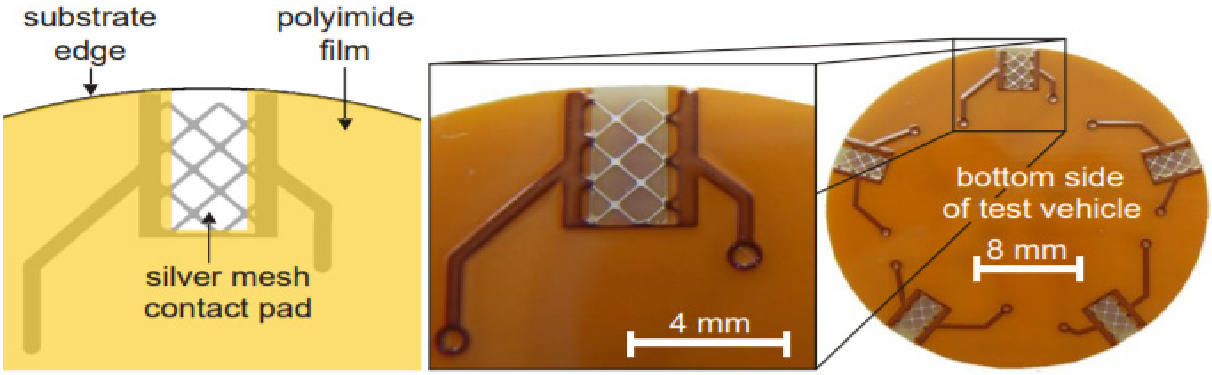


Figure 65: PCB with silver mesh

Lamination Process:

1. Loading the pressure on the upper encapsulation plate.
2. Heat the whole assembly to achieve the melt temperature of the NCA film.
3. Cool down to wait the deformed NCA film solidifies.
4. Release the pressure.

Note:

1. Encapsulation method: transfer moulding
2. The material for NCF: the high melting thermoplastic polyurethane TPU. It melts between 155 °C and 170 °C. (As a common material for the training suit, the melting point of Nylon is around 220(Nylon-6)-265°C(Nylon-66). For a short time heating, it should be no problem.)
3. Lamination environment: 100 µm thick film of the TPU is laminated on top and bottom side of the fabric. Lamination pressure is 0.7 N/mm2. Heating temperature is 195 °C. The temperature needs to be held for 30 seconds. Then it should be cooled at least until the temperature dropped below 100 °C to be well below the low viscous phase of the adhesive. Then the bond force is released.
4. TPU adheres well on the polyimide film and FR4. They can be the material of the printed circular board.
5. It can use multiple layers of TPU between the PCB and the textile ribbon cable to make a better connection and bonding.
6. For the current cycling shirt, Elitac finds the PU may have some trouble to be bound on to the cycling shirt material. However, their cooperating company designed another structure and solved this problem. This needs a better study.

Advantage:

Suitable for mass-production

The assembly is thinner, compared to other concepts.

This concept does not need the user to take some parts off before washing.

The positioning of the PCB during lamination might be a challenge.

There might be an adhesion problem between the encapsulation and the PU film.

Concerns:

The lamination area of TPU is probably not stretchable.

It is not clear whether this bond is strong enough to endure more washing cycles.

It is not sure what the melted TPU looks like, maybe it will affect the aesthetically looking of the end products.

Evaluation:

Manufacturing easiness

Detach and reassemble easiness(For user)

Washability(Waterproof and the interconnection strength)

Connection reliability when not washing

Aesthetics

Wearing comfort(Size, stretchability, material)

Vibration perceiving

Short circuit protection

2.2.2 Safety pin quick connection for textile ribbon cable (A4)

This concept is to make a quick connection between a unit module to the conductive yarn embroidered fabric using the structure of a safety pin (Figure 66).

Figure 66: Safety pin

Here we use four separate safety pins(or similar structure) for connection as we are using the I2c protocol. The head of the safety pin will be connected with the PCB board, and the pin will go through the fabric and conductive yarn for mechanical and electrical connection. The assembly can be seen in Figure 67.

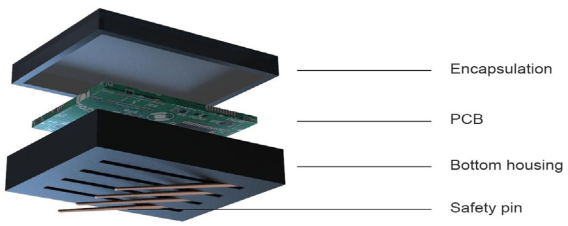


Figure 67: Explosive view of concept A4

The embroidered trace can be wider, so it could have a better connection with the pin, as shown in Figure 68. It can also use conductive fabric or conductive ink for this contacting area. The resistance is not a problem if you only use this conductive material for a small area.

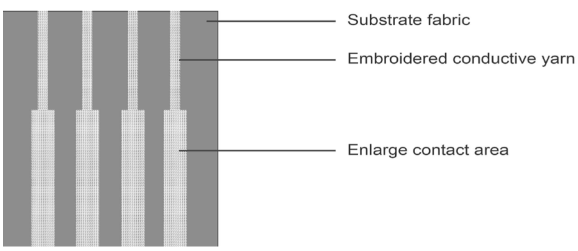


Figure 68: Enlarging conductive area

Figure 69 shows the side view of the assembly:

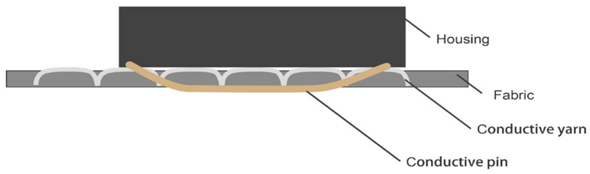


Figure 69: Enlarging conductive area

Locking mechanism and detail structure

For constructing the locking mechanism, one concept of using a separate locking and pin mechanism is proposed as Figure 70. The "locking hook" is soldered with the PCB board individually. The pin is fixed on the housing with glue. The pin and the hook only make contact when the whole assembly is locked.

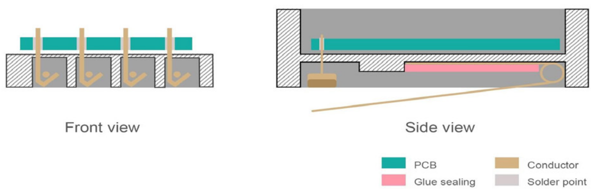


Figure 70: Locking mechanism

Quick experiment of the pin connection:

Here it is tested with the sewed-on-fabric silver-plated yarn and a stainless steel hand sewing needle(shown in Figure 71). The needle has a similar structure as the pin needle of the safety pin. For a quick test, it is decided to use a hand sewing needle instead. The tested conductive trace is sewed five times; thus, it has a wider contacting area.

It is first using the resistance meter to test the resistance of the 5-centimetre conductive trace, as shown is 8.6 ohm. The resistance is 1.4 ohm. Then the needle is inserted in the conductive trace; thus, it makes contact with the non-insulated conductive yarn. It can be seen the resistance from the beginning of the trace to the end of the needle is 9.9 ohm. A similar result also happens to the one stitch and three times stitches conductive trace. The conclusion is that the needle-yarn connection only has a slight resistance, which is neglectable.

Figure 71: Test of connection

Advantage:

It is a quick and modular connection.

Concerns:

The pin may damage the structure of the shirt if being connected and detached too much. The weight of the PCB and housing might loosen the fabric of the connection area.

Users may have problems putting the pin through all the conductive traces. Making contact with four pins at the same time is a challenge.

The insulation of the contact area might be a problem, as it also makes contact with skin. To have a TPU layer laminated inside the shirt might be a solution.

Evaluation:

Manufacturing easiness

Detach and reassemble easiness(For user)

Washability(Waterproof and the interconnection strength)

Connection reliability when not washing

Aesthetics

Wearing comfort(Size, stretchability, material)

Vibration perceiving

Short circuit protection

2.2.3 Construction of the conductive mesh

This concept is to have a quick surface contact connection based on a double-sided conductive mesh. Argued by Akihito Noda and Hiroyuki Shinoda, the I2C data can be transferred along with the dc power supply based on frequency division multiplexing(Figure 72). It means the clock and the data signals can be captured from the power by using a modulation and demodulation circuit. This extra functional circuit will enlarge the size of the PCB. On the other hand, it gives possibilities for a more flexible and modular design for the sensing and actuating system for smart textiles. For the set up of conductive mesh, it only needs two wires instead of four, while four wires are commonly used in standard I2c protocol..

Akihito Noda and Hiroyuki Shinoda proposed one concept in their paper: This concept is based on a double-sided conductive mesh having two layers of fabrics embroidered conductive yarns and an insulation layer in between(Figure 73). A special connector with needle and socket transfer power from both sides and make a mechanical connection(Figure 74).

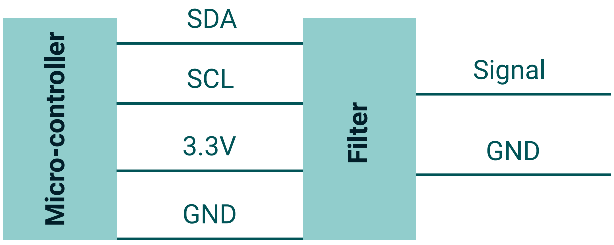


Figure 72: 2-wiring I2c principle

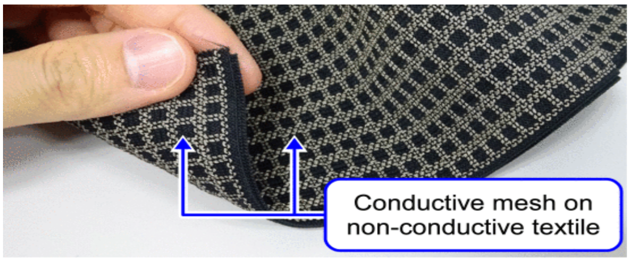


Figure 73: Example of double-sided conductive textile.

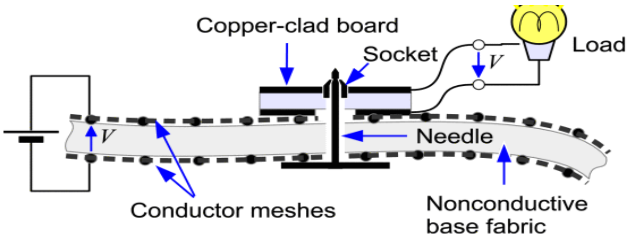


Figure 74: Connector designed by Akihito Noda

The advantage of this concept is the high flexibility and easiness of attaching different sensors and actuators at different locations. Moreover, it is also possible to use the conductor with less conductivity as the mesh structure will significantly reduce the resistance. However, the multiple layers make the whole textile thick and non-breathable, which are significantly valued for a cycling shirt. Using this concept as a starting point, several new constructions are proposed as follows:

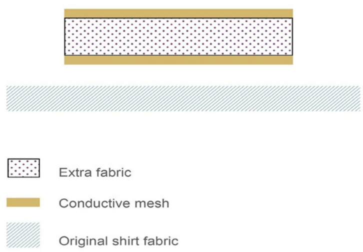


Figure 75: Double-sided construction

As using the conductive mesh, an extra mesh layer is needed to build the construction. Here are generally two constructions: Figure 75 shows the conductive mesh is placed on both sides of the extra fabric layer, while there is no conductor on the original cycling shirt fabric; Figure 76 shows the two conductive mesh could be placed on the extra layer and the cycling shirt fabric respectively. The different construction leads to different solutions.

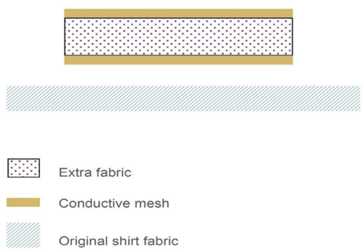


Figure 76: Single-sided construction

2.2.4 Paper clip connector system for double-sided conductive mesh construction(D3a)

This concept is based on the double-sided conductive mesh(see Figure 75), the two sides will be supplied with low voltage power of plus and minus. It uses a paper clip structure for making quick electrical contact with the surface of the non-insulated terminal of the conductive mesh(Figure 77). One difference with the real paper clip is that the two clip legs are separate and responsible for plus and minus. The legs can be soldered onto the PCB respectively(Figure 78).

Figure 77: Paper clip concept

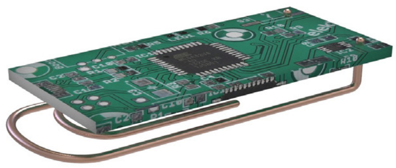


Figure 78: Connection with PCB

Figure 79 shows the top and bottom view of the connection to the double-sided conductive mesh. The two legs are connected to the two sides of the mesh respectively, thus making a circuit.

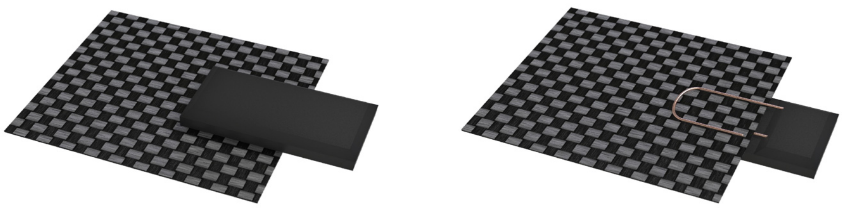


Figure 79: Connection with conductive mesh

The conductive mesh will need some holes to enable the leg to go through the mesh from one side to the other side, and there are many ways to achieve this goal: having hollow patterns like spacer mesh(Figure 18) or slightly cut the mesh just to let the leg pass. The whole mesh with the non-insulated conductor might be dangerous(not sure); thus, it is recommended to remove the insulation coating at certain connection points by chemical solvent or heating. This might reduce the flexibility of making a connection by the end-user.

Figure 80: Example fabrics with holes

Advantage:

Fast attachment and detachment.

Concerns:

The PCB might be too big and bulky due to the extra filter module, thus it makes the clip connection vulnerable. It also affects the looking.

It is not clear how difficult to make the double-sided conductive mesh with hollow and keep aesthetically pleasing at the same time.

Not sure the user can perceive the vibration accurately.

The waterproof performance of the conductive mesh.

Evaluation:

Manufacturing easiness
Detach and reassemble easiness(For user)
Washability(Waterproof and the interconnection strength)
Connection reliability when not washing
Aesthetics
Wearing comfort(Size, stretchability, material)
Vibration perceiving
Short circuit protection

2.2.5 Snap connector system for single-sided conductive mesh construction (D3b)

This concept is based on the single-sided conductive mesh, as shown in Figure 14. Two half snap buttons are placed on both conductive meshes respectively, contacting the conductive surface of the mesh, thus enabling the electricity to pass through the snap button(Figure 81). Those snaps are placed on the fabric permanently.

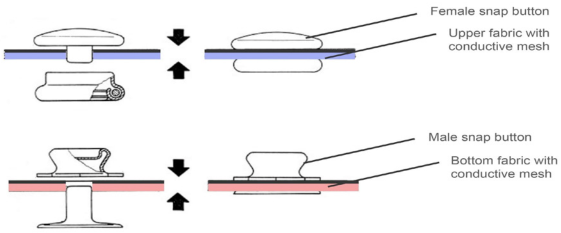


Figure 81: Assemble on the conductive mesh

The PCB and the housing will be between the two layers of the conductive mesh(Figure 82). There are the other half of the snap buttons for fitting the ones on the top and bottom conductive mesh. Inside the housing, the wiring will connect the snaps and the PCB to transfer power, it can be soldered or compressed in the snap button as the standard way to assemble the snap button on the fabric.

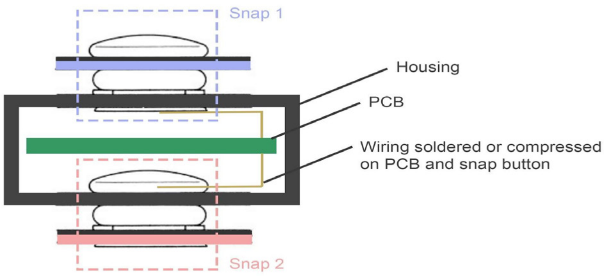


Figure 82: Illustration of the inner structure

There are various snap buttons available. The following are two of them: press studs(Figure 83) and the carpet fastener(Figure 84). They should be adequately chosen regarding the thickness and the deformability of the carrier material. It has not tried these two snap buttons. However, what is clear now is the carpet fastener is more suitable for the thin carrier. Even hard material(like plastic) is also working for the carpet fastener. It is not clear whether the press stud snap needs the carrier material to be soft.

Figure 83: Press stud

Figure 84: Carpet fastener

Figure 82 shows the working principle of the concept. Just look at the illustration, it can be perceived the housing is rigid and not comfortable. Taking a step further, this working principle can be transferred to a more user-friendly product. Figure 85 and 86 illustrate how this works: This assembly also uses the same structure as shown in Figure 82, as the PCB module is placed between the two layers of the conductive mesh. There are also half snap buttons assembled on the conductive mesh fabric respectively, even though they are placed at different vertical locations to reduce the thickness of the whole assembly. Just to fasten the two snaps, it makes the electrical circuit. The PCB module can be quickly taken off when the shirt needs to be washed.

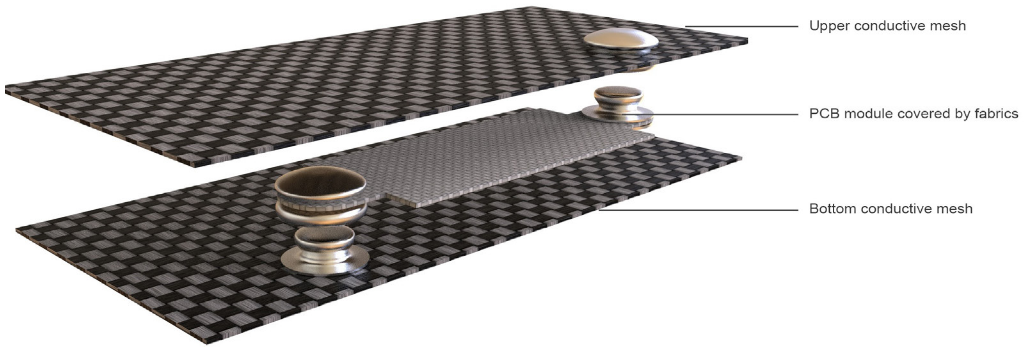


Figure 85: Illustration of the inner structure

Figure 86: Illustration of the inner structure

Figure 87 shows the detailed assembly of the PCB module. Instead of a rigid housing, it is proposed to use the polyimide (flexible PCB technique) for constructing the PCB and cover by two layers of insulated fabric to protect the circuit from sweat. The snaps are connected with the PCB by stretchable conductive wiring(or yarn embroidery) to give this PCB module a certain stretchability. This needs more exploration.

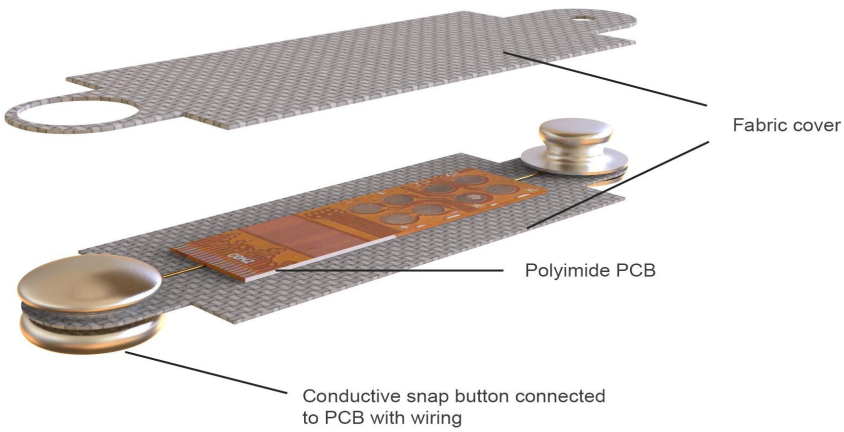


Figure 87: Illustration of the inner structure

Advantage:

Fast attachment and connection

Using soft material to increase comfort while wearing

Reliable connection (The fixation strength of the snap button is reliable).

It aesthetically looks like ordinary clothes as the snap buttons are quite commonly used in the clothes.

There is no other rigid housing.

Concerns:

To make the cover of the PCB insulated, that part of the fabric is not "breathable". It is not clear how this will affect the cycling experience if the user gets sweaty.

The stretchability of the PCB module needs more exploration and argumentation.

The IP of the conductive mesh.

Evaluation:

Manufacturing easiness

Detach and reassemble easiness(For user)

Washability(Waterproof and the interconnection strength)

Connection reliability when not washing

Aesthetics

Wearing comfort(Size, stretchability, material)

Vibration perceiving

Short circuit protection

2.3 Evaluation

The evaluation form is generated to have an overview of the performance of different concepts. It is a slightly revised Harries profile method for this project to have a neutral scoring. Eight criteria are generated based on the design goal and the list of requirements, which covers all aspects of these concepts. The total scores are calculated as well.

Table 4: Evaluation form

	A1	**A4a**	**D3a**	**D3b**
Manufacturing easiness	+	0	+	+
Detach and reas-semble easi-ness(For user)	++	-	+	+
Washability(Water-proof and the inter-connection strength)	0	++	++	++
Connection reli-ability when not washing	++	+	0	++
Aesthetics	0	+	0	+
Wearing comfort(-Size, stretch-ability, material)	=	+	=	++
Vibration perceiving	++	+	-	+
Insulation for protect the circuit from short circuit	+	-	+	0
Total	9	4	5	10

2.4 Design directions:

After the discussion with the supervision team and the company, it is decided to proceed concept D3a and D3b further. The two-wirings system using conductive mesh is promising. Other than the positive result from the datum method, it is also evaluated more straightforward for the manufacturing and easier to use for the users. Manufacturers do not have to carefully align the conductive yarns to the position on the fabric with the exact intervals, nor have to make sure the PCB is positioned correctly during the lamination process. Besides, for the concept A1, Elitac already had some experience in this direction. However, they found building a waterproof housing on top of PU is a foreseen challenge, as it is challenging to find the material that bounds to PU.

In a nutshell, it has not chosen which concept between D3a and D3b is going further. What has an agreement is the system should be built based on the conductive mesh. D3a and D3b, even including the original concept by Akihito Noda and Hiroyuki Shinoda can be improved and need several tests to evaluate their performances. As this direction is relatively new, it deserves more exploration.

Chapter 3 Concepts development

Taking a step further of the design decision during the previous design phase, two chosen concepts are iterated and a new concept is generated. All three concepts are based on the two-wiring system of conductive mesh. A study on the conductive fabric is performed, as it is the essential component for making the conductive mesh. The functional prototypes of all the concepts are built and tested. The final concept will be chosen by the test outcomes and the predefined design requirements.

3.1 Concepts development and prototyping process

3.1.1 Clip concept

The clip concept is iterated from concept D3a. Compared to the paper clip mechanism in the last round of ideation, the new mechanism(Figure 88) gets the inspiration from the pen clip. It has a more reliable connection, larger contact area and is easier for building the housing.

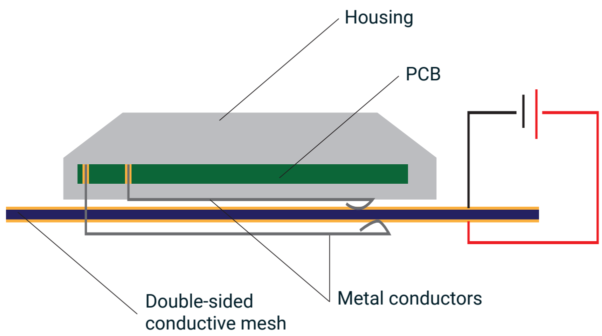


Figure 88: Section view of the Clip concept

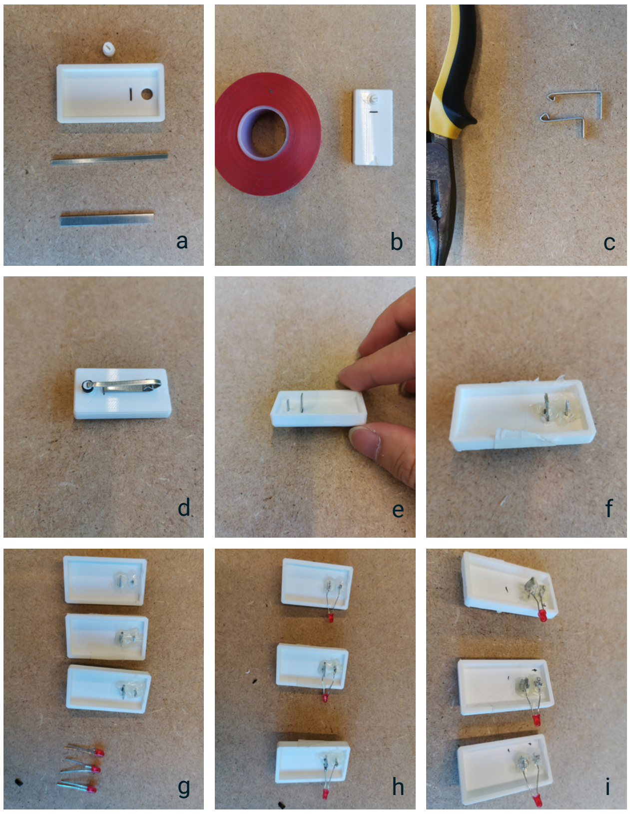


Figure 89: Prototyping process for the Clip concept

Figure 89 shows the prototyping process for the clip concept: Prepare the components(Figure 89a), press the press-fit fixer into the plastic housing and wrap it with rubber tape(for adding friction) (Figure 89b), bend the two zinc pin into a particular shape(-Figure 89c), put the bent zinc conductor into the right position(Figure 89d), use the hot glue gun to fix the conductor with the housing(Figure 89f), follow the same step and make another two assemblies(Figure 89g), solder the LEDs on(Figure 89h), reinforce the interconnection with the hot glue gun(Figure 89i).

The fixer is used to fix the whole assembly with the eyelet ring(Figure 90). The eyelet ring is a common way to reinforce a hole in the fabric. It consists of two parts and needs to be pressed by a plier, thus the two separate parts deform a bit and bite each other.

Figure 90: Eyelet ring

Figure 91: Finished prototype

The finished prototype assembled on the conductive mesh through the eyelet ring is shown in Figure 91.

3.1.2 Snap button concept:

The snap button concept is iterated from concept D3b. This three layers assembly consists of two layers of single-sided conductive mesh, the electronics are in between, connected to both layers with two separate metal snap buttons, as shown in Figure 85, 86 and 87. It is decided to use a flexible PCB in this concept and seal the electronics with a rubber-like material. This is to allow the electronic part to have a bit of flexibility, thus it is more comfortable for the user to wear. The flexible PCB is also thinner than the rigid PCB, which makes it easier to install the snap button. The structure of the snap button-through PCB design is shown in Figure 92.

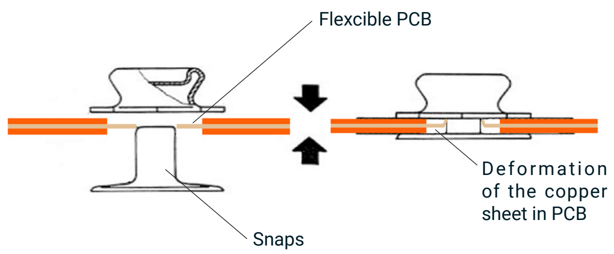


Figure 92: Snap button through flexible PCB

As it is difficult to use the existing flexible PCB for the prototyping, it is decided to use the laminating pouches(Figure 93) as a substitution. This pouch consists of two layers. The outer layer is made of Polyethylene Terephthalate(PET), and the inner layer is made of Ethylene-Vinyl Acetatefor(EVA) as the hot melt glue(Zentesi. August, 2017). When two layers of pouches are laminated, the EVA of the inner layer starts to melt and finally bond to each other. The finished lamination stuff has a similar mechanical performance as the Kapton material, which is used to produce the flexible PCB. This method is suitable to make a quick test instead of designing a flexible PCB from the beginning.

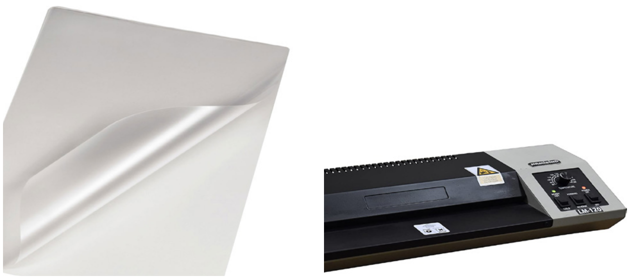


Figure 93: Lamination pouches and lamination machine

Figure 94 shows the prototyping process of this concept: Punch a 5mm hole on one layer of the pouch and laminate two pouches with two copper tape in between(Figure 94a), assemble the snap buttons(Figure 94b), solder the Led on the assembly(Figure 94c), use the hot glue gun to reinforce the soldering interconnection(Figure 94d), make other two mechanisms by following the previous steps(Figure 94e), place the insulation tape(Figure 94f).

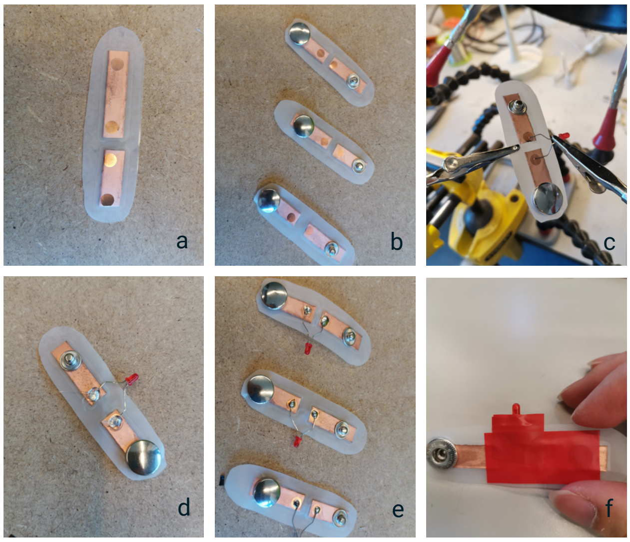


Figure 94: Prototyping process for the Snap button concept

3.1.3 Bun concept:

This concept is an iterated concept of the project done by Akihito Noda and Hiroyuki Shinoda(2019). Compared to their previous work(Figure 73 and 74), this concept has a certain level of waterproof, a reduction in the thickness and an appealing look. Figure 95 shows the illustration of this concept:

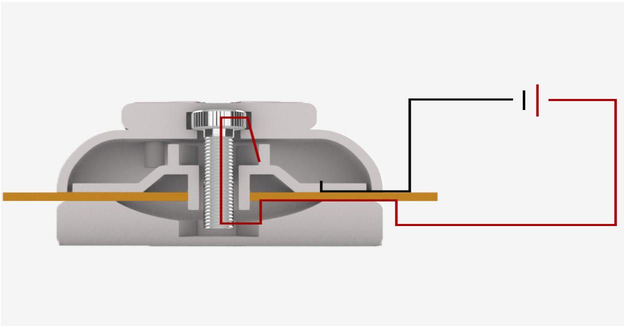


Figure 95: Snap button through flexible PCB

The prototyping process can be seen in Figure 96: Prepare the components(Figure 96a), wrap the cut copper tape onto part4(Figure 96b), put the nut at the bottom of part4 and make contact with the copper tape A(Figure 96c), fix the nut with tape(Figure 96d), solder the wire onto the copper tape B(Figure 96e), bond the copper tape B with wire onto part3(Figure 96f), put the gasket and another nut on the screw(-Figure 96g), bond the screw cap into the hole of part1 by hot glue gun(Figure 96h), place the other wire and make sure the conductor come across the hole of part2(Figure 96i), use the third nut to fix part1 and part2, make sure there is a contact between the screw and the wire(Figure 96j), pressfit part3 to part1 and part2(Figure 96k and Figure 96l), solder the led, put the assembly through the eyelet ring and screw fasten it onto the conductive mesh(Figure 96m).

Note: In this prototype, it is using M3*16 screw and the supplementary nuts and gasket.

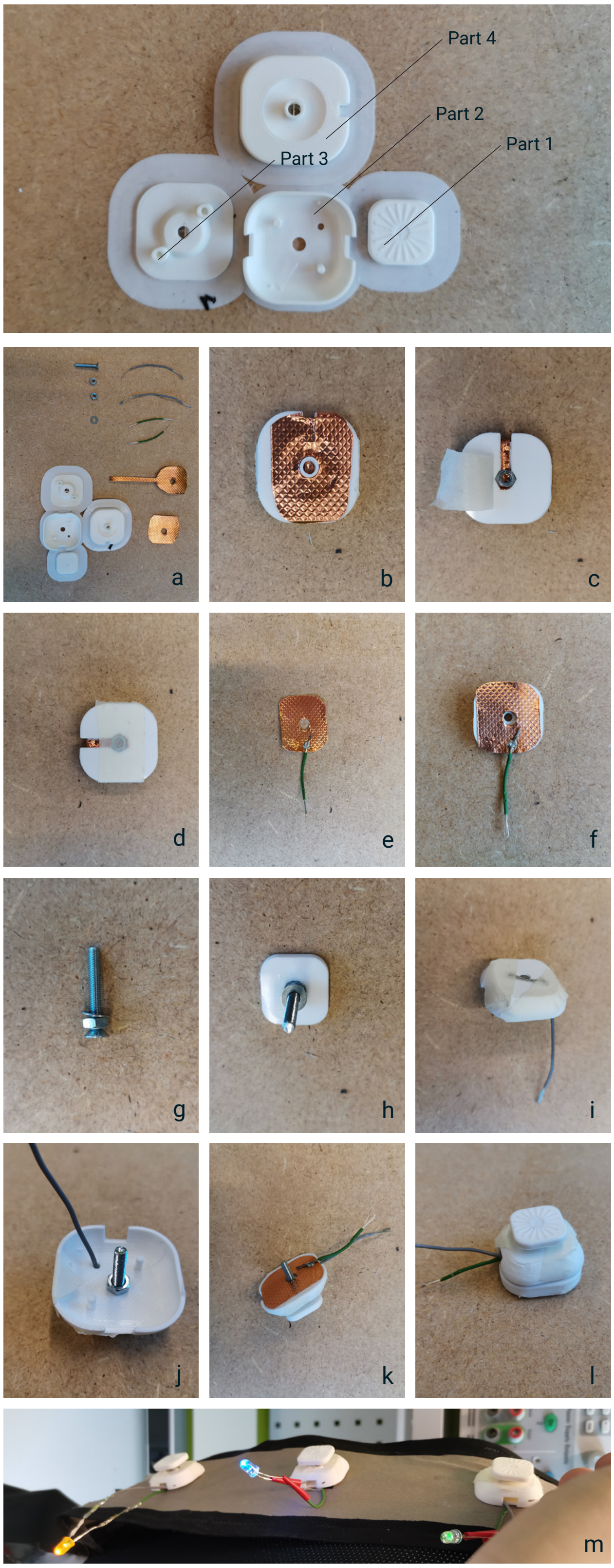


Figure 96: Prototyping process for the Bun concept

3.2 Conductive mesh study

Conductive mesh, the basis of these concepts, can be made in several ways:

1. **Embroider conductive yarns on the fabric(Figure 97).**
2. **Heat press the conductive fabric on the carrier fabric with vliesofix(Figure 98), a special tape for heat press bonding.**
3. **Print or laminate conductive epoxy or metal grid on the fabric(Figure 99).**

Figure 97: Embroider conductive yarns

Figure 98: Vliesofix

Figure 99: Printed conductive epoxy

Having a comprehensive consideration on the stretchability, cost, aesthetics, thickness, weight, flexibility, breathability, manufacturing difficulties and conductivity, it is decided to use the heat press process to make the conductive mesh. To heat press(or called lamination) one layer of conductive fabric on the carrier fabric, the whole assembly consists of layers: the carrier fabric, vliesofix and the conductive fabric. Figure 100 shows the illustration of the single-sided conductive mesh..

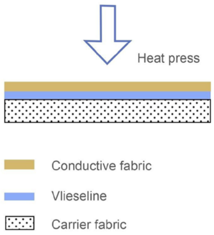


Figure 100: Assembly of heat press technique for making conductive mesh

The characteristics of all three layers will influence the performance of the whole assembly. For making the mesh, it is decided first to use lycra for the carrier fabric, as it is the typical material used in the sport shirt, with an excellent stretchability and breathability. Elitac had experience with the vliesofix and did multiple tests, with their recommendation, UT8 made by Protechnic is used here. This vliesofix is of strong bonding force and together with good stretchability.

The next step is to select the conductive fabric. Conductivity, stretchability, comfort are the primary consideration. After preliminary research, it is found four candidates: Fabric1 Kazhtex SCN020, Fabric2 Kazhtex SCN016-YL, Fabric 3 Softmesh, Fabric 4 Steelcloth. In Table 5, it can be found the relevant information of these fabrics.

Table 5: Information of conductive fabrics

Name	Figure	Stretchability	Thickness	Conductive material	Electrical resistivity	Flexibility	Link for manufacturer
Kazhtex SCN020		Good, more than 20%	Less than 0.2mm, can be changed by the manufacturer	Plated silver	less than 0.01 ohm.m	Good	https://www.silver-fiber.com/
Kazhtex SCN016-YL		One dimension stretchable, more than 20%	Around 0.5mm, can be changed by the manufacturer	Plated silver	less than 0.01 ohm.m	Good	https://www.silver-fiber.com/
Softmesh		Less than 10%	Less than 0.2 mm	Woven metal fiber	Around 0.01 ohm.m	Good	https://mindsetsonline.co.uk/shop/softmesh/
Steelcloth		Less than 10%	Around 0.5mm	knitted steel	Around 0.01 ohm.m	Neutral	https://mindsetsonline.co.uk/shop/steelcloth/

3.2.1 Resistance measurement

Conductivity is the essential value for the conductive fabric, and it can change due to the environment and various processes. What is more, the electrical resistivity is not apparent enough for this project, as the contact area is quite small. It can not only use the resistivity formula to calculate the resistance when the contacting point is much smaller than the width of the conductor.

$$R = \rho \frac{\ell}{A}.$$

Research question: Is the conductivity of these conductive fabrics be able to drive the electronic system of the cycling shirt after the heat press?

The four conductive fabric candidates are cut into 10 cm * 10 cm square pieces(Figure 101). As in all the modular mechanism concepts, the connection area is relatively small, compared to the whole conductive fabric. Therefore, it is decided to use pin measurement instead of measuring the sheet resistance. To get a feeling of the varying range of the fabric resistance, the maximum and the minimum resistance is measured. Using a liner strip fabric for the conductive wiring, the maximum resistance is at the edge, shown as measurement A(Figure 102a). On the other hand, the minimum resistance is at the middle lane of the fabric, shown as measurement B(Figure 102b).

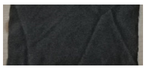
*Figure 101: 10cm*10cm conductive fabric samples*

Figure 102a: Measurement A

Figure 102b: Measurement B

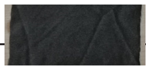
Table 6 shows the resistance of these fabric candidates under original conditions(not being heated, bonded, pressed and stretched).

Table 6: Resistance before heat press

Code	Figure	Direction	Measurement A(ohm)	Measurement B(ohm)
A		/	4.1	2.9
B		Warp(Stretchable)	3.5	2.6
		Weft(Non-stretch-able)	2.1	1.6
C		/	4.5	3.5
D		Warp	11.5	5.5
		Weft	not conductive	not conductive

A and B have better conductivity. Compared to C and D, fabric A and B are also stretchable. Thus it is decided only to heat press these two pieces of fabric. When the assembly temperature goes back to the room temperature, the measured resistance after the heat press is as Table 7:

Table 7: Resistance of fabric A and B after heat press

Code	Figure	Direction	Measurement A(ohm)	Measurement B(ohm)
A		/	3.3	2.6
B		Warp(Stretchable)	2.5	1.7
		Weft(Non-stretch-able)	1.4	1.2

Compared to the original fabric, it can be seen that these silver-plated fabrics have a resistance drop after the heat press. The reason is speculated that the vliesofix fixes part of the conductive fabric, thus the conductive fibre touches each other more than before.

Comparison with the resistance requirement:
According to Appendix A, the linear resistance of the conductor in this system should be no more than 4.46 ohm/m. Even if the most conductive fabric(number2) is chosen, the linear resistance of a 10 centimeters wide fabric is around 12 ohms/m. It is almost three times higher than the requirement.

However, this problem is solvable from two aspects: lowering the resistance of the fabric and optimizing the current electronics. The resistance of the conductive fabric is not fixed. It is using 10 centimeters wide fabric for the testing. However, it can also use the fabric to make the shirt itself. It will decrease the resistance significantly, as the width of the conductor is much larger than before. The thickness of the fabric can also be changed, according to the manufacturer, Kazhtex. An estimation could be given based on the fomular of resistivity.

$$R = \rho \frac{L}{A} = \rho \frac{L}{Wt}$$

Here q is the resistivity, A is the cross-sectional area, and L is the length. The cross-sectional area can be written as Wt, where W is the width, and t is the thickness of the fabric. To get a three times smaller resistance, the width can be enlarged three times, that is 30 centimetres in this project. Otherwise, the thickness of the fabric needs to be three times larger. However, this calculation can just give an estimation. As the conductive fabric in this project is not used as a linear conductor(the modular mechanism is only connected to several points on the fabric), the width of this fabric does not simply have a linear relationship with the resistance. The real-life resistance will be slightly larger than the calculation.

For now, there is a big room for the extra thickness, because the tested fabrics are all still quite thin. On the other hand, the electronics can also be optimized. One solution is to change the haptic motor that needs a smaller voltage input. Both of the solution directions are possible, and they can be used together. As the calculation is complex with irregular conductor shape, it will be tested directly to validate whether the system can work.

3.2.2 Waterproof performance

For the preliminary prototyping, it is using lycra for the insulation layer. However, this fabric can absorb water which may lead to a failure of the whole system. The finished conductive mesh should have an IP44 enclosure(Requirement 9). It means the conductive mesh should be protected against water splashes from all directions(The enclosure company, n.a.). In Chapter 3.3.4, waterproof performance is tested. A better insulation fabric is chosen as well.

3.3 Performance test

As the mock-up of the three concepts are done, it is designed several tests to evaluate the performance on different aspects of each concept. The test result will be the primary consideration to choose the most suitable concept for the future embodiment.

Criteria:
Based on the design requirements in chapter 2.1, some related requirements are noted as the evaluation criteria: **robustness, electrical reliability, waterproof performance and aesthetics**.

3.3.1 Wearing test

The modular mechanism will stay on the shirt when the user is putting on/off the shirt. The electronics do not have to work during this wearing process. However, there must be no components falling off from the shirt. Thus it is designed this test to validate the physical connection solidity of the different mechanism.

Research question: Do the different concepts have enough physical connection force to prevent the mechanism falling from the shirt when being put on and off?

Process:
It is invited four participants to put on and off the shirt five times each. Three modular mechanisms of each concept are attached to the shirt(with no power supply). After five rounds of wearing, the status of these prototypes is checked to see if there is any detachment.

Result:
There is one falling(1 in 12) of the clip concept after five rounds of putting on and off. There is no falling of the Snap button concept and the Bun concept. Furthermore, one prototype of the Clip concept is observed to have rotation during the test by one participant(Figure 103b). This rotation may not lead to the fail of the electrical connection, but could add the risk of the data communication.

Figure 103a: Falling during wearing

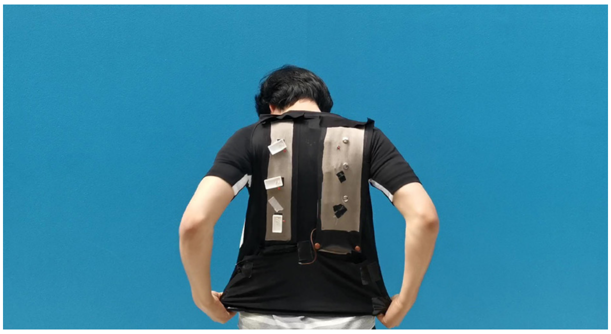


Figure 103b: Rotation during wearing

3.3.2 Buckling test

Along with the 2 hours cycling exercise, the repetitive movement could happen on cyclist's back. These movements can be concluded as stretching, folding and twisting. The design must work continuously during the 2 hours cycling(Requirement 3). In this test, it is evaluated if these repetitive movements would affect the electrical connection between the modular mechanism and the conductive mesh. A robotic arm is set up to simulate the flex and fold during the practical wearing by the users. Each moving cycle of the robotic arm is set up with 3 points. Along with the route of these 3 points, the stretching(Figure 104a), folding(Figure 104b) and twisting(Figure 104c) are included in the movement.

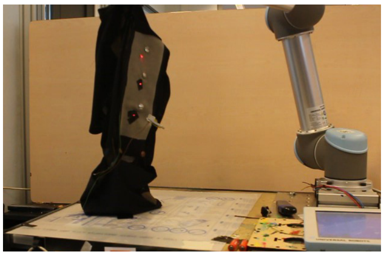


Figure 104a: Stretching movement

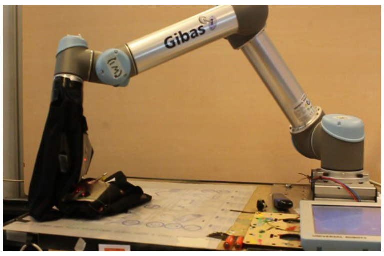


Figure 104b: Folding movement

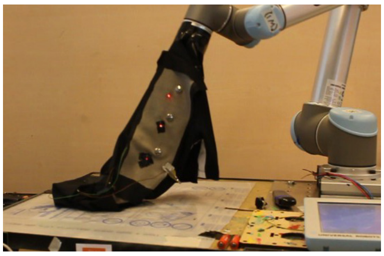


Figure 104c: Twisting movement

The modular mechanism is attached to the shirt with the way as designed. Then it is powered by two 1.5V batteries, and each of them connects with an Led for easy observation. Each concept has three prototypes, attaching to the different location of the shirt. To have a clear comparison, it is tested with two concepts together, one on the left and the other on the right of the shirt. The layout of the six prototypes is in symmetry to make sure they get similar tension and tearing force. The shirt is fixed on the robotic arm and the bottom carrier board with tape. The test had more than 500 cycles(Figure 105) and took around two hours each.

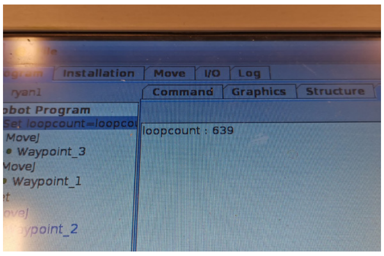


Figure 105: The testing cycles

Result:

There is no apparent connection failure for all of these concepts during the 500 cycles, all the LEDs keep working consistently.

Discussion:

In this test, it can be validated that the repetitive movement will not lead to a connection failure, at least with the LED. However, the movement may cause noise that leads to the instability of the electricity through the LEDs. The noise might be so instant that it is hard to observe the LEDs blinking directly by human eyes, neither the regular low-speed camera. The noise is acceptable for a simple power supply system, while with data bus integration, it probably leads to the failure of the communication. Thus, an extra test is needed to evaluate the signal stability of these concepts.

3.3.3 Test of the signal stability:

Mentioned in the Buckling test, a signal stability test is essential for choosing the right mechanism. In this test, it is using a Tektronix oscilloscope to monitor the real-time voltage change of the modular mechanism. It is using channels together(yellow and blue in Figure 106) to have a comparison of different concepts.

Figure 106: Set up of oscilloscope

A participant is invited for this test. This participant is asked to wear the cloth which already has all the electronics working(Figure 107). Two prototypes in symmetry position of different concepts are connected to the oscilloscope at the same time with the different channel(yellow for the left concept and blue for the right concept). When setting up, the girl is asked to do the following movement: arm up, arm down, arm left, arm right, arm upper left, arm upper right, arm bottom left, arm bottom right, rowing, strenuous rowing. The oscilloscope is observed and recorded in the meantime. The test goes for three rounds to test the prototypes at different locations to exclude the influence of the body position.

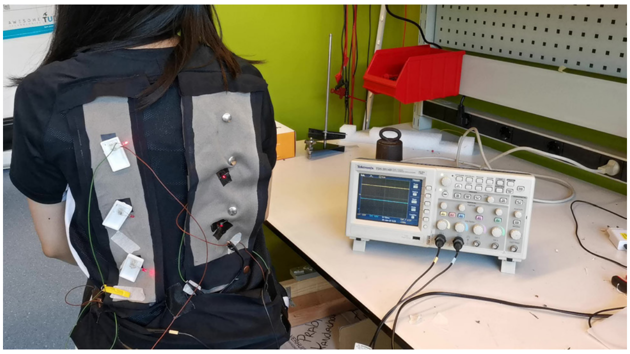


Figure 107a: Test of the Clip concept and the Snap button concept

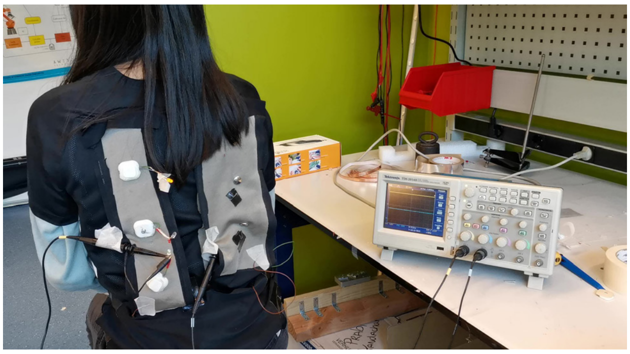


Figure 107b: Test of the Bun concept and the Snap button concept

Results:

As shown in Figure 108, the Clip concept generates much noise when the participant starts moving, while the other two concepts are quite stable. The voltage remains at the range between 2.2V to 2.3V. This slight change is because the resistance of the conductive fabric changes when the fabric is being stretched, twisted and folded.

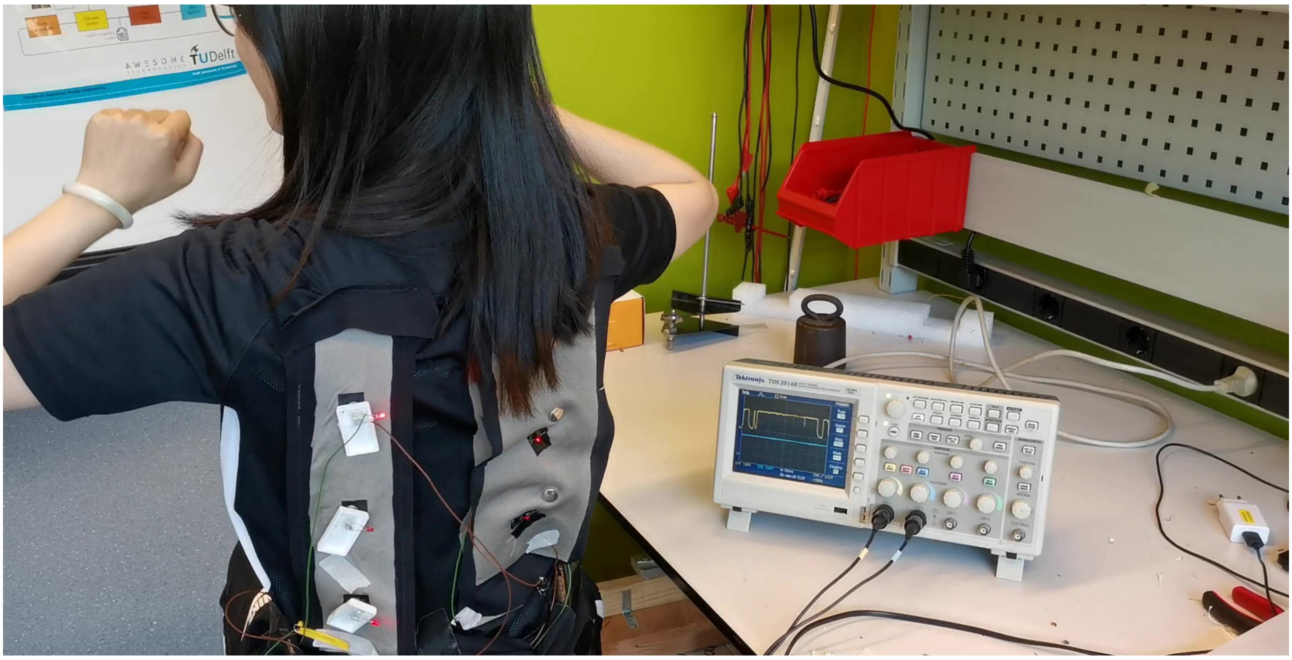


Figure 108a: Noise generated by the Clip concept

Figure 108b: The waves of Bun concept and the Snap button concept

3.3.4 Waterproof test

The cycling shirt will be used outdoors. In Amsterdam, the capital of the Netherlands, it is estimated that there are 133 rainy days per year(Weather Atlas, n.a.). Therefore, a certain level of waterproof(IP44, based on Requirement 9) is necessary for the system to avoid the short circuit caused by moisture. Otherwise, there will be more than one-third time that the product cannot be used. The test outcome can help to select concepts(the double-sided system is for Bun and Clip concept, the two layers of the single-sided system are for the snap button concept)

Research question: What is the waterproof performance of the two structures of a two-wiring conductive mesh(double-sided and the two layers of single-sided)?

Method:
Prepare the conductive mesh system and a small cup filled with tap water(Figure 109a). Make sure the two conductive fabric wirings are insulated. Pour the water on the fabric(Figure 109b). Because the conductive fabric does not absorb water so quickly, the water drip will stay on the fabric for a while. Mark the location of these drips and choose three areas with water for each concept(Figure 110).

Wait for 10 minutes, until the water drip is invisible, which means the fabric absorbs the water completely. Use the resistance meter to measure the resistance meter of the three chosen areas respectively. The two pins of the resistance meter need to contact the different side of the conductive fabric to see if the insulation fabric still works(Figure 111). All the figures will be recorded.

Figure 109: Waterproof test

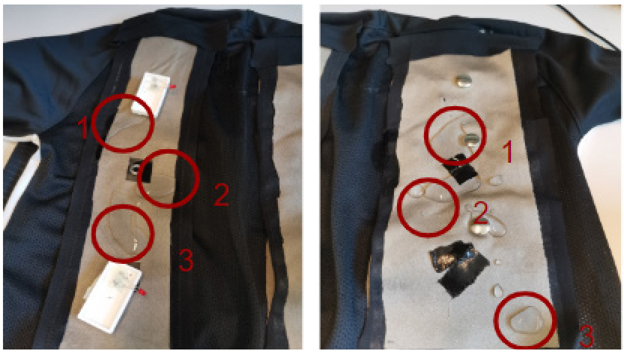


Figure 110: Mark the testing location

Figure 111: Measured resistance

Results:
The results can be seen in Table 8

Table 8: Results of the waterproof test

	Double-sided mesh system(left)	Two layers of single-sided mesh system(right)
Resistance at area 1	440ohm	3.8ohm
Resistance at area 2	590ohm	4.7ohm
Resistance at area 3	1244ohm	7.2ohm

Discussion:
It can be seen that both mesh systems are not insulated when being wet. The two layers of single-sided mesh system are even worse, nearly having a short circuit already. The double-sided system has a higher resistance, but still not insulated anymore. The reason why the double-sided system has a higher resistance is probably that it has an extra layer of vliseline, which makes the water more difficult to go through the assembly. Nevertheless, both systems need to improve the performance on the waterproof.

Further study:
A possible solution is using a waterproof fabric for the insulation layer instead of lycra. It is finally chosen Extreme textile 72139(Figure 111), which is breathable, stretchable and waterproof. It is heat pressed to a double-sided conductive mesh. The same process is followed as the previous waterproof testing. It shows a much better result than lycra, as shown in Table 9. It can be seen the resistance is more than ten times higher than the lycra system. Comparing the resistance of the conductive mesh, this resistance should not be a problem. However, it is not clear yet if this will influence the signal transferring. It is recommended the electronic engineers to have a further study on this aspect.

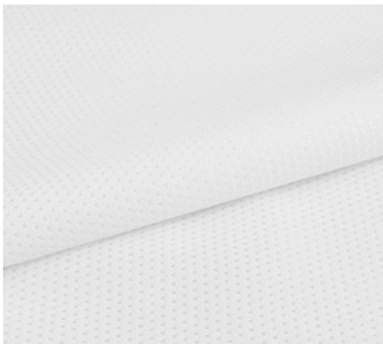


Figure 111: Extreme textile 72139

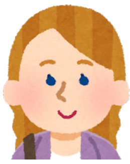
Table 9: Results of waterproof fabric

	Original double-sided mesh system using lycra	New double-sided mesh system using waterproof fabric
Resistance at area 1	440ohm	11.44kohm
Resistance at area 2	590ohm	5.89kohm
Resistance at area 3	1244ohm	10.64kohm

3.3.5 Interview on the aesthetics potential

Aesthetics is the criteria that could be easily neglected during this project. However, it plays an essential role in the end product. In the current world with great material prosperity, consumers pay special attention to the look and feel of the products. For clothes, aesthetics is even more critical.

The aesthetics evaluation is done by a quick interview with two fashion designers, as fashion designers are the people who will deal with the looking of the shirt in the future. Getting a glimpse on which concept is of the fewest influence on the looking and more accessible for them to design in a later stage is important. Thus, two fashion designers, Linda and Ma, are invited for the interview. The working principle of both concepts are clearly explained, so they understand what is possible to be changed(e.g. the size and shape of the conductive mesh, the shape and looking of the housing) and what is not(e.g. the mesh structure). The results are as follows:



Linda:

I love the snap button concept, and I feel there is more potential on this concept. It hides the electronics, that is good. People can only see a snap button outside, so it is easier for me to design the shirt. On the other hand, the electronics hiding inside the fabric creates weird bulges and folds, that is nearly inevitable.

I do not like the clip concept because it looks like some boxes hanging outside the fabric randomly.

I have a slight preference in the Bun concept. If I have to choose one concept and develop further, I will go for this concept. It looks more integrated and seems to have the least risks among the three candidates.

Ma:

I like the snap button because it has a sense of technology. However, I feel the electronics in the between layers are tough to deal with, especially if you have a horizontal and vertical layout together with seven haptic motors. I also feel it might not be comfortable for the users to wear it.

The Bun concept, it has a rigid housing, which makes it less like a cloth. To be honest, I can imagine if there are seven boxes on my shirt, it already feels like I am wearing a power strip. On the other hand, it is easier for the fashion designers as it is fixed well and does not add more wrinkles and challenges. Users should feel more comfortable when wearing this concept.

I do not like the clip concept at all. There is no aesthetics to this concept.

Conclusion

As fashion designers, Linda and Ma have a consensus: Compared to making the electronics visible and standing out, the electronics should have the least influence on the cloth itself. That is the reason why they prefer the snap button concept at the beginning. The first impression of the snap button concept is just a few snap buttons on the fabric, which matches our cognition of what the cloth should look like. Though they believe the looking of the snap button concept is the ideal appearance, they do realize that the inside electronics are hard to deal with. The wrinkles caused by the housing of electronics are unavoidable, which also leads to the concerns of wearing discomfort.

The Bun concept, they both talked about it does not look like a shirt. The rigid housing hardly matches the fabric. There is rarely an existing shirt with this extra stuff, that is why they feel this concept looks weird. However, they admit that this structure is really easy to be attached to the shirt and does not cause further problems or wrinkles. This is the most straightforward concept for designers to work on. They also have the feeling that compared to the other concepts, the Bun concepts have the least contact area(flat as well) with the human body. This makes it more comfortable to wear.

The clip concept also has a rigid part, which they already do not like. This concept is not fixed on the shirt as well, which makes it have an even worse aesthetics potential. Both of the fashion designers do not want to talk more on this concept.

Discussion:

Even though both of the fashion designers like the look and feel of the snap button concept, they finally choose the Bun concept for more practical concerns. However, the Bun concept can be improved to be more like the snap button to get advantages of both concepts. One possible direction is to make the screw holder look like a snap button, using a round shape and metal paint.

3.3.6 Mechanism resistance measurement

It is also measured the resistance and the voltage drop of all three modular mechanisms for each concept to see if the way of connecting will produce extra resistance, the result can be seen in Table 10:

Table 10: Results of measurement

	Clip prototype	Snap button prototype	Bun prototype
The voltage between the two legs of Led (the furthest from the power)	2.21V	2.39V	2.35V
The voltage between the two legs of Led (the second farthest from the power)	2.55V	2.42V	2.56V
The voltage between the two legs of Led (the third furthest from the power)	2.59V	2.67V	2.69V
The voltage of power source	2.86V	3.0V	2.96V
The average resistance of the interconnection area	2.0ohm	0.4ohm	0.6ohm

Result:

There is no remarkable difference in the mechanism resistance. All three concepts seem to have a good conductivity at the interconnection area.

3.3.7 Decision making

The following table gives an overview of the evaluation of the test outcomes. After a discussion with the supervision team and the company, the Bun concept is chosen for embodiment as it fits the list of requirements better, as well as the company's strategy. However, the Bun concept is not perfect. There are still some problems need improvement.

Table 11: Test results

	Clip concept	Snap button concept	Bun concept
Wearing test	-	+	+
Buckling test	+	+	+
Signal stability	-	+	++
Waterproof	-	- -	- -
Aesthetics potential	-	+	++
Mechanism resistance	+	+	+

3.4 Design direction

As the outcome of the tests and the agreement together with the supervision team and Elitac, the Bun concept is chosen for further development.

The prototypes prove that this mechanism could be working as it has high reliability. However, the way of making the prototypes does not fit the real manufacturing process. For the next design phase, more effort will be put on:

Optimize the structure of the housing, thus it can be manufactured.
Minimize the thickness and size of the assembly.
Make the conductive mesh and the modular mechanism have an IP44 enclosure.
Design the look and feel of the assembly, thus it matches the aesthetic style of the textiles.

Chapter 4 Concepts finalizing

In this chapter, it is explained how is the chosen concept developed step by step to the final design. The working principle, function of different parts, aesthetic and user experience consider-ation are thoroughly elaborated.

4.1 Aesthetics design

4.1.1 Design of the modular mechanism

As mentioned in the trend analysis, having an appealing looking is also an essential requirement(requirement 7 and 15). Unlike other smart products, this modular mechanism is attached to the cycling shirt, thus their aesthetic styles should match each other. According to the interviews with two fashion designers in chapter 3.3.5, the design should have the least influence on the looking of the shirt. The look and feel of the design will focus more on how to deal with the relationship between the shirt and the hardware, instead of only making the modular mechanism look cool.

To get inspiration, the mood board is generated(Figure 112). It is started with three keywords: simple, sporty and technology. Searching related products by these keywords in some famous design websites(e.g. Behance, Pinterest), the inspirations are gathered.

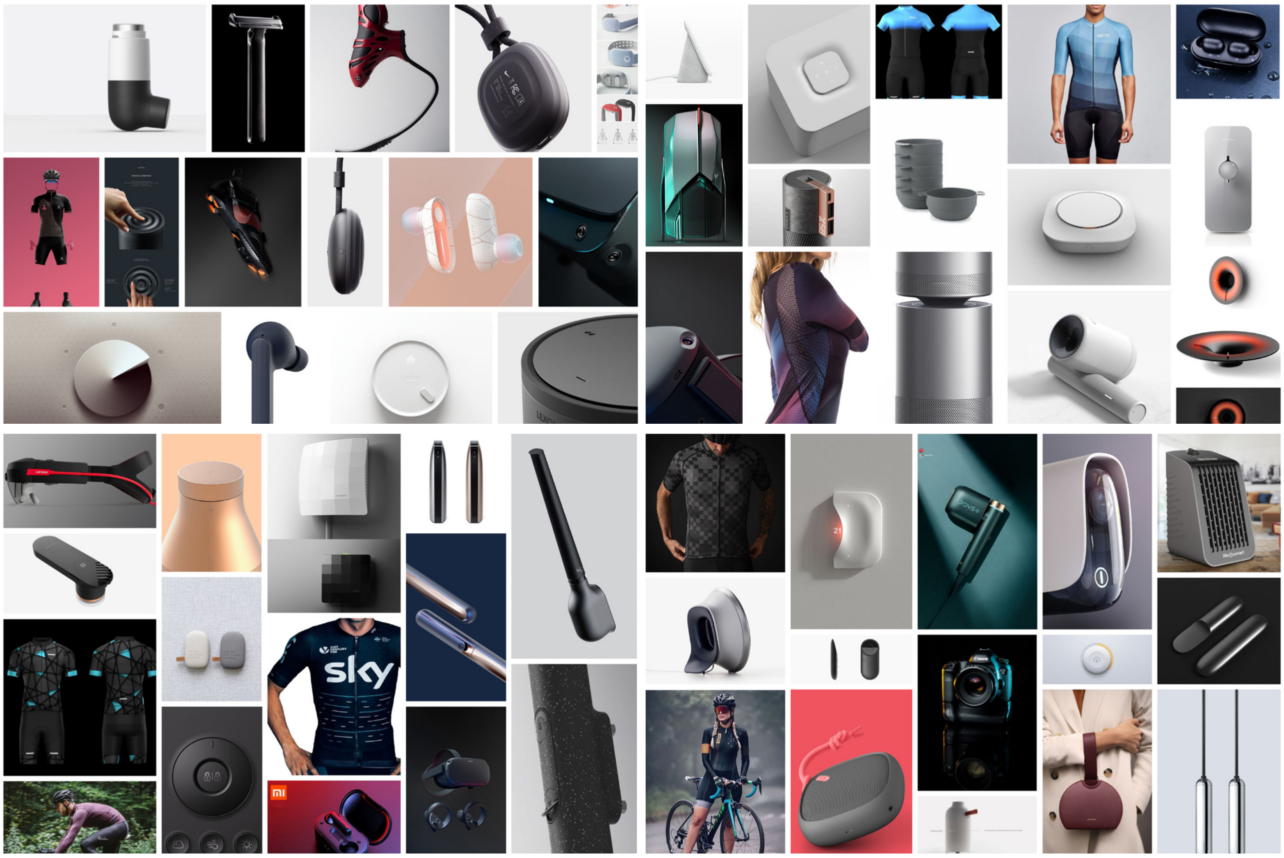


Figure 112: Inspiration

Based on these inspirations, sketches(Figure 113) and quick 3d models(Figure 114) are done to generate forms and dive in design details.

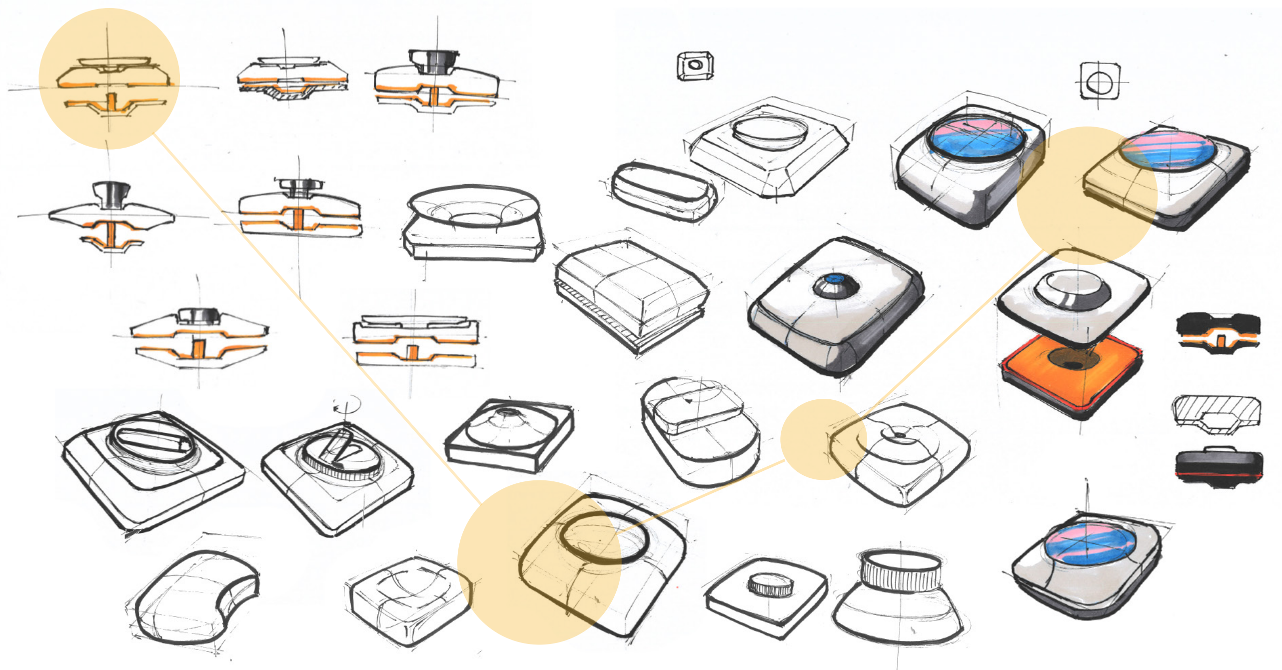


Figure 113: Sketches

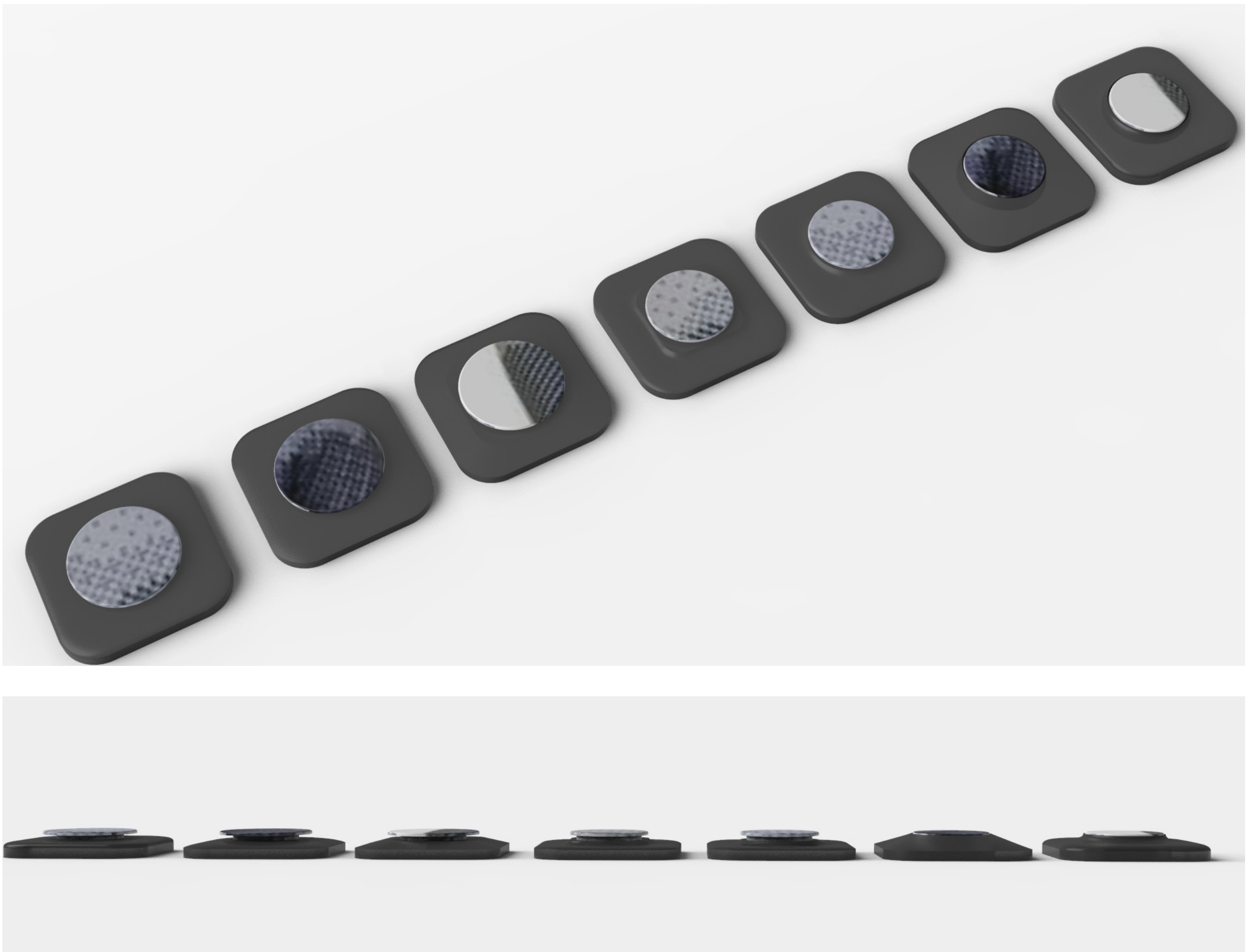


Figure 114: Quick 3d models

4.2.2 Design of the shirt

Figure 115: Shirt design

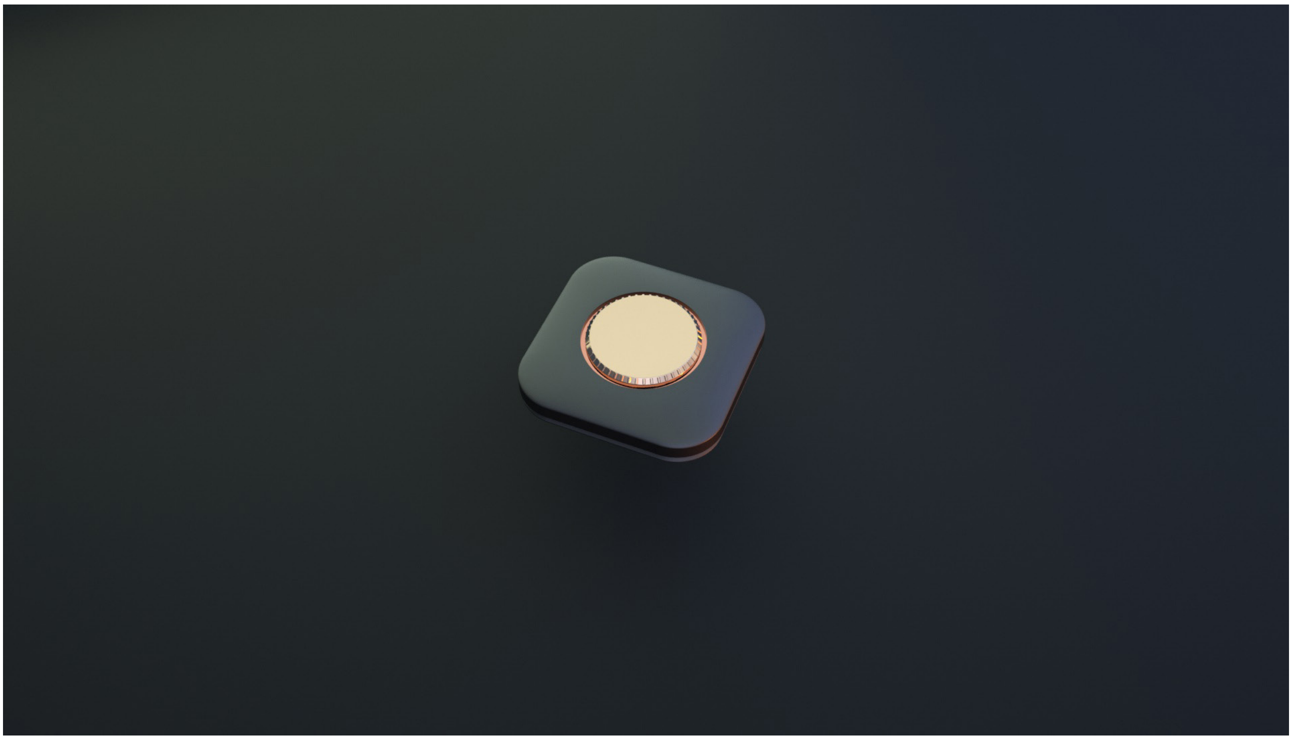
Here it also did some sketches on the possible looking of the cycling shirt(Figure 115).

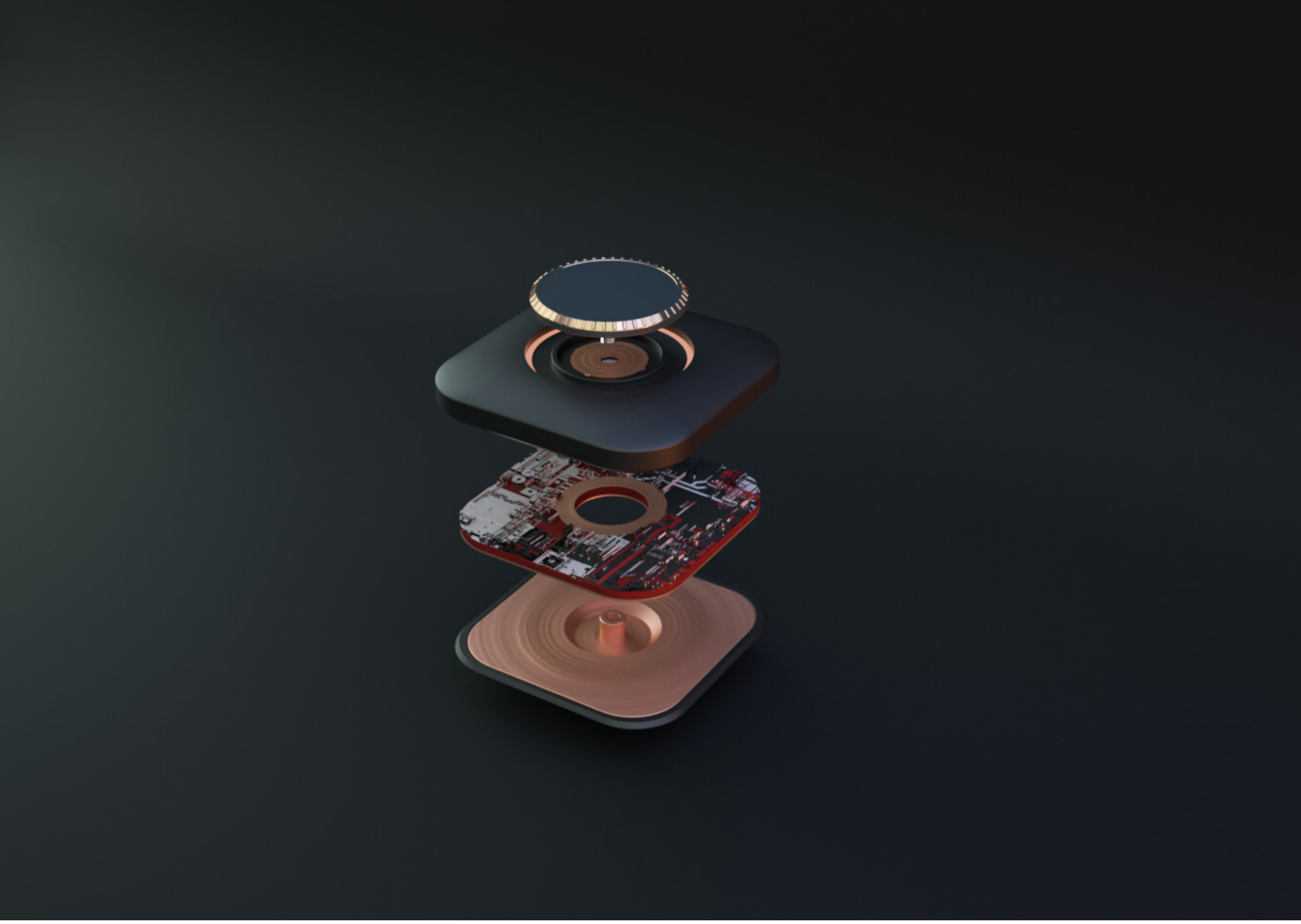
These sketches will be used for building the final prototypes and a preliminary inspiration for the fashion designers who will work on this project later.

4.2 Final design

4.2.1 General feeling

The whole design is in a gentle curvature shape, thus it gives a sense of comfort and thinness. The main body is painted in matte grey, which makes it look “hiding in the shirt”.






4.2.2 Inner structure and working principle

Section view

Figure 116 shows the inner structure of the design.

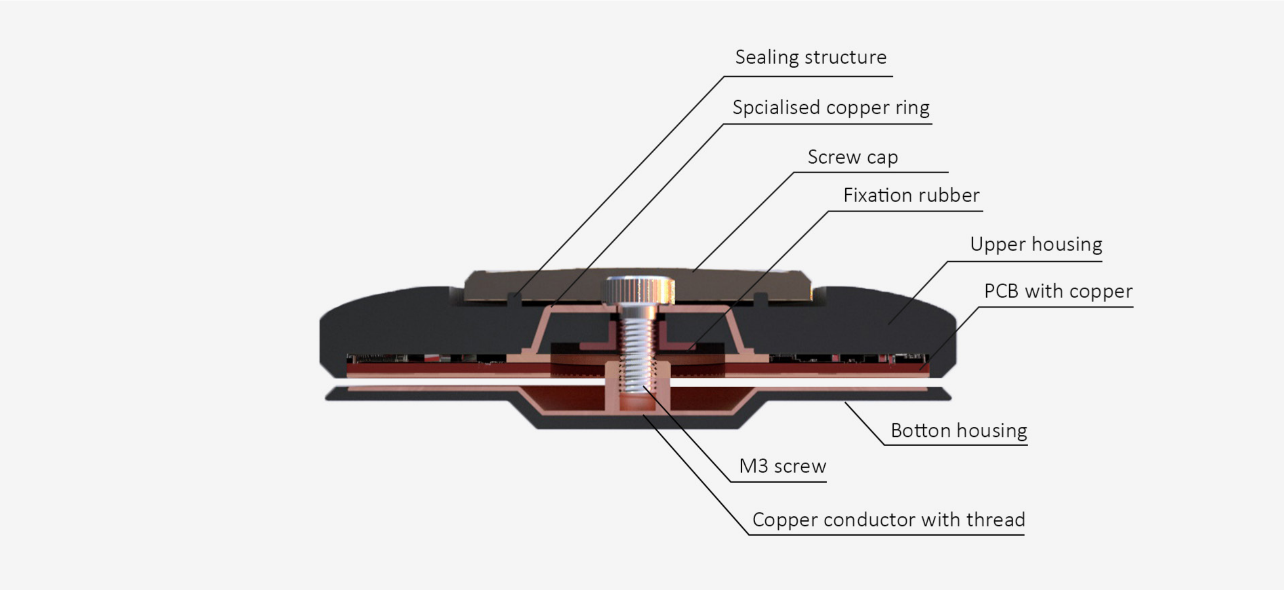


Figure 116: Section view

Conductive mesh

The conductive mesh is an assembly of three layers of fabric: two layers of conductive fabric and one insulation layer. The insulation fabric layer in the middle of the conductive fabric. Plastic eyelet rings are installed at specific areas on the conductive mesh for the fixation of the electronics, as shown in Figure 117. The conductive mesh will be sewed on the back of the cycling shirt as a piece of fabric.

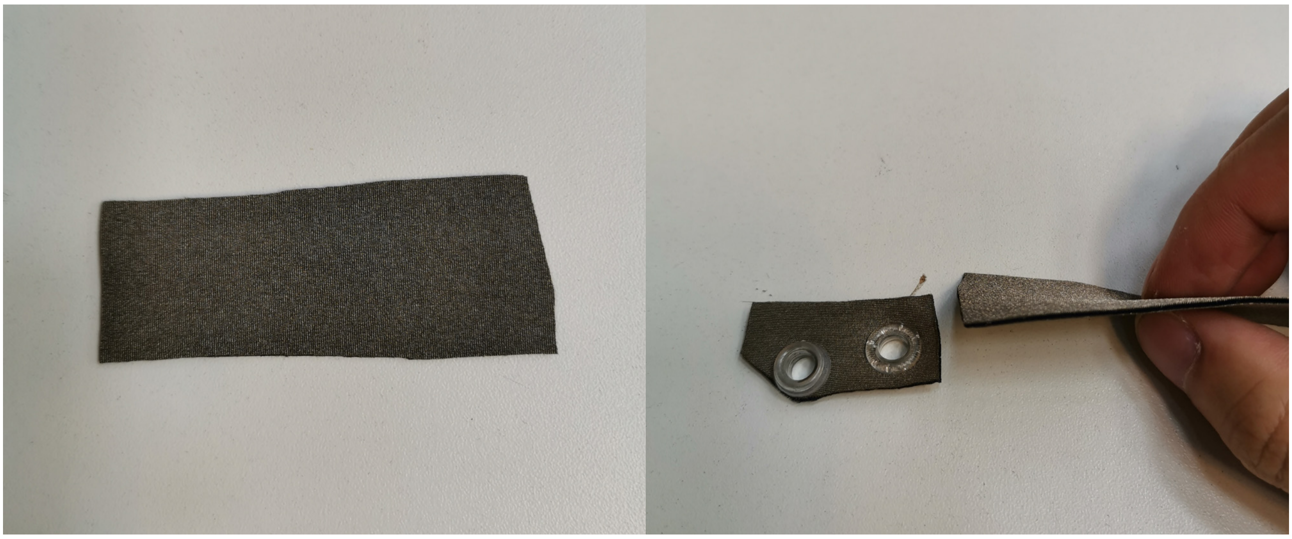


Figure 117: Conductive mesh and eyelet ring

PCB design

The PCB has a two-sided structure: one side with all the electrical components soldered on, the other side is mounted with the silver grid to have contact with the conductive mesh(Figure 118). There is a 12mm hole in the middle of the PCB, to leave enough space for the eyelet ring.

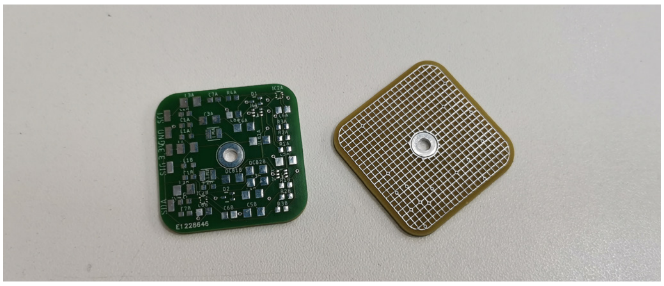


Figure 118: PCB design

Assembly

Figure 119 shows the assembling process of the modular design. Put the bottom part underneath the conductive mesh; put the copper tube with thread through the eyelet ring; put the upper part on the other side of the eyelet ring; use the finger to rotate the screw cap until the two parts are compressed.

Figure 119: Assemble process

Circuit diagram

Figure 120 shows the circuit flow of the finished assembly.

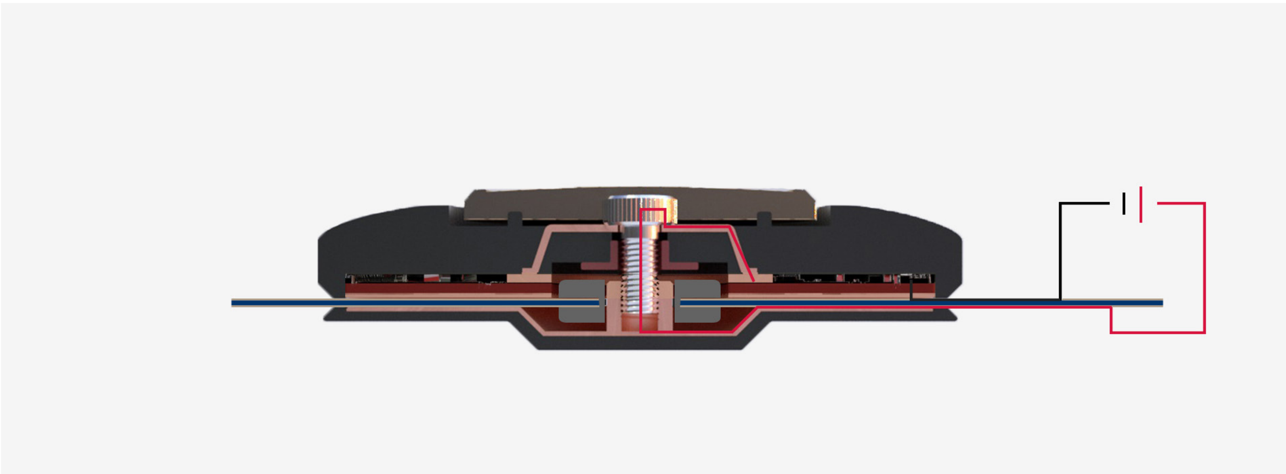


Figure 120: Circuit flow

2-wirings I2c system

Figure 121 shows the working principle of the electrical system for this project.

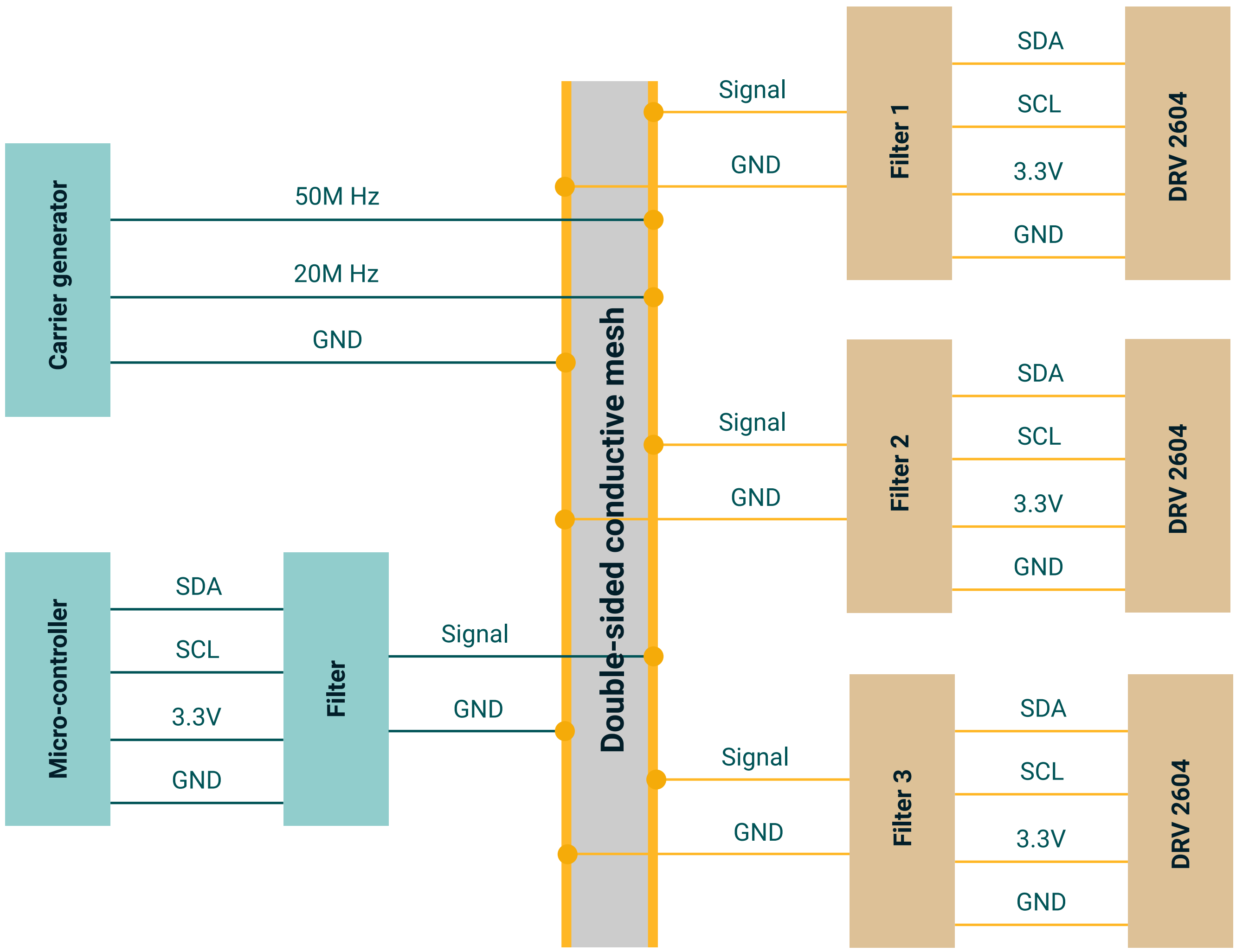


Figure 121: 2-wirings I2c system

4.2.3 Design details

Screw cap

The screw cap(Figure 122) is fixed with the hexagon screw. It enlarges the surface of the screw, making it easier to rotate. Some quick prototypes are made to find the best form for rotation, the details can be seen in Appendix C.

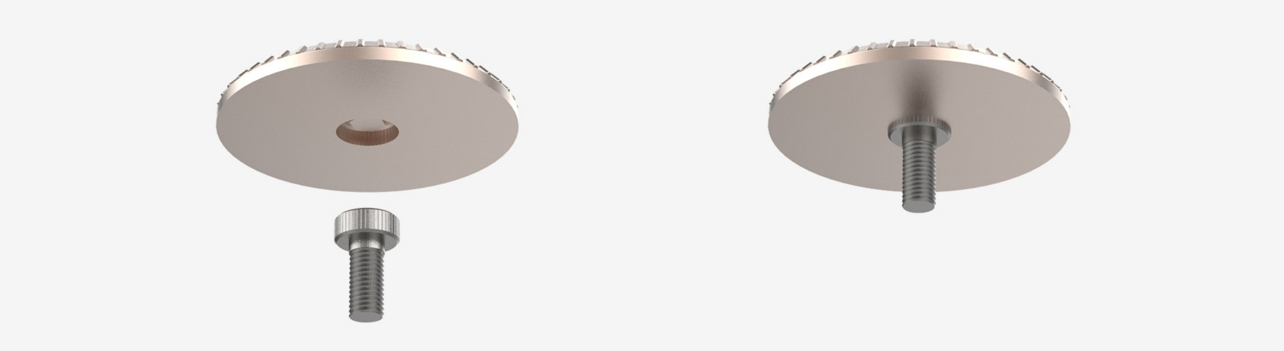


Figure 122: Screw cap design

Waterproof

The housing completely covers all the electronic parts. An extra sealing structure(Figure 123) on the upper housing is compressed by the screw cap. It prevents the rain fall inside the housing, which could leads to a short circuit.

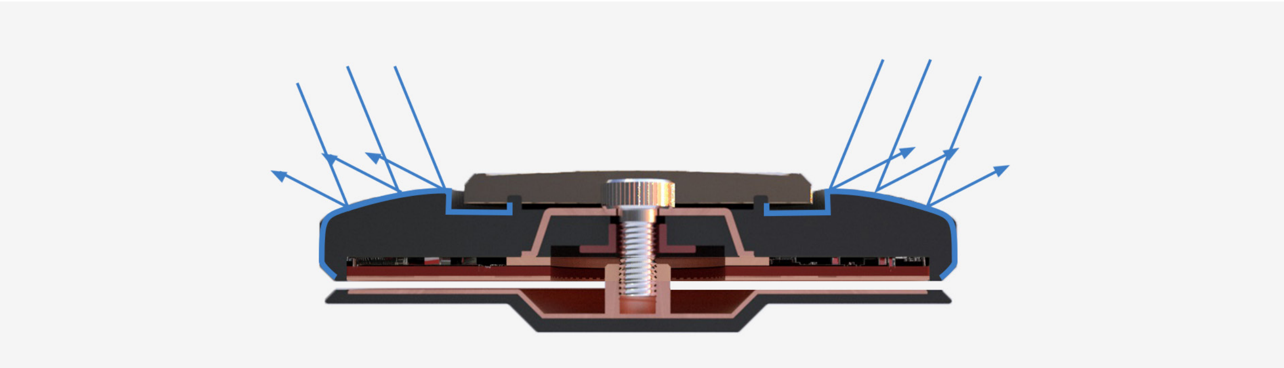


Figure 123: Sealing structure

Specialised copper ring

The copper ring is aimed to have contact with the screw. It is soldered on the PCB and moulded inside the housing, as shown in Figure 124.

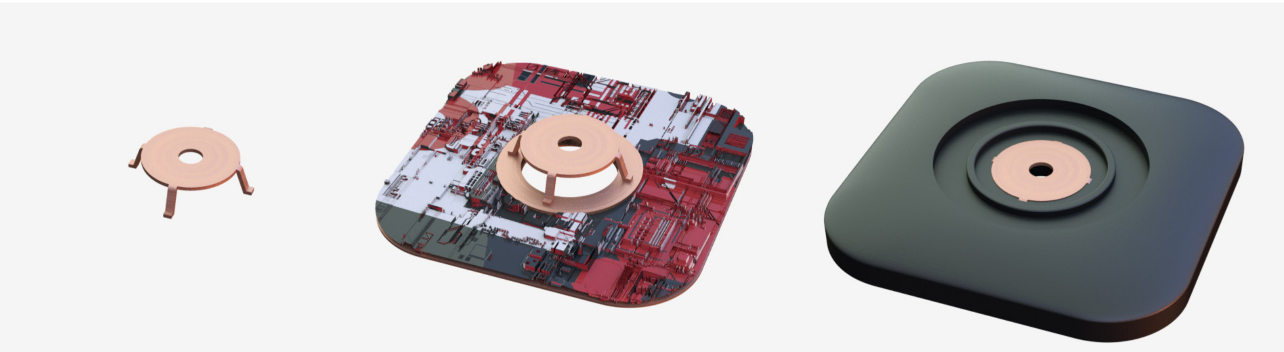


Figure 124: Assembly of the copper ring

Fixation rubber

The fixation rubber(Figure 125) is fixed on the screw by friction. It prevents the screw detach from the upper housing when the upper and bottom housing are not assembled together.

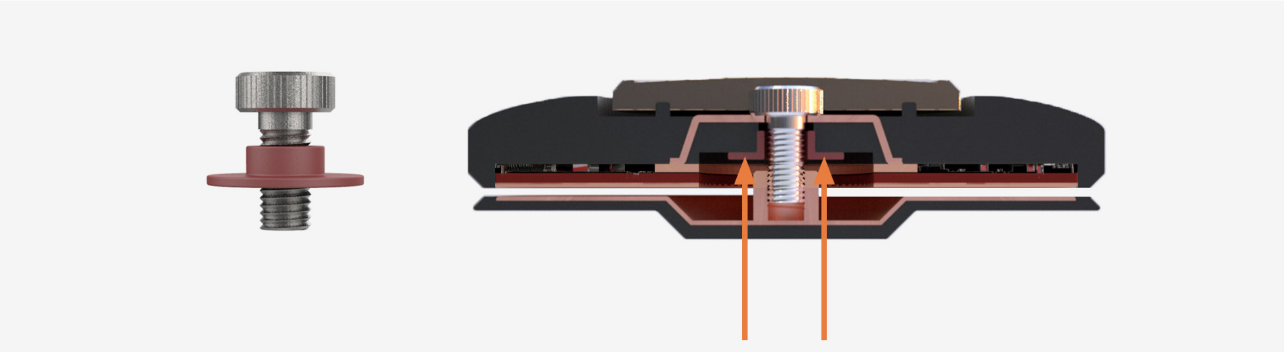


Figure 125: Fixation rubber

Groove

The groove design(Figure 126) makes it easier to detach the two housing parts.

Figure 126: Groove design

Bottom housing shape

The design of bottom housing(Figrue 127) reduces the contact area with human skin, so that it is more comfortable for wearing the shirt.

Figure 127: Bottom hosuing shape

4.2.4 Scales and technical drawings

Figure 128 shows the technical drawings of the design. Compared to the last iteration, the thickness is reduced from 22mm to 12mm.

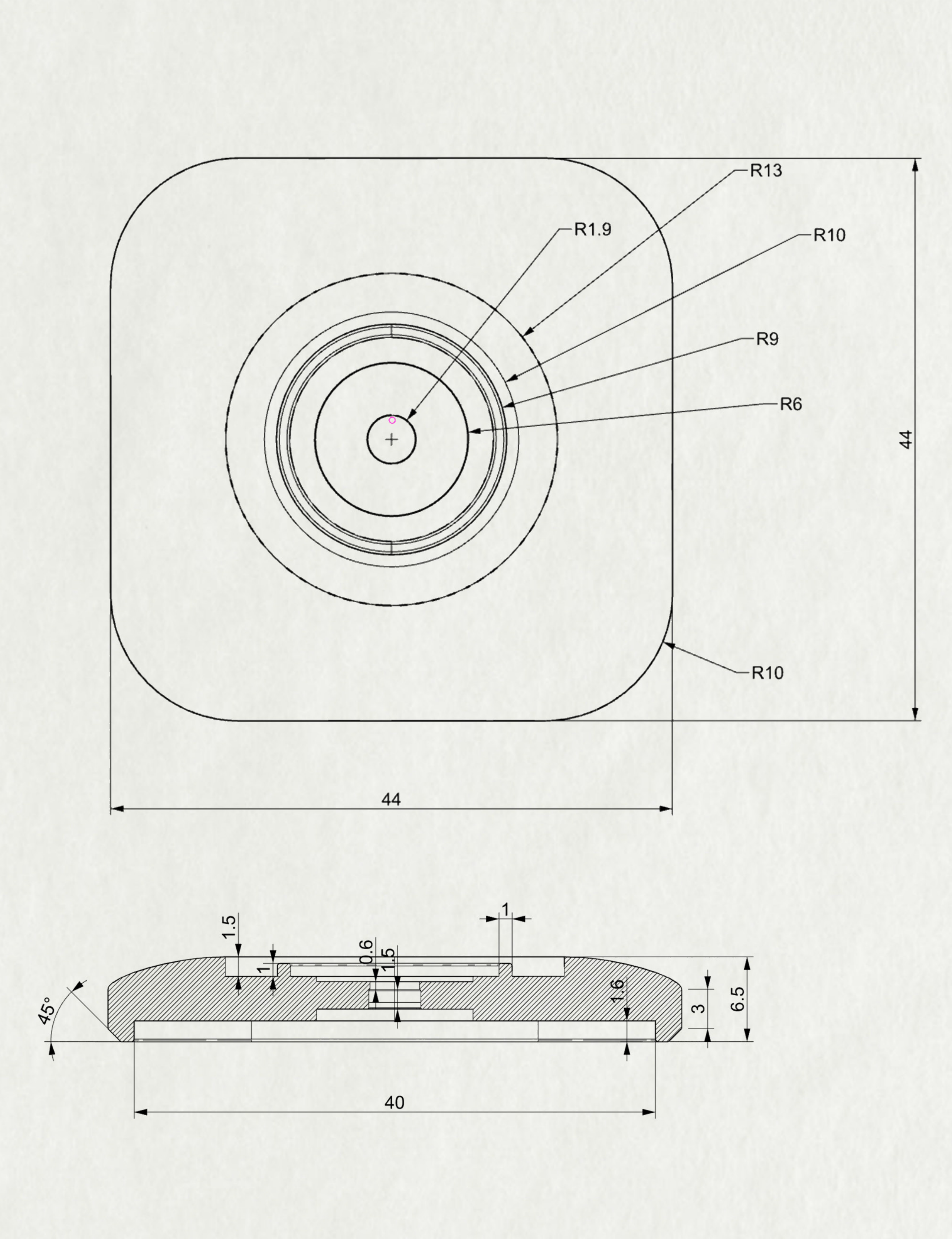


Figure 128a: Technical drawing of the upper housing

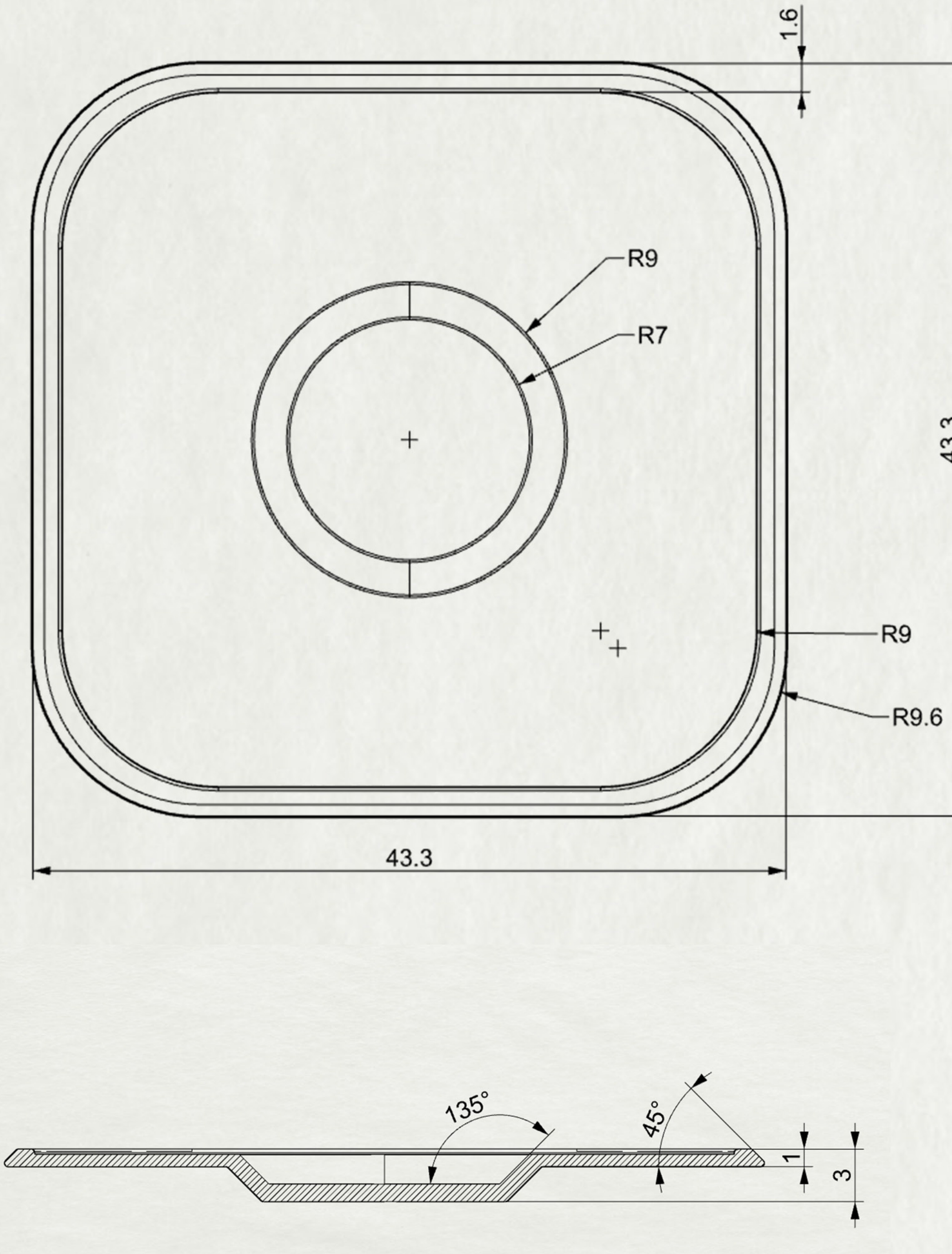


Figure 128b: Technical drawing of the bottom housing

4.2.5 Customized Screw cap

To make it more personalized and match the aesthetic of different textiles, the screw cap is designed in a modular way so that only the cap needs to be painted in different patterns instead of the whole housing. That is also one of the reasons why the surface area of the cap is that large.

Chapter 5 Embodiment Design

This chapter elaborates the material selection and manufacturering process for the design. A prototype is made. There is also cost estimation in the final section.

5.1 Material and components selection

Table 12 gives the manufacturer information of all the components of the design:

Table 12: Material and components selection

Components	Material/Type	Manufacturer/ Website link	Price
Screw cap	ABS	Custom made	Estimated €0.49
Screw	Hexagon M3*8mm Steel screw plated with silver	Standard steel screw can be bought from: https://www.banggood.com/120PCS-M3-Allen-Bolt-Hex-Socket-Head-Cap-Screw-Nut-Assorted-Kits-5-20mm-p-1166156.html?rmmds=buy&cur_warehouse=CN	around €0.01 per piece
PCB	one side components, another side is the silver grid	/	/
Specialised copper ring	silver-plated copper	Custom made	Estimated €1.14
Upper housing	TPR80-90 shore A	Custom made	Estimated €1.1
bottom housing	TPR80-90 shore A	Custom made	Estimated €0.63
Copper conductor with thread	silver-plated copper	Custom made	Estimated €1.31
Conductive fabric	Kaztex silver-plated fabric SCN016-YL	https://www.silver-fiber.com/	€30 per square meter
Insulation fabric	Extreme textile 72139, 75% Polyester (PES), 25% Polyurethane (PU)	https://www.extrem-textil.de/en/lining-laminate-z-liner-elastic-waterproof-breathable-white-95g-sqm.html	€4.78 per meter(1450mm in width)
Eyelet ring	PC 350#5.5*10.5*6mm	https://item.taobao.com/item.htm?spm=a230r.1.14.30.5abb5870jCyK-Wa&id=549262322904	€3.5 per 100 sets
Fixation rubber	rubber	Custom made	€0.34

The decision of silver-plated conductor

All the conductors in the design are recommended to use the same material to prevent galvanic corrosion. Galvanic corrosion is an electrochemical process in which one metal corrodes preferentially when it is in electrical contact with another, in the presence of an electrolyte(Wikipedia, June 2020). A similar reaction also happens inside the primary cells.

In the working environment of this project, the module will be exposed to human sweat and rain, which can be considered as an electrolyte. It is important to use the same surface material to avoid corrosion. The reason for choosing silver is because of its solderability and anti-corrosion performance. The conductive mesh is using silver-plated technology as well. On the other hand, though copper is easily corroded when exposed to air, it is much cheaper than silver. A good strategy is using copper as the inner material and plate a thin silver layer outside the copper conductors, thus it is solderable, anti-corrosion and cheap.

There is no specific material required for the screw. It can be easily found with a steel screw, while a copper M3 hexagon screw is not. Thus it is recommended to plate silver to the standard steel screw.

TPR for the upper housing

Due to the complex structure and fastidious requirements on the thickness, moulding is suggested the most accessible and cheapest fabrication method for the housing. TPR is a common material for this technique. It has outstanding chemical resistance and high impact strength(Star rapid, n.a.), which makes it an ideal insulation material of the cycling environment. There are several reasons for choosing TPR:

1. TPR is softer than plastic material like ABS, thus makes the module less aggressive and less likely to hurt the user when it accidentally breaks.

2. Insert moulding is suggested as the fabrication method for the housing(the reason will be explained in Chapter 5.2). The injected material will have close contact with all the electrical components. In contrast, the rigid material like ABS has the risk to make these soldered electronics dislocated because of the deformation during curing. Soft materials like TPR can avoid this problem.

3. The injected thermoplastic will completely fill the inner space of the assembly. It gives enough physical support for the specialised copper ring to withstand the force placed by the screw. What is more, this solid structure is suggested to have less attenuation for vibration transmission compared to cavity structure.

The shore hardness is a typical value to describe the hardness of polymers(like Rubber, plastics). Table 13 gives a feeling of the shore value by conventional products. For this project, it is suggested to have 80-90 shore A for the TPE housing, which has a right balance of the physical strength and softness.

Table 13: The shore values for common applications

Hardness	30 Shore A	40 Shore A	50 Shore A	60 Shore A	70 Shore A	80 Shore A	90 Shore A
Application	Art gum erasers	Can tester pads	Rubber stamps	Screen wiper blades	Shoe heels	Shoe soles	Type-writer rollers

ABS for the bottom housing and the screw cap

ABS is the most common thermoplastic material for moulding. It is solid and provides excellent physical strength. Considering the thin metal sheet for the bottom copper conductor, the housing is necessary to have rigid support. That is why it is using ABS instead of TPR here. The screw cap can use ABS as well. The fixation of the screw and the rotation requires a high physical strength for the screw cap, thus ABS is chosen as the material.

PC for Eyelet ring

Most eyelet rings in the market are made of metal because they have better tenacity when deformed. However, in this concept, the metal eyelet ring will connect the two sides of the conductive mesh. This will result in a short circuit and lead to the failure of the whole system. It is necessary to use the insulation material for the eyelet ring. PC eyelet rings are the only standard product available in the market.

5.2 Manufacturing techniques & process

5.2.1 Manufacturing techniques

Insert moulding of the TPR housing

Insert moulding is the process of moulding the molten material around the inserted component to produce a finished multi-components part(Stack Plastics, INC.). It reduces the cost, does not need an extra sealing process for waterproof, and as mentioned in Chapter 5.1, it gives enough physical support and is good for the vibration transmission as well. Figure 129 shows the preliminary idea of the moulding.

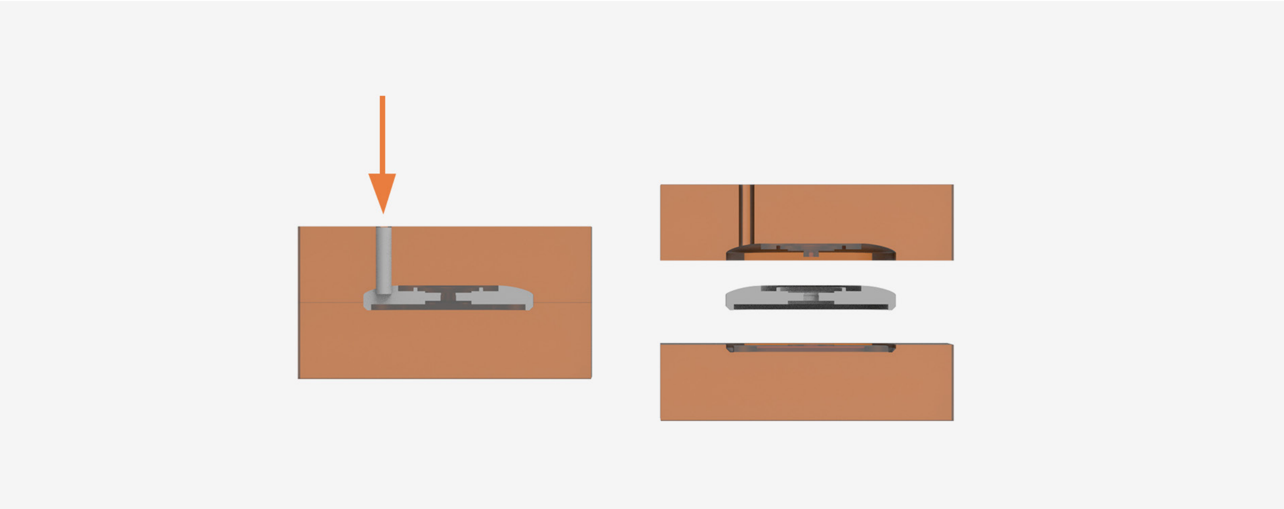


Figure 129: Illustration of moulding

Stamping forming of the specialised copper ring conductor

The specialised copper ring conductor can be produced by stamping forming processes. This process is to place the flat sheet metal into a stamping press machine, where the material will be stamped into a particular shape by the tool and die surface. Figure 130 shows the preliminary idea of the stamping.

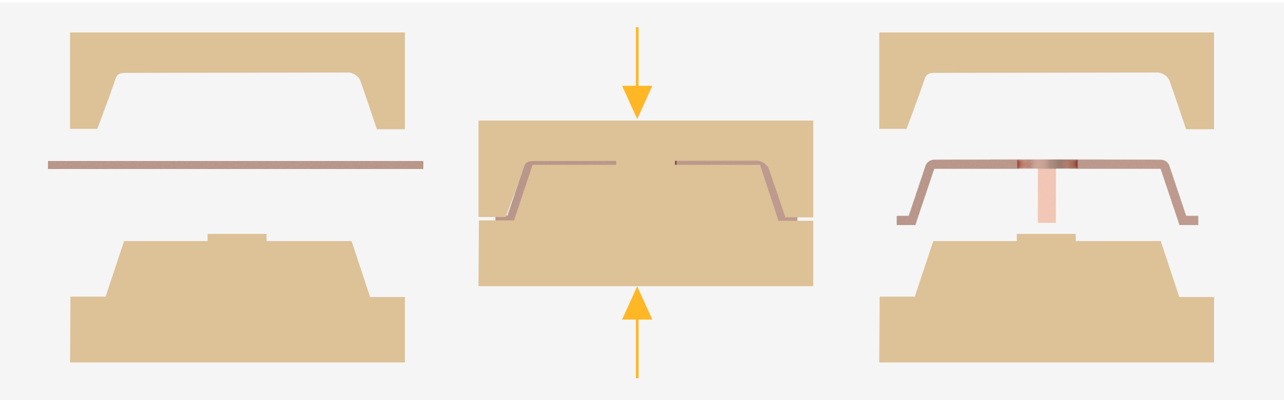


Figure 130: Illustration of stamping

Stamping forming and welding of the bottom copper conductor

This bottom copper conductor consists of a thin copper pad and an 5mm copper tube with the M3 screw thread. The stamping process can also be used in the copper pad production of the bottom copper conductor. The copper tube can be bought directly. When cut in proper length, the thread can be drilled. The finished copper tube and the copper pad can be welded together.

Set up of the conductive mesh

The finished cycling shirt is made by sewing different textile parts together. Chapter 2.2.3 already explains the heat press process of making the double-sided conductive mesh, so it is more interesting just to explain the following steps.

Laser cutting fabric

Cutting fabric is one of the essential processes during clothes production. Laser cutting, which is already widely used in the high-end garment factories, is a highly efficient technique for this process. It is fast, accurate, and most importantly, it can prevent the shortcut of the two-sided conductive mesh. For the hand cutting, it has a great chance that some fibres are exposed to the unclean cutting edge, thus the top conductive surface connects to the bottom conductive surface. Considering the multiple cutting times(basic shape and the holes for all eyelet rings), there is a big possibility that the finished conductive mesh assembly is not insulated from top to the bottom.

However, laser cutting can solve this problem. The edge cut by the laser gun is clean, and the edge is also burnt a bit. The burnt edge is ideal for removing and insulating the exposed conductive fibres. Figure FIXME shows the section view of the hand-cut edge and the laser-cut edge. What is more, with the proper setting, all laser cut garments can be considered having the same performance. It helps to keep the products the same standard and makes sure there is a high qualification rate.

Eyelet ring stamping

The plastic eyelet ring is often thicker than metal as it needs to stand enough physical strength. Thus the plastic one is more difficult to stamp compared to the metal one. Using a manual tool for stamping could lead to failure(Figure 131). Fortunately, most factories have a more professional stamping tool to keep the stamping process perpendicular to the operation surface(Figure 132).

Figure 131: Successful eyelet ring(top) and failed eyelet ring(bottom)

Figure 132: Stamping machine

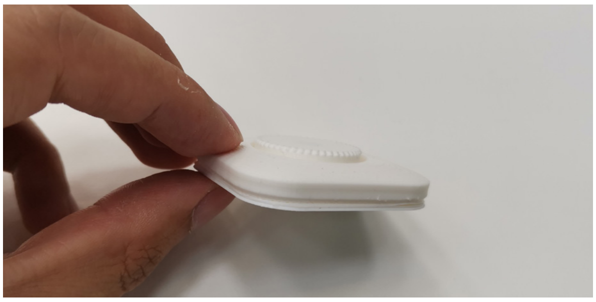
5.2.2 Manufacturing processes

Figure 133 shows the manufacturing processes.

Figure 133 : Manufacture process

5.3 Prototyping

It shows the final prototype. In this prototype, the double-sided conductive mesh is stitched on the cycling shirt. Seven modular mechanism are assembled on the shirt as well. The system is driven by Arduino. In one mechanism, it is connected an LED to show the working status. The Arduino is running the "blinking" program, thus it can be seen the LED flashing constantly.



5.4 Cost Estimation

According to the input from Elitac, the finished cycling shirt should be sold no more than €212. It includes €50 for the computer part, €10 for the electronics per unit and at least 50% profit. For the cycling shirt, the mobile phone can be used instead of a seperate computer. So it excludes the cost for computers in this estimation. The cost for the cycling shirt should be less than €140(including 7 units and the shirt itself). The pure cost for the housing and shirt are around €70. Considering the cost for the shirt, the seven housing should be less than €40. That is around €5.7.

In the scale of 10,000 production quantities, the cost of manufacturing one module is estimated €5.05 excluding the PCB. The total cost is estimated as €44.8 including the conductive mesh, seven eyelet rings and seven sets of modules. The cost of PCB, labour and deliveries are not included. The detailed calculation can be seen in Table 12 and Appendix D.

Chapter 6
Recommendation & evaluation

Recommendations are given in this chapter. The final design is seen as a totally innovative technical solution that differs any products in the market, which has a great market potential. Designers and engineers could improve the current design and do more performance tests to make the production ready. This project, however, is finished in terms of the graduation project. The evaluation for the design process is also given here.

6.1 Recommendation

Conductive fabric

Now it is using the silver-plated fabric produced by Kazhtex. This fabric has a good performance on the physical properties and conductivity. However, the fabric can only be screen printed(Figure 134) or printed by a sublimation machine(Figure 135). The screenprint and sublimation can not be used freely either. Careful consideration needs to be made to maintain the contacting area between the conductive fabric and the modular mechanism. A larger area of screenprint will also add extra thickness and reduce the breathability of the cycling shirt. These difficulties may lead to a result that there is a big chance that there will be a piece of fabric of the shirt in brown, which is the original colour of the conductive fabric.

The brown area could significantly limit the look and feel design of the shirt. Fashion designers have to put more effort into dealing with the color, while this brown color does not always match the sporty style.

However, this problem could be solvable. The conductive fabric of Kazhtex is made by knitted silver-plated conductive yarns. To give more aesthetic opportunities, the conductive yarn could also be knitted with many other different yarns. Thus the finished raw fabric will have other looking, and it is not needed to do the printing on the fabric afterwards. Reduce the usage of conductive yarns will probably reduce the conductivity of the fabric, but it can be covered from other aspects, such as larger fabric, extra thickness.

To get a specialized fabric needs to cooperate with the manufacturer closely, and it takes time. It is recommended that Elitac need to plan as early as possible if Elitac decides to go in this direction.

Figure 134: Screen printing

Figure 135: Sublimation

Various size

It is recommended the housing should have a set of fixed sizes(e.g. small: 44mm * 44mm, medium: 55mm * 55mm, large 60mm * 60 mm) instead of redesigning the whole housing when integrating different electronics. This will reduce the cost of mould for injection moulding, time and labour significantly. Defining the exact dimensions for these types needs careful calculation and decision according to Elitac current smart system and the company's future direction. Without fully understanding all this information, the example dimensions mentioned above is just to give an elaboration.

Be aware of the silver price

Due to the overprinting, there is a significant devaluation of USD from March of 2020. Till August 1st of 2020, the USD already devaluates 20%. This leads to the appreciation of precious metals(Figure 136), which also includes silver, the raw material of the conductive fabric. In the foreseen 2 or 3 years, the price of these metal will not drop so easily. Elitac should keep a close eye on the supplier of the conductive fabric because the price of these silver-plated products already starts fluctuation.

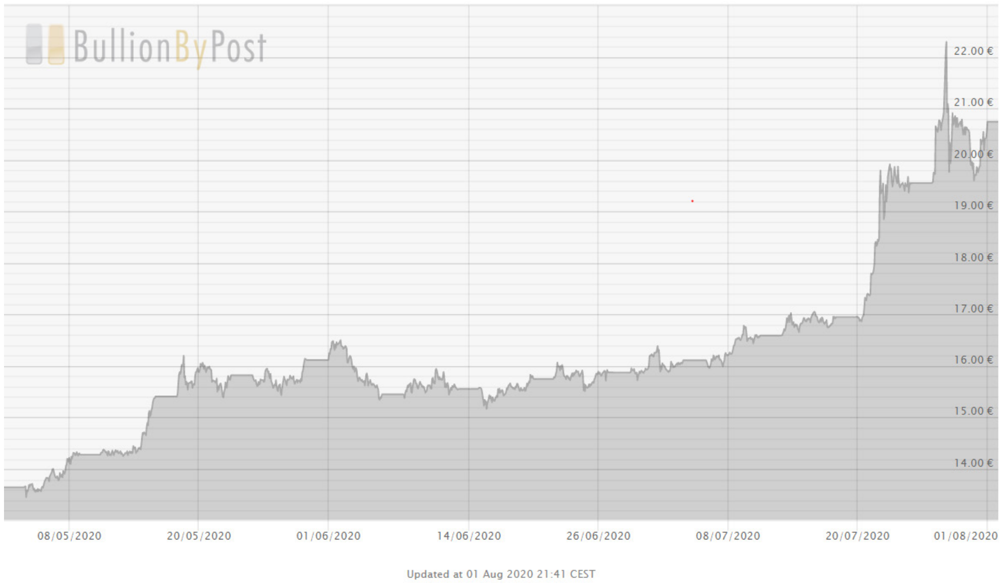


Figure 136: Silver price from May 2020 to August 2020

More study on user interaction and ergonomics

In this project, it is more focused on finding a technical solution, while less effort was made on studying user interaction. To make it a good commercial product, perfecting the user interaction is necessary. For the next project, it is proposed the following studies:

Contact area with skin:

The bottom part of the design will have direct contact with skin. It is not clear yet what size and shape will have the least influence on user comfort. To find the best form, it could be to set up a test with a series of different sizes' bottom housing with real cyclists. The round corner of the contact area can also be studied along with the test.

Assemble time

Based on the requirement 10, the whole system should be set up in 2 minutes. Considering getting the products out of the packaging box, running the software and connecting with the power supply are also time-consuming, it will be good if each haptic module can be assembled in 6~7 seconds.

Because the screw pitch of the current design is too small, it needs 5 turns or more to fixate the two module parts properly. With 7 haptic modules, this assembly process can be painful and time-consuming. If a higher pitch screw can be found, it could be an optimization. However, a new way of connection is also worth exploration instead of a screw. Chapter 1.3.1.6 showed the magnetic pogo pin, which could be an option. A specialised magnetic pogo pin needs to fit the current eyelet ring structure, which also has a risk of having an extra thickness for the whole module. Thus it should be considered carefully if a new connection mechanism worthies investment.

6.2 Evaluation

Methodology

The diverging-converging model is used as the primary methodology in this project. This idea is through the whole project. In the research phase, it is first explored various interconnection techniques and wirings. With careful comparison and analysis, the scope is narrowed down to 4 promising wirings. Trend analysis and user journey map are used to form the list of requirements for the project. After that, there are several rounds of ideation and design iteration. Datum method and Harries profile are used for making the design decision during each round. These methods prove to be really helpful for boosting the project.

Result

The project has an excellent result. Checking with the design requirements and the design goal, it is not difficult to see most of the requirements are fulfilled. Among them, requirement 2, 3, 4, 5, 7, 10, 12, 14, 15 and 16 are fulfilled and validated. The list of requirements is formed for making a commercial product. Thus it is not possible to validate all in this six months' project. However, all requirements are considered carefully along with the design process, and the end results seem promising. Even though requirement 1, 6, 8, 9, 11 and 13 have not been tested yet, the final design already shows the great possibilities for a successful product. The result can be a remarkable starting point for the next project, and I believe Elitac and the faculty will love the result.

Project management

It turns out to be successful management of this project. It left some flexible time during each design stage to prevent the unexpected issue. Working from home is challenging at first, as it makes people more difficult to concentrate. However, when getting used to it, I feel even more efficient with this working status. It also results in two weeks more advance than planned, so a new design iteration is made during this time. That adds great values for this project.

Communication

The coronavirus did not influence close communication with the supervision team. At all milestones of these projects, it makes sure that the opinion of all the supervision team members is carefully considered. All essential design decisions are made with the whole team. It also has frequent consultants with many experts to get insights and practical instruction on research, design, electronics and manufacturing. The proper communication with the supervision team and all these experts help the project be promoted smoothly.

Reflection

During the five tough months, I did not think of much about my personal feelings. When it comes to an end, complex emotions and memories start to immerse. I believe it is the right time now to write them down.

As an international student, I had a struggling time when I entered this faculty for the first year. The way of design is quite different from my previous experience, where the cultural shock even enlarges the cognition gap. I have experienced a time that it seems all the teachers in the faculty are against me and force me to accept the Delft method. This feeling reached a peak when I got a red light alert for my midterm presentation of AED. But that is also the time that I started to reflect myself seriously and try to understand the design logic of this faculty. Thanks for the tough time, I began to integrate Delft design method into my own design thinking, and it really helps the afterwards projects and even the difficulties in my life.

I learnt to do the reflection.

During the graduation project, I occasionally ask for the general feedback to Kaspar, Adrie and Guus, things like “am I in the right direction?”, “do you feel confident in me?”. Kaspar even tells me I do not have to be that nervous. I consider this as the sequelae from my tough time. On the other hand, I believe this self-reflection during the project and always ask for the input from my supervisor is a good strategy that keeps everything goes smoothly.

My supervisors are nice people, which makes communication even more straightforward. My unproven personal feeling is that it seems the technicians in the faculty are the most kindly people. To the contrary, technicians are usually the people I want to get least in touch in China. I still remember I just mentioned I could not access the internet during a free chat with Adrie. After one hour, he has already solved this problem for me, while I did not even ask him for help. Another time was I got negative feedback a month before the green light meeting. After the group meeting, I received the emails from Adrie and Guus. They helped me list the key points of the meeting, find some illustrations which could be helpful for the next meeting, and were worried I might be frustrated. At that time, I know they truly stand by my side and think for me. They are not just using students as a tool, which I know many people are doing so. These people make me have a sense of mission to deliver the best result, not only for me but also for them.

Taking a look at the whole project process, it fits my plan in general. Though there were issues like coronavirus, lack of material and divergence of design directions, we managed that. I enjoyed nearly all the parts of the design process, except for the reporting. Reporting is like a devil for most Chinese people as I know so far. It is not only because of the language but also because we did not get the training. However, if you ask me what is my biggest improvement during the two years master, I would say I learned how to write the report in Delft style. Still, I wouldn't say I like it though. Hopefully I will not write another one in the future.

In a nutshell, I really enjoyed this project and met so many nice people during the process. They do have not only the magnificent knowledge and academic attainments but also a pure and kind heart that is always willing to help. They worth their reputation and my highest praise. Thank you, Kaspar, Adrie, Guus and everyone who has helped me in these five months. This project will never achieve this progress without your help!

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Appendix A: Calculation of resistance

The tactile motors are placed on two traces: the horizontal trace and the vertical trace, see Figure 137. The horizontal vibration trace indicates the direction while doing navigation and the vertical one sliding vibrates to give feedback on the cycling speed. Both of the horizontal and vertical traces will only maximumly have one motor working at the same time respectively, which means this vibration system will have a maximum two vibration motor working at the same time.

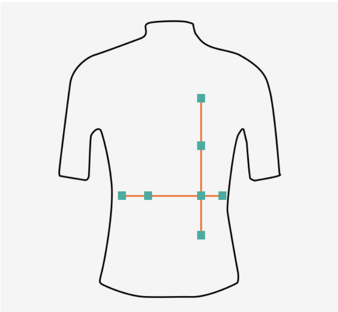


Figure 137: System illustration

All the tactile motors are using the parallel connection, as shown in Figure Fixme. Both the horizontal and vertical traces have four tactile motors, while there is one motor shared at the joint. In other words, there are seven tactile motors in this system. The furthest motor to the power supply is estimated at around 0.4 meters. While calculating the circuit, the length of the cable will be doubled to connect the motor to the power. That means the longest cable should be:

0.4*2=0.8(m)

This cycling shirt is using the DRV2604 as the tactile motor(see Figure 138). It starts working with 0.6A peak current, while the minimum required current to keep a motor running is 0.1A. In the ideal condition, the main current should be fulfilled as 0.7A(0.6+0.1).

Figure 138: DRV2604

Power supply by smartphones or power bank is usually 5V. The tactile motor works properly when getting an input voltage of more than 4V(). On the other hand, a lower voltage above 2.5V could also drive a tactile motor, while it takes a bit longer time to make it working properly(getting enough vibration strength). Based on this, the highest acceptable voltage drop is 2.5V(from 5V to 2.5V) to drive two motors running, while the ideal drop is less than 1 volt.

In the ideal condition:

The maximum resistance in the cable should be lower than:

R=1V/0.7A = 1.42ohm

The linear resistance should be:

R/0.8m = 1.78ohm/m

In the acceptable condition:

R=2.5V/0.7A = 3.57ohm

The linear resistance should be:

R/1m = 4.46ohm/m

For the conductive fabric and conductive sheet, it is using the sheet resistance unit “ohm.m”. To make it easy to compare with the linear resistance, the unit can be converted as follows:

For a 0.1mm conductive sheet, if an 1.75 mm conductive trace are made, the ideal resistance should be:

1.78 ohm/m * 1.75 * 10 -3 m * 10 -4 m = 3.16 * 10 -7 ohm.m

The maximum resistance should be no more than:

4.46 ohm/m * 1.75 * 10 -3 m * 10 -4 m = 7.81 * 10 -7 ohm.m

If the traces are made 10 mm wide, the ideal resistance should be:

1.78 ohm/m * 10 * 10 -3 m * 10 -4 m = 1.78 * 10 -6 ohm.m

The maximum resistance should be no more than:

4.46 ohm/m * 10 * 10 -3 m * 10 -4 m = 4.46 * 10 -6 ohm.m

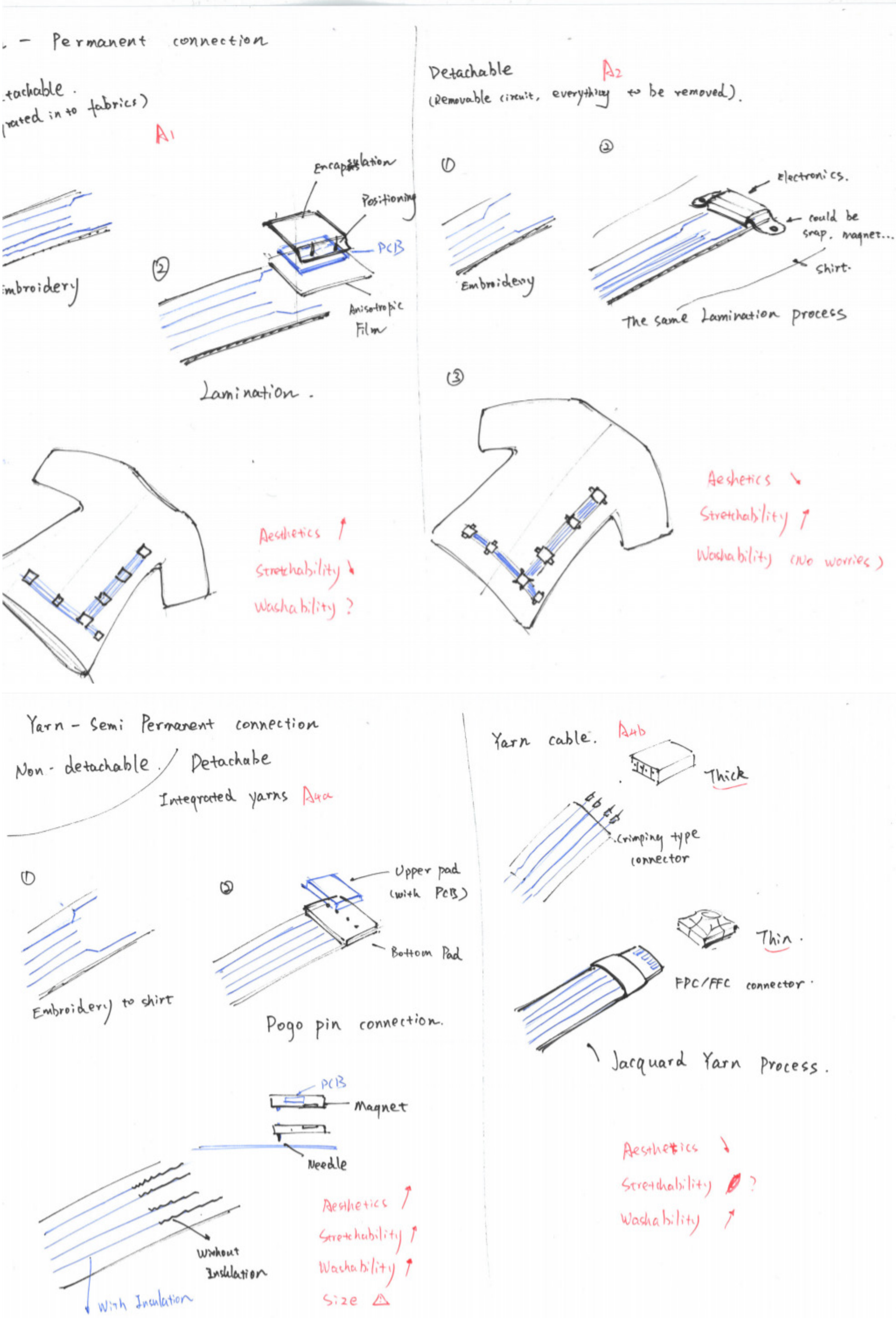
To conclude, the cable with the resistance lower than 1.78 ohm/m (3.16 * 10 -7 ohm.m for 1.75 mm wide trace and 1.78 * 10 -6 ohm.m for 10mm wide trace) is the ideal choice. If can not be fulfilled, the resistance must lower than 4.46 ohm/m (7.81 * 10 -7 ohm.m for 1.75 mm wide trace and 4.46 * 10 -6 ohm.m for 10mm wide trace) to keep the system running.

To have a feeling of the sheet resistance, the sheet resistance of the common material can be seen in Table 14.

Table 14: Resistivity of the common material

Metal	Resistivity /(W m)	Material	Resistivity /(W m)
silver	1.6×10^{-8}	carbon	35 to 5000×10^{-8}
copper	1.7×10^{-8}	graphite	800×10^{-8}
aluminium	3.2×10^{-8}	germanium	0.65
lead	21.0×10^{-8}	silicon	2.3×10^{-3}
manganin (alloy)	44.0×10^{-8}	pyrex glass	10^{12}
eureka (alloy)	49.0×10^{-8}	PTFE	10^{12} to $\times 10^{16}$
steel (varies)	10 to 100×10^{-8}	quartz	5×10^{16}

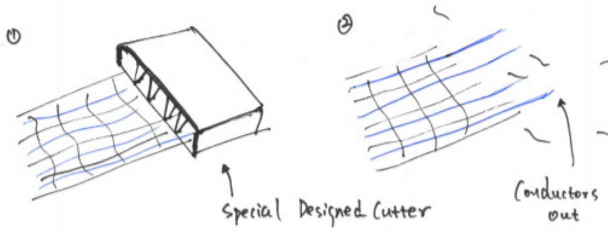
Appendix B:Sketches of ideas

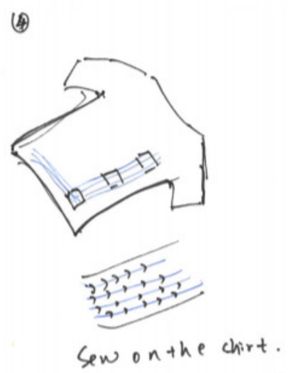


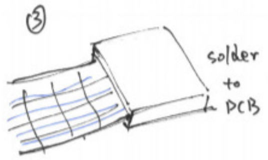
Textile Ribbon cable

(Example : Amohr Tape)

Permanent connection. B1







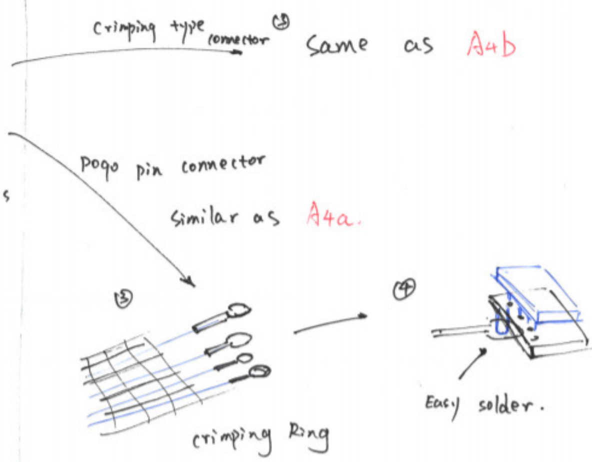
Aesthetics ↘

Stretchability ↗

Washability ⚠

Semi-permanent connection. B4

(~~conduct~~ connectors)



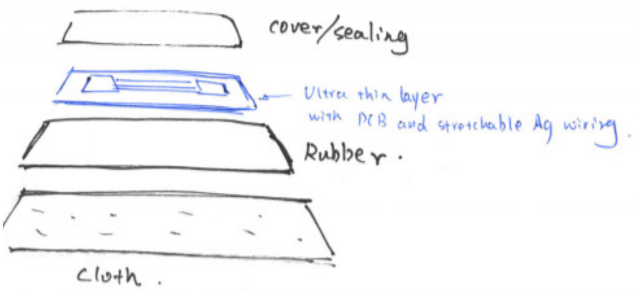
Aethetics ↘

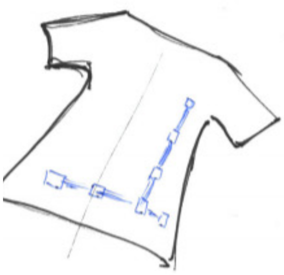
Stretchability ↗

Washability ↗

Laminated cable.

Permanent connection. C1





~~Aeth~~

Aethetics ↗

Stretchability ↗

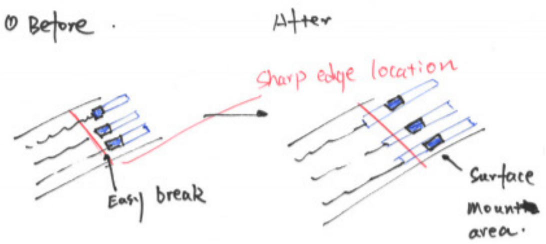
Washability ↗

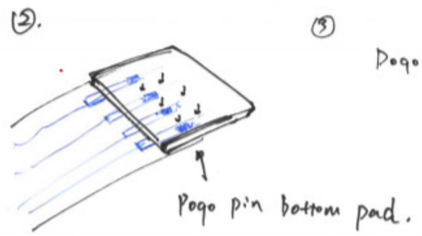
Sealing ⚠

Mass-production size/scale ⚠

Semi-permanet connection. C3

(Improving the copper-PU FPC).





③ Pogo pin connect

Aethetics →

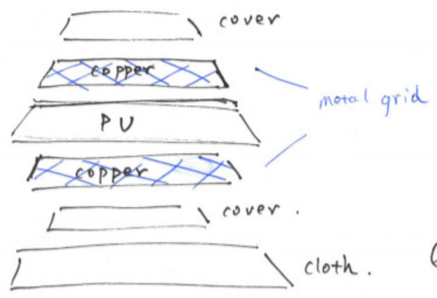
Stretchability ↗

Washability ↗

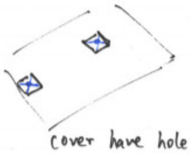
Conductive Mesh.

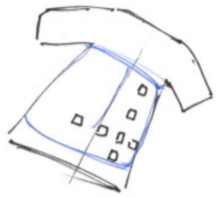
Semi - Permanent connection. D3

①

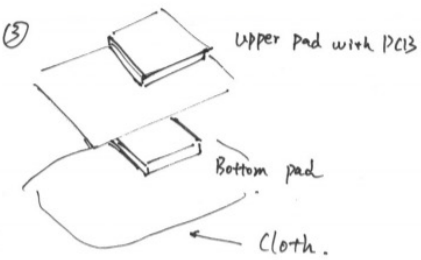


②.





③



Aesthetics →
Stretchability ↗
Washability ↗
Modularism ↗
Signal reliability ↘

Appendix C: Screw cap selection

The main function for the screw cap is to enlarging the force area. According to Requirement 10, each module should be assembled in 15 seconds. To get the ideal form of the screw cap, it is designed several caps(Figure 139) and measured the assembling time duration with the current housing design(Figure 140) for each of them. The results are recorded in Table 15.

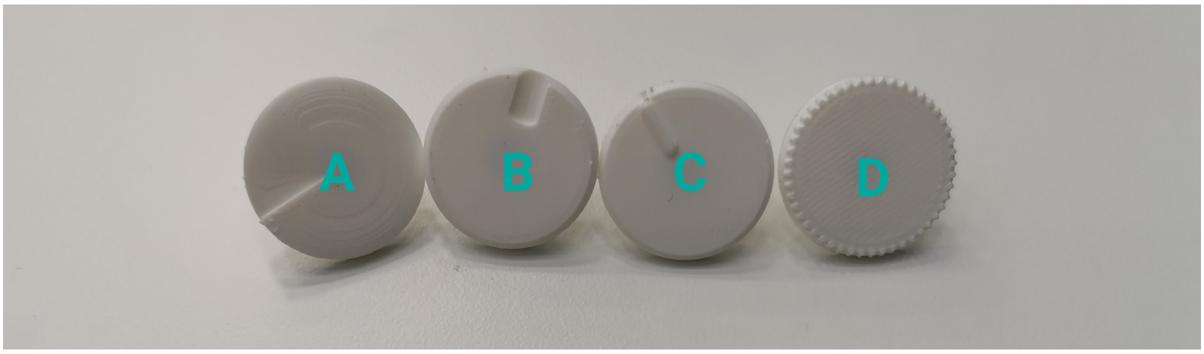


Figure 139: Form of the caps

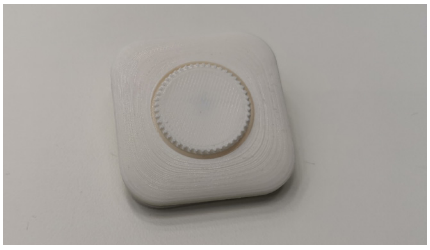


Figure 140: Form of the caps

Table 15: Results of assemble time

Cap	A	B	C	D
Assemble Time	10s	9s	11s	5s

In the test, it is using one-finger operation to rotate the cap disk. An interesting finding appears during the test.: For form A, B and C, the notch which adds friction to help rotation is only in one direction. During the rotation, these notches sometimes dislocate with the operation finger because the finger was rotating too fast. This significantly increase the assemble time. On the other hand, form D have notches in all directions and do not have this problem. Based on the test result, the ideal choice of the screw cap design is form D.

Appendix D: Cost estimation

Figure FIXME shows the result of the cost estimator in Custompartnet. The quantities, materials, production techniques and scales of these components are clearly defined in the estimator. For the screw cap, upper housing and bottom housing, ABS is used as the input because TPR is not available in this estimator. However, the material price for ABS and TPR are almost the same(Figure 141). Thus it is reasonable to use the result as an estimation.

For the copper conductor, it can not estimate the same production method as proposed previously. As an alternation, die casting is used here to have a feeling of the cost. Die casting is also a possible technique for making these components, though the thickness may not able to be as thin as the design.

Part Information

Quantity: 10,000
Material: Acrylonitrile Butadiene Styrene (ABS), Molded
Envelope X-Y-Z (in): 0.78 x 0.78 x 0.10
Weight (oz): 0.03
Tolerance (in): Not critical (> 0.02)
Surface roughness (μin): Not critical (Ra > 32)

Process Parameters

⊞ **1. Injection Molding**

Cost Summary

1. Injection Molding	$5,849 ($0.585 per part)
Material cost	$79 ($0.008 per part)
Production cost	$1,159 ($0.116 per part)
Tooling cost	$4,612 ($0.461 per part)
Total cost	**$5,849 ($0.585 per part)**

Figure 141a: Screw cap

Part Information

Quantity: 10,000
Material: Acrylonitrile Butadiene Styrene (ABS), Molded
Envelope X-Y-Z (in): 0.78 x 0.78 x 0.10
Weight (oz): 0.03
Tolerance (in): Not critical (> 0.02)
Surface roughness (μin): Not critical (Ra > 32)

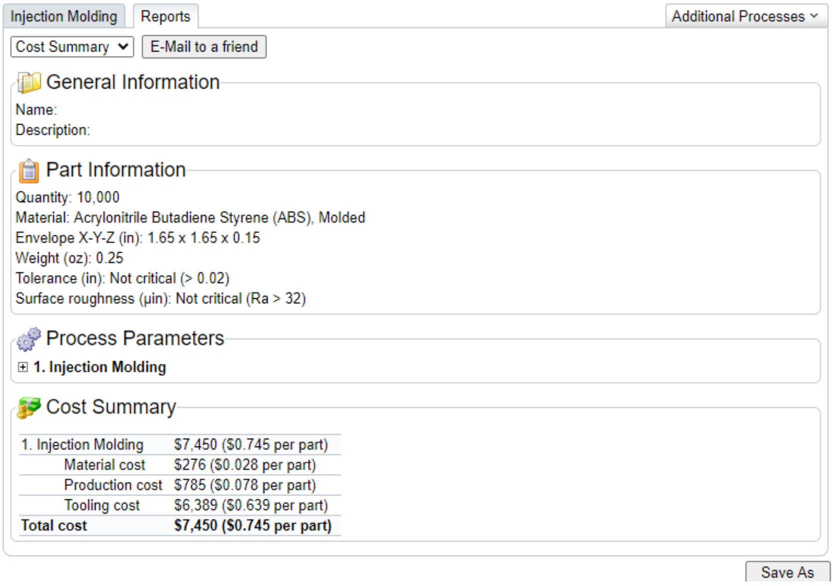
Process Parameters

⊞ **1. Injection Molding**

Cost Summary

1. Injection Molding	$5,849 ($0.585 per part)
Material cost	$79 ($0.008 per part)
Production cost	$1,159 ($0.116 per part)
Tooling cost	$4,612 ($0.461 per part)
Total cost	**$5,849 ($0.585 per part)**

Figure 141b: Upper housing



Injection Molding | Reports | Additional Processes

Cost Summary | E-Mail to a friend

General Information

Name:
Description:

Part Information

Quantity: 10,000
Material: Acrylonitrile Butadiene Styrene (ABS), Molded
Envelope X-Y-Z (in): 1.65 x 1.65 x 0.15
Weight (oz): 0.25
Tolerance (in): Not critical (> 0.02)
Surface roughness (µin): Not critical (Ra > 32)

Process Parameters

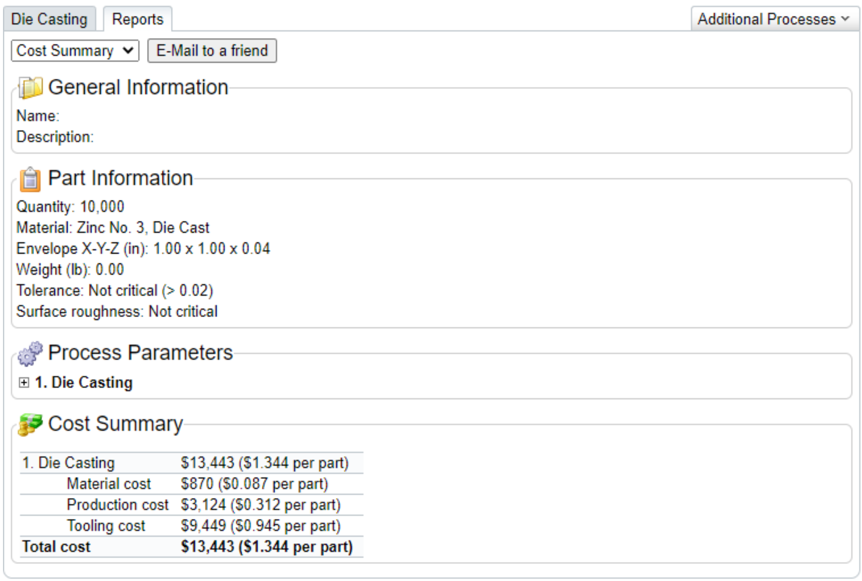
⊞ **1. Injection Molding**

Cost Summary

1. Injection Molding	$7,450 ($0.745 per part)
Material cost	$276 ($0.028 per part)
Production cost	$785 ($0.078 per part)
Tooling cost	$6,389 ($0.639 per part)
Total cost	**$7,450 ($0.745 per part)**

Save As

Figure 141c: Bottom housing



Die Casting | Reports | Additional Processes

Cost Summary | E-Mail to a friend

General Information

Name:
Description:

Part Information

Quantity: 10,000
Material: Zinc No. 3, Die Cast
Envelope X-Y-Z (in): 1.00 x 1.00 x 0.04
Weight (lb): 0.00
Tolerance: Not critical (> 0.02)
Surface roughness: Not critical

Process Parameters

⊞ **1. Die Casting**

Cost Summary

1. Die Casting	$13,443 ($1.344 per part)
Material cost	$870 ($0.087 per part)
Production cost	$3,124 ($0.312 per part)
Tooling cost	$9,449 ($0.945 per part)
Total cost	**$13,443 ($1.344 per part)**

Figure 141d: Copper ring

Die Casting | Reports | Additional Processes

Cost Summary | E-Mail to a friend

General Information

Name:
Description:

Part Information

Quantity: 10,000
Material: Zinc No. 3, Die Cast
Envelope X-Y-Z (in): 1.60 x 1.60 x 0.04
Weight (lb): 0.00
Tolerance: Not critical (> 0.02)
Surface roughness: Not critical

Process Parameters

1. Die Casting

Cost Summary

1. Die Casting	$15,489 ($1.549 per part)
Material cost	$870 ($0.087 per part)
Production cost	$3,124 ($0.312 per part)
Tooling cost	$11,495 ($1.149 per part)
Total cost	**$15,489 ($1.549 per part)**

Figure 141e: Copper conductor with thread

Injection Molding | Reports | Additional Processes

Cost Summary | E-Mail to a friend

General Information

Name:
Description:

Part Information

Quantity: 10,000
Material: Acrylonitrile Butadiene Styrene (ABS), Molded
Envelope X-Y-Z (in): 0.25 x 0.25 x 0.25
Weight (oz): 0.00
Tolerance (in): High precision (<= 0.005)
Surface roughness (µin): Not critical (Ra > 32)

Process Parameters

1. Injection Molding

Cost Summary

1. Injection Molding	$4,142 ($0.414 per part)
Material cost	$79 ($0.008 per part)
Production cost	$672 ($0.067 per part)
Tooling cost	$3,392 ($0.339 per part)
Total cost	**$4,142 ($0.414 per part)**

Figure 141f: Copper conductor with thread

Material group	Number of offers	Total amount	Average amont per offer	Number of prices	min. price (EUR/kg)	max. price (EUR/kg)	average price (EUR/kg)
ABS	72	847.4 to	11.8 to	44	0.28	1.00	0.58
TPE	23	246.4 to	10.7 to	12	0.15	1.00	0.51

Figure 141g: Price of ABS and TPE