FINAL MASTER THESIS

TU Delft
Integrated product design

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3D PRINTING ELECTRONICS TOWARDS FLEXIBLE TACTILE SENSORS

TU Delft

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Preface

This master thesis is set up by the department of mechatronics design and is performed to obtain the degree of Master of Science at the faculty of industrial design engineering at the Delft university of technology.

This graduation project needs to show my expertise and interests in the field of 3D printing and electronics. It applies this knowledge by an exploration on how these fields can benefit from each other and apply this to an environment of human and technology fields.

This thesis needs to follow and show proof of competence on my development trajectory of the past years studying industrial design engineering. This development trajectory has been mainly focussed on the expertise of research and development (R&D) in the field of technology, focussing on the research into and development of technological advancements and innovations, and the embodiment of these innovations into modern smart products.

I sincerely want to thank my supervisory team, consisting of Wolf Y. Song, Z. Doubrovski and A. Kooijman, for their excellent guidance and devotion of time during my graduation project. Additionally, I want to thank J. Wu for his excellent help and collaboration during the exploration of printing opportunities.

The field of printed electronics is yet to be explored fully in our faculty. I am truly excited to be a part of and contribute to the exploration into this field and the contribution of knowledge in this exciting field of modern technologies.

Rick H.C. van de Ven

Integrated Product Design
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Glossary

Acronyms

AM Advanced manufacturing
PCB Printed circuit board
FDM Fused deposition modelling
TPU Thermoplastic polyurethane
FFF Fused filament fabrication
DOD Drop-on-demand

Terms

Tactile sensing
The ability to sense and measure the contact pressure between two surfaces or objects

Tactile imaging/mapping
A visualisation of distribution of pressure by the ability to sense and map contact pressure over a measurable area

Printed electronics
A collection of printing technologies that allow for printing electrical devices and structures on various substrates.

Characterisation terms

Repeatability
The ability of a sensor to repeat a measurement when it is met with the same environment. It defines if the sensor provides a constant readout when the same load is applied.

Linearity
The extent to which the measurements curve deviates from the ideal curve. Optimal linearity shows a linear ideal curve.

Hysteresis
The difference in sensor output of two measurements at the same point but with different direction. in relation to pressure sensors these directions are loading / unloading.

Stability
Defines how stable the output of the sensor is, based on the amount of fluctuation or noise in the output.

Resolution
The ability of a sensor to measure small differences in readings. It defines how well the sensor can differentiate between different variations in load force.

Accuracy
It defines how well the sensor is performing in an absolute sense. It is defined according to the aspect it is sensing of its environment compared to its real value or its recognised standard.

Drift
Relates to a change in readout of the sensor over a longer time. Most sensors experience this and, when the drift is not significant, can be accounted for and corrected.

Abstract

Scope
The research described in this thesis explores the field of 3D printing technologies in the fabrication of printed, flexible tactile sensors and explores new possibilities and opportunities in the fabrication. The research is aiming at new ways of applying 3D printing fabrication techniques to develop easily applicable sensing structures to flexible, wearable applications.

Exploration
Exploration into sensing principles and sensor designs for the printed fabrication of these tactile sensors results in the main design drivers of piezoresistive sensing and capacitive sensing to act as sensing mechanism for the developed sensors.

Selection
Fabrication principles are selected according to design thinking methods, and select and evaluate the trace design, substrate selection and 3D printing technique used in defining a concept proposal.

Design & Fabrication
The performed exploration and design selection result in the concept proposal of a 3D printed tactile sensor using a TPU-coated nylon fabric substrate and ink-dispensed sensing structure using a Voltera V-One 3D printer. The sensing element is embedded into the fabric using heat sealing. A scalable, adaptable sensing array is proposed to allow for embedded tactile imaging capabilities.

Validation
The developed tactile sensor is validated by analysing a characterisation of the sensor readouts. A validation setup using a loadcell and vertical load is used to allow for the plotting of the sensors' characteristics and linearity.

Conclusion
The research concludes in a foundation towards the use of the 3D printing technologies of ink jetting/-dispensing to develop embedded sensor to be used in a large variety of tactile sensing/imaging applications.

Discussion
Validation shows evidence of significant measurement repeatability, while showing less proof for precise accuracy and resolution. Additional work needs to improve physical durability of the traces and connections.

1 INTRODUCTION

This chapter will introduce you to the field of 3D printing and its relation with the fabrication of wearable pressure sensing and imaging

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1.1 Pressure sensing

Force sensing is an inherent part of modern technology. It has many applications in a large variety of fields. From industrial machinery to commercial cars, measuring instruments or even the screen of your mobile devices. Recent innovation still largely applies the principles of force sensing and explore new ways of using these principles. An example of a field in which modern innovation is exploring the possibilities of force sensors is the application of wearables. An exploration on new opportunities for these sensors can benefit a large variety of innovations and provide new technological opportunities.

Pressure sensing is mostly reached by measuring a change in electrical material properties of a certain material and uses this to derive an applied force. Which material properties are used is largely defined by the sensing principle that is applied by the sensor. A variety of sensing principles exist, which is elaborated further later in this thesis.

In literature, the terminology force sensing, pressure sensing, and tactile sensing is used frequently and are used interchangeably. We shortly define these terms for understanding purposes. While force, pressure and tactile are very related to each other, we identify some small differences. Force is a value composed of a single magnitude and vector. The concept is mostly used in the field of physics, used in calculations. When a force in the physical world is mentioned, it mostly refers a net force. Pressure closely relates to force by being defined as the distribution of many small forces over an area or body. It mostly refers to forces relating gasses and liquids. When talking about a force in the natural word, pressure is mostly referred to. Finally, when force/pressure sensors are being applied to fields of application involving the sensing and measuring of contact pressure, the term tactile sensing is often referred. Tactile sensing is defined as the contact pressure between two surfaces.

It is often used in the fields of artificial skin robotics, human body monitoring and wearable applications while these involve contact pressure between objects. Therefore, this thesis will mostly focus on the term tactile sensing in its research.

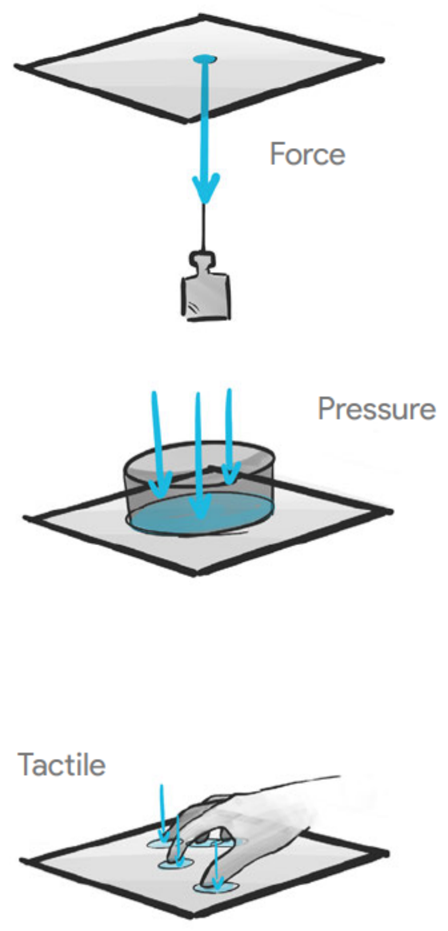

Figure 1 - defining terminology of pressure sensing

1.2 Tactile imaging

The ability to sense and map contact pressure over a measurable area can be beneficial for a variety of fields. Tactile imaging translates the contact pressures of an area that is measured by arrays of tactile sensors to visualise the pressure distribution of a specific surface. This tactile imaging can have a variety of different application fields.

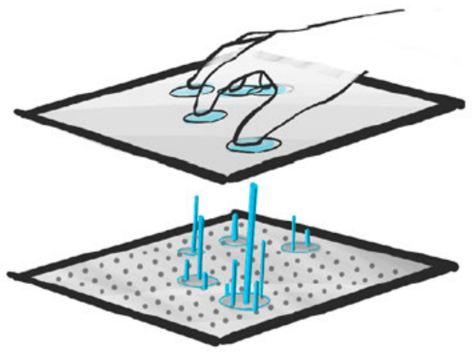

Figure 2 - Tactile imaging visualisation

Tactile imaging can specially be useful in the field of healthcare and health monitoring. Applications like the development of prosthetics, monitoring forces applied to a body, or healthcare devices can all benefit from tactile sensing capabilities. [1] An additional field of application that can benefit from tactile imaging is to use tactile sensors for body pressure mapping in applications like the field of automotive and sports, or as tool to collect vital information in the fields of product design, manufacturing, ergonomics studies, research or quality control. [2] a third application field which is significantly benefiting from the developments of tactile sensing is the field of artificial skin and soft robotics. [35] The tactile sensors can provide robotics with sensory feedback of contact pressure distribution with tactile imaging to let robotics interact with its environment.

The application of tactile imaging can be categorised into 3 main fields, namely: object identification, tactile visualisation and sensory feedback. These main applications all use the measurements from tactile imaging but use it to achieve different things. Object identification uses the pressure distribution and feeds this to a learning algorithm to identify the characterisations of the grasped object. The tactile sensing can also be used as inputs for interaction with the environment for soft robotics by using tactile imaging as sensory feedback. Tactile imaging can however also be used for tactile visualisation, in which the pressure distribution is visualised to provide body pressure mapping. This mapping can be used in applications as for example an information tool for research and ergonomics.

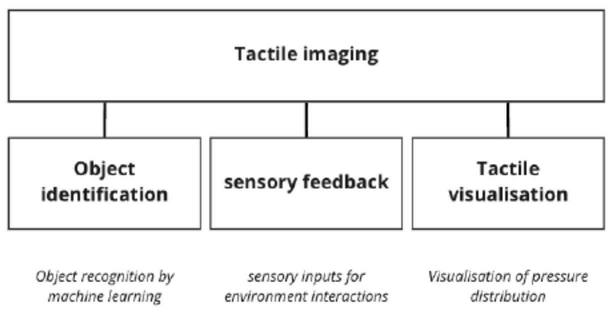

Figure 3 - Categorisation of tactile imaging applications

To make use of these tactile sensing applications, a lot of recent studies and development has been focused on the development and fabrication of flexible pressure sensors. [3] A specific field focuses on how these pressure sensors can be embodied into wearables to function as wearable tactile sensors. [4] The most recent developments focus on exploration and development of unique fabrication methods used to develop sensors with extended fabrication possibilities. [5]

1.3 3D printing

The technology of 3D printing has seen a great increase in interest as fabrication method in recent years, while it allows for the development of ultra-personalised products and low-cost production. 3D printing has become largely available by firms and individuals, and can provide easier production of products. It allows for a cheap fabrication method of complex structures and can therefore create opportunities in the fabrication of complex systems and products. Due to the increased interest, today's availability of different plastics like electrically conductive filament or flexible filaments can bring new opportunities in the fabrication of force sensing applications. Moreover, recent developments of printers which print conductive materials based on inkjet or paste deposition technologies further increase the possibilities that 3D printing can have on printed electronics.

One of the leading technologies in printed electronics is the use of inkjet printing in combination with conductive ink. This technology is popular in the field of printed electronics because of certain advantages it has over other 3D printing technologies. These advantages include a highly automated process resulting in reproducible results and a stable process, little to no wastage of material inks used, and the fact that the process does not require contact with the substrate enabling for more variety in substrate selection.

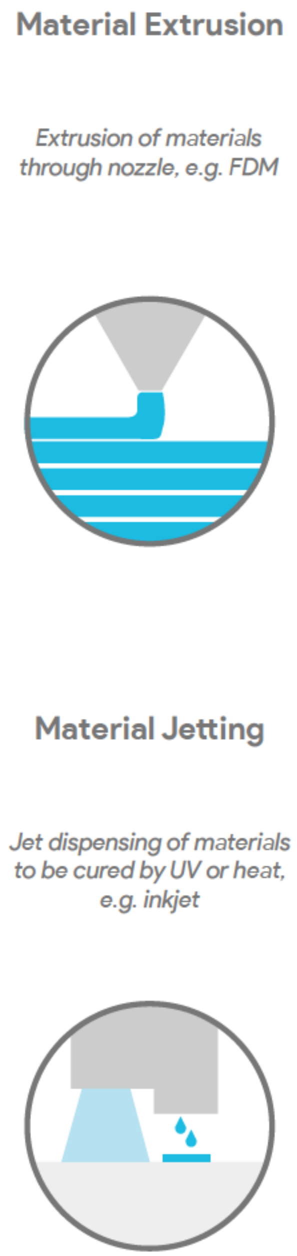

Figure 4 - 3D printing technologies

1.4 Printed electronics

Printed electronics is a collection of printing technologies that allow for printing electrical devices on various substrates. It combines electronics manufacturing to traditional text/graphic printing. These printing technologies consist of traditional contact-printing and non-contact printing methods as well as newer printing technologies. Within these printing technologies, 3D printing has become one of the participators within the field of printed electronics through recent innovations and development.

A significant number of reviews and studies have been performed on the technologies that allows fabrication in the field of printed electronics. Taking a review posted in the IEEE sensors journal as an example [6], different technologies can be identified which can be classified in traditional graphic contact-printing, like gravure or flexography printing, or non-contact printing, like inkjet printing. An article posted in the journal for progress in advanced manufacturing [7] adds to these identified technologies by reviewing how the progress in 3D printing and other advanced manufacturing technologies can create fabrication opportunities in printed electronics. Looking at these reviews provides a solid understanding of the current progress and understanding of the technologies used in the field of printed electronics and is a large source of knowledge for this research.

The use of 3D printing into printed electronics is largely dependent on the development of specialised conductive materials. Special polymer plastics are developed with conductive properties by the addition of graphitized carbon material or graphene. These conductive plastics are used as filament for material extrusion. A second development which has a large impact on electronics printing is the development of solvent-based nanoparticle inks, which used nanoparticles to give the inks conductive properties when cured.

Figure 5 - inkjet printed traces on nylon substrate seen trough a microscope

2 PROJECT DEFINITION

This chapter will define the scope and focus of the project and starts to open up towards possible opportunities. It also describes the approach of the project regarding the scope

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2.1 Knowledge gap

The opportunities that increasingly growing widely available 3D printing technologies can bring, like ultra-personalised products and low-cost production, can have a significant benefit to the development of wearable tactile sensors. However, while a lot of current research into fabrication methods is focused on the use of 3D printing methods focussing on technologically advanced methods, little has been researched into how the fabrication of sensors can benefit from accessible 3D printing like FDM or even inkjet printing.

The field of printed electronics is still largely focussed on the use of traditional graphic printing methods like screen printing or gravure printing and linking these technologies with the manufacturing of flexible PCBs by conductive inks. Although some progress has been made in the exploration of how 3D printing can add to these printed electronics technologies, these explorations are still very limited.

2.2 Objectives

While a lot of technological advancements are being made in the development and fabrication of wearable tactile sensors, there is still a very limited amount of research being done on how the technology of 3D printing can provide additional benefits to the fabrication of these tactile sensors. Therefore, the main objective for this research is to explore the opportunities that 3D printing can impose on flexible, wearable, tactile sensors.

The main objective for this thesis can be defined accordingly:

Exploring the exponentially growing field of 3D printing techniques to fabricate sensors on flexible materials to be used in wearable products.

This thesis will be an exploration into development of 3D printed tactile sensors to be embedded into smart products. This thesis will not focus on the implementation of the researched technology into a final product, but merely function as a resource for future researchers and designers to implement printed tactile sensors into smart products and provide new fabrication methods and knowledge into the field of printed electronics.

2.3 Scope

We see recent significant developments into wearable tactile sensors and how the use of advanced manufacturing methods can create new opportunities for these tactile sensors. How might the use of 3D printing technologies add to these developments and create new opportunities. The scope of this project is the exploration and development of 3D printed wearable tactile sensors, requirements for these tactile sensors are defined by using the development of a smart pressure mapping glove as an application of these wearable sensors.

The development of wearable tactile sensors has a variety of applications which can be explored when trying to research the use of 3D printing as fabrication method. In this research thesis, the focus of application for these wearable pressure sensors will be towards a smart sensing glove. A MIT research study describing the development of a smart sensing glove [8] shows how these wearable pressure sensing can be applied. This research focussed on how 3D printing can create new opportunities towards the development of these sensors, through an exploration of new designs that needs to show and prove these new opportunities.

The main goal of the development of a smart sensing glove is an exploration of how flexible, wearable tactile sensors can be applied in wearable applications and how the advanced manufacturing method of 3D printing can add to the fabrication of these sensors.

The research will mainly aim at the areas of human and technology. We try to explore the current developments into the state-of-the-art technologies of electronics 3DP and fabrication of wearable flexible pressure sensors into a smart glove by the means of a design thinking process and apply a designers' holistic view to improve upon the human aspects around applying wearable sensors in a human-centred approach with regards to expressiveness, adaptivity and human feel.

2.4 Opportunities

The use of 3D printing technologies can give new opportunities to the development of tactile sensors that will be explored in this research. The following opportunities are identified and explored through a design approach of continuous iteration.

New working principles:
the use of 3d printing as fabrication method might be able to bring new working principles to tactile sensors which are not able to be fabricated by traditional manufacturing methods.

Ultra-personalised products:
fabricating a smart sensing glove by 3D printing allows the design of parameterised products which are adapted to the individual, making it possible to fabricate a smart sensing glove which custom fits the user.

Easier, low-cost fabrication:
3D printing, while proven to be excellent at a fast way of fabricating a product without much manual labour and cost, brings opportunities of fabricating a personalised product on demand without costly manufacturing.

Wearable applications:
while 3D printing can produce elaborate structures, it might be able to integrate sensing structures into the product while fabricated. Electronics 3D printers also have the possibility of creating thin sensor structures on flexible substrates, making them more suitable for wearable sensors.

2D electronics into 3D structures:
while most commercial electronic circuitry is only suitable for 2D applications, the use of 3D printing can create opportunities in incorporating electrical sensing circuits in 3D structures.

2.5 Approach

Design process

To explore the opportunities of 3D printing, this research is largely focussed on hands-on exploring of fabrication opportunities, by continuously testing and prototyping with the use of the available 3D printers at the digital fabrication lab of the IDE faculty.

The project consists of two prominent phases, namely a discovery phase and a development phase. The discovery phase mostly focusses on an exploration of different technologies than can be used to fabricate tactile sensors. It is split into a research and exploration phase in which, in parallel, theoretical knowledge is built while applying this knowledge into fast and iterative prototypes. This discovery phase defines which sensing principles are being used into the development of a final prototype. The second phase, the development phase, focusses on taking this sensing principle and explore and develop a functional sensor. The sensor design is embodied into a final sensor and validated on its performance.

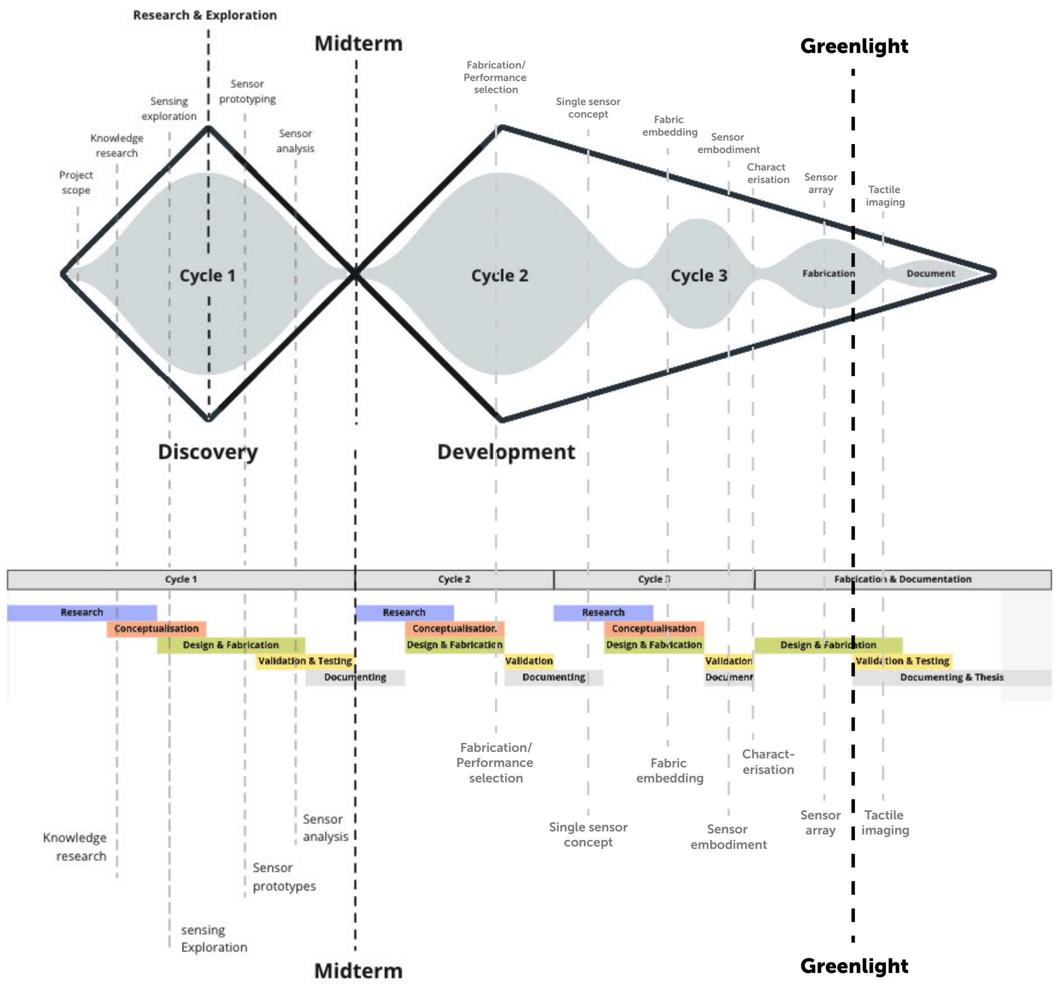

Figure 6 - overview of project planning and phase

The process of the project can be best defined into 3 cycles, in which every cycle has a different end-result focus. Cycle 1 focusses on generating substantial knowledge about the theory and explore the different technologies of tactile sensing. It finishes with a thoroughly explored solution space of concepts and possible sensing principles to be used in the next cycle. This next cycle focusses on taking these principles and developing a tactile sensor and exploring different fabrication methods to realise these sensors. A final cycle explores the opportunities the proposed sensor design can have on the defined application field of the scope.I also validates the embodied sensor to analyse performance.

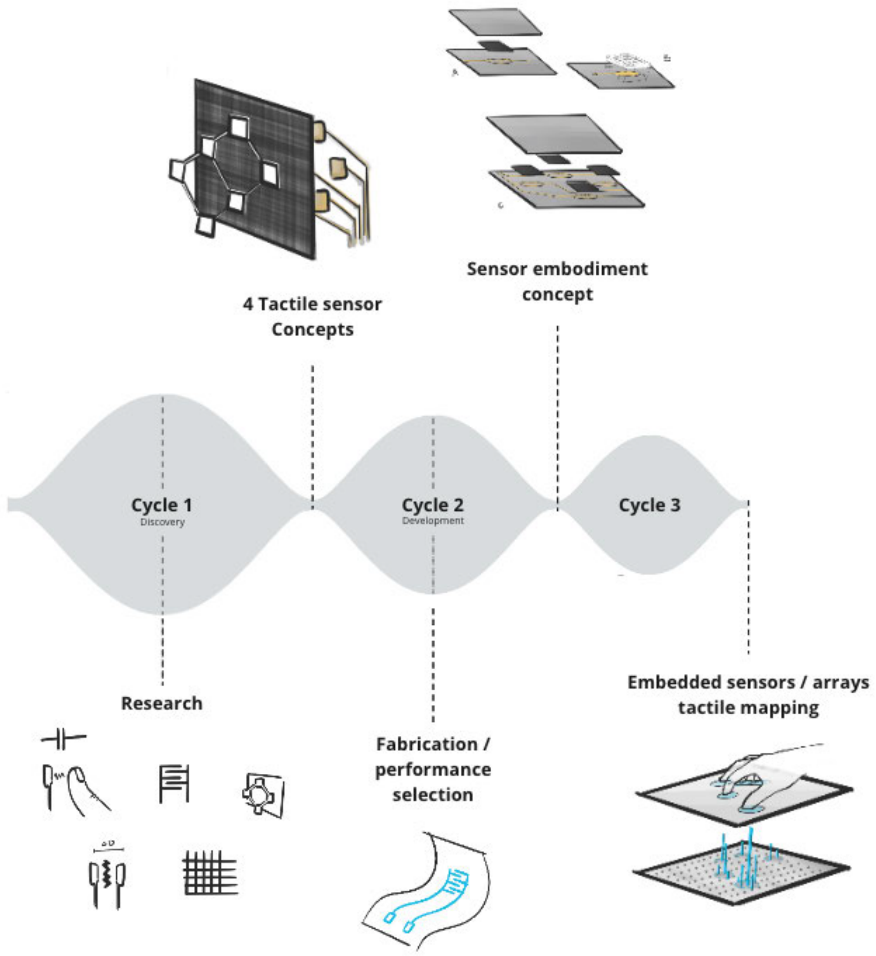

Figure 7 - overview of project cycles and result

Thesis outline

This thesis summarises the exploration and development of this research according to several chapters. It is based on the steps and research which has contributed most to the results of the exploration. A full overview of all research, prototypes and analysis can be found in the appendix to this thesis.

This thesis proceeds to document the exploration by the following chapters:

Research & analysis – To create a solid understanding of the design space we are designing in, this chapter summarises the knowledge that is acquired by research and required In the proceedings of the exploration. It also describes related research and projects regarding the scope of this thesis.

List of requirements – Describes the main goal of this thesis and lists the requirements that are set for the development of a printed sensor.

Concept – After a solid understanding of the field we are designing in, this chapter describes some key design ideas, which are used in defining, selecting and evaluating some concepts to be explored further.

Embodiment – After a selection and evaluation of fabrication principles defined in the previous chapter, we develop a sensor design by embodiment of the design proposal and analyse its performance.

Figure 8 - conductive PLA traces printed on a Ultimaker S5

3

RESEARCH & ANALYSIS

This chapter provides a solid understanding of the design space, and summarises related studies and the research & analysis to provide a structured foundation in this design space.

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3.1 Related work

There has been a lot of recent attention to the development of flexible, wearable tactile sensors in the academic field. Significant research is being performed on reliable fabrication to create tactile sensors with a large variety of applications. Recent progress in robotics and healthcare can greatly benefit from these tactile sensors. This section focusses on related studies into the field of printed fabrication of tactile sensors, the integration of these tactile sensors into products and application of these integrated sensors towards tactile imaging. printed electronics is mainly explored in traditional graphic printing methods, this research will mainly focus on AM 3D printing while this is the scope of this research.

Printed tactile sensors

There has been a significant contribution of research into the field of tactile sensors and focus on different methods of fabrication for these sensors. Most of these approaches depend on novel printing technologies to fabricate (components of) a flexible tactile sensor. Most tactile sensors consist of a sensing element, flexible substrate and flexible electrodes. A review posted in 'polymers' research journal, focussing on 3D printing technologies for flexible tactile sensors [5], identifies 5 approaches of fabrication a flexible tactile sensor, namely:

- 3D printing moulds for micro structuring substrates, electrodes and sensing element
- 3D printing flexible substrates or sensor body
- 3D printing sensing element for tactile sensors
- 3D printing flexible electrodes for tactile sensors
- Fully 3D printing tactile sensor

3D printing technologies that have been previously explored and researched in the field of tactile sensors mainly consist of 4 types of printing technologies, namely photopolymerization-based 3D printing (e.g. stereolithograpy (SLA)), fused deposition modelling (FDM), direct ink writing (DIW), material jetting, and electrohydrodynamic (EHD) 3D printing [5]. These printing technologies are used to allow for the defined approaches of fabrication of tactile sensors.

Almost all tactile sensors are based on a selection of sensing principles, which act as sensing element for the tactile sensor to function. These principles are piezo-resistance, strain based piezo-resistance, capacitance and piezo-electric.

Significant studies have showed the development of tactile sensors with these technologies and principles [5] and are summed up in table A and can be found at the end of this thesis.

▷ *Table A*

While the scope of this research is the exploration of opportunities of easily accessible printing approaches, we focus on the studies that make use of 3D printing based on FDM printing or non-contact inkjet printing. A paper by the university of Twente describes the development of a flexible force sensor using FDM printing with TPU filament [9]. It describes the fabrication of a proof of concept of a parallel plate capacitor and corresponding readout circuit. This research indicates the possibility FDM printing can have on the development of easily manufacturable integrated force sensors. The same result can be seen in a different study focussing on a fully FDM 3D Printed Flexible capacitive transducer [10].

Tactile sensor integration

While a lot of research has been performed on the development of flexible tactile sensors and their fabrication, we can also find significant academic progress in the research into the integration of these sensors into products. Integrating tactile sensors into product by wearable applications can create significant opportunities in interaction, data gathering and tactile imaging.

Several studies have been previously performed to research the developments of a smart sensing glove/hand that try to achieve the same tactile mapping as defined in this scope. A recent study and review on the progress of tactile sensing in robot hands [11] sums up these smart sensing gloves and can be seen in table B. These studies have researched the integration of tactile sensors into a robot hand to allows for tactile sensing as sensory input or graph sensing. It demonstrates the opportunities that integrated flexible tactile sensors can bring.

A different integration method of printed tactile sensors for tactile mapping can be seen in a thesis published by the university of mid Sweden [12], which describes the design of a tactile imaging sensor array for pressure distribution monitoring in wheelchairs. The researchers present a screen-printed tactile sensor with objective to perform tactile mapping on a person sitting in a wheelchair (see figure 9).

▷ *Table B*

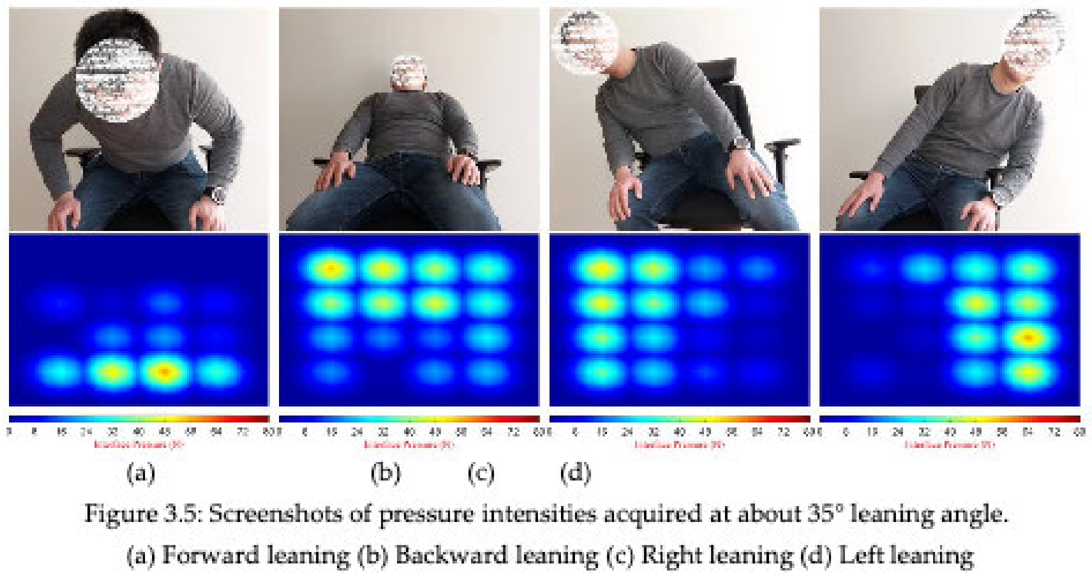


Figure 9 - example study of tactile sensors integrated into products [12]

Tactile imaging application

The integration of tactile sensors into surfaces can bring additional opportunities in the topic of tactile imaging. Several studies show how an array of integrated tactile sensors can allow for tactile imaging and how this tactile imaging can be used in

A recent study by researchers of MIT [8] shows the developments of a smart sensing glove, which makes use of an array of tactile sensing points to measure the pressure distribution on the surface of a hand (see figure 10). This data is then used to, with the use of a neural network, predict the object that is grasped by the human hand and infers the material properties of that object. This tactile sensing has a goal to function as sensory feedback for soft robotics to interact and manipulate objects. The research in this thesis will build upon the knowledge from this study and researches how we can achieve the sensory feedback of tactile sensors by using a different fabrication method to find new opportunities of the fabrication of these tactile sensors.

A review posted in a journal for sensors and actuators, titled: a review of tactile sensing technologies with applications [13], perfectly sums up some key application industries for the application of tactile sensing. The review identifies, among others, applications like biomedical, robotics, consumer products. These applications range from robot applications to posture analysis to diagnostics tools and textile/clothing integration. A full overview of all proposed applications, including key areas and challenges, can be found in table C.

▷ *Table C*

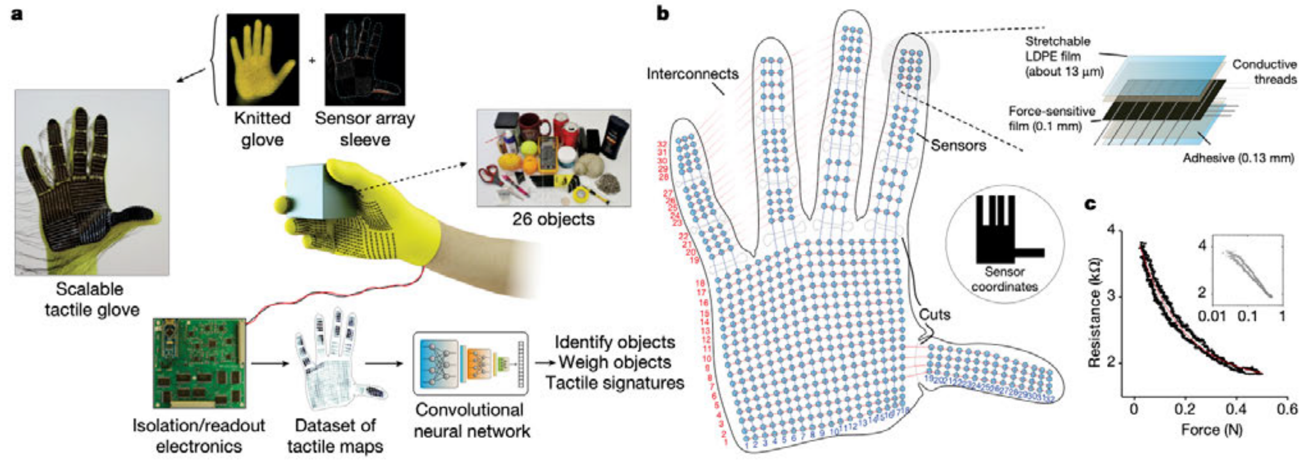


Figure 10 - overview of example study showing possible application of tactile imaging [8]

3.2 Force sensing overview

Various methods exist for electronically measuring the force that is being applied onto an area. This overview will give a brief overview of these principles. This overview provides a solid understanding of how force sensing is achieved. Pressure sensing depends on measuring a change in material properties which can be linked to an applied force. The sensor function by transforming the applied pressure into an electrical signal. Below, the common sensing principles are discussed.

Strain sensing

Strain gauges make use of the physical properties of conductive materials related to the resistance these materials have with relation to their geometry. When the geometry of a conductive material is deformed, their electrical resistance changes accordingly. When the material is stretched, its electrical resistance will increase. Conversely, compression of the material will result in a decrease of electrical resistance.

Piezoresistive sensing

While piezoresistance also depends on the material deformation, it vastly differs from the working principle of strain gauges. The material changes in electrical resistance while the application of pressure causes the particles in the material to touch conduction electrodes. The range of resistiveness of force sensing resistors are far bigger than strain gauges.

Capacitive sensing

capacitive sensing takes advantage of a change in capacitance between two conductors. This principle functions by measuring the capacitance between two parallel opposing conductive plates. The two conductors are often separated by a dielectric functioning as a polarised insulator to increase capacitance. To function as a force measuring sensor, the dielectric consists out of a deformable material, e.g. an elastomer, making the sensor change in capacitance when a force is applied due to compression of the dielectric.

Piezoelectric sensing

The piezoelectric effect is widely used in the fabrication of various sensors and makes use of the physical properties of some materials to accumulate an electrical charge when mechanical stress is applied. When a force is applied to the material, an electrical voltage potential builds across its sides. Piezoelectric force sensors are able to measure this electric potential and derived the applied pressure.

Additional sensing methods

Additional sensing methods exist but are beyond the scope of this research. The research excludes these sensing methods, like barometric sensing, optical sensing or a variety of aditional sensing principles as described in an excellent resource of a modern sensor handbook [14]. Since such working principles are hard to mimic with the use of 3D printing due to their physical requirements.

This research will mainly focus of the working principles of piezo-resistance and capacitance, since these principles are the most feasible to reproduce with conventional 3D printing. Strain sensing would be an additional possibility, but difficult due to the necessity of significant stable resistance in printed traces. The construction of sensors that make use of these working principles will be elaborated next.

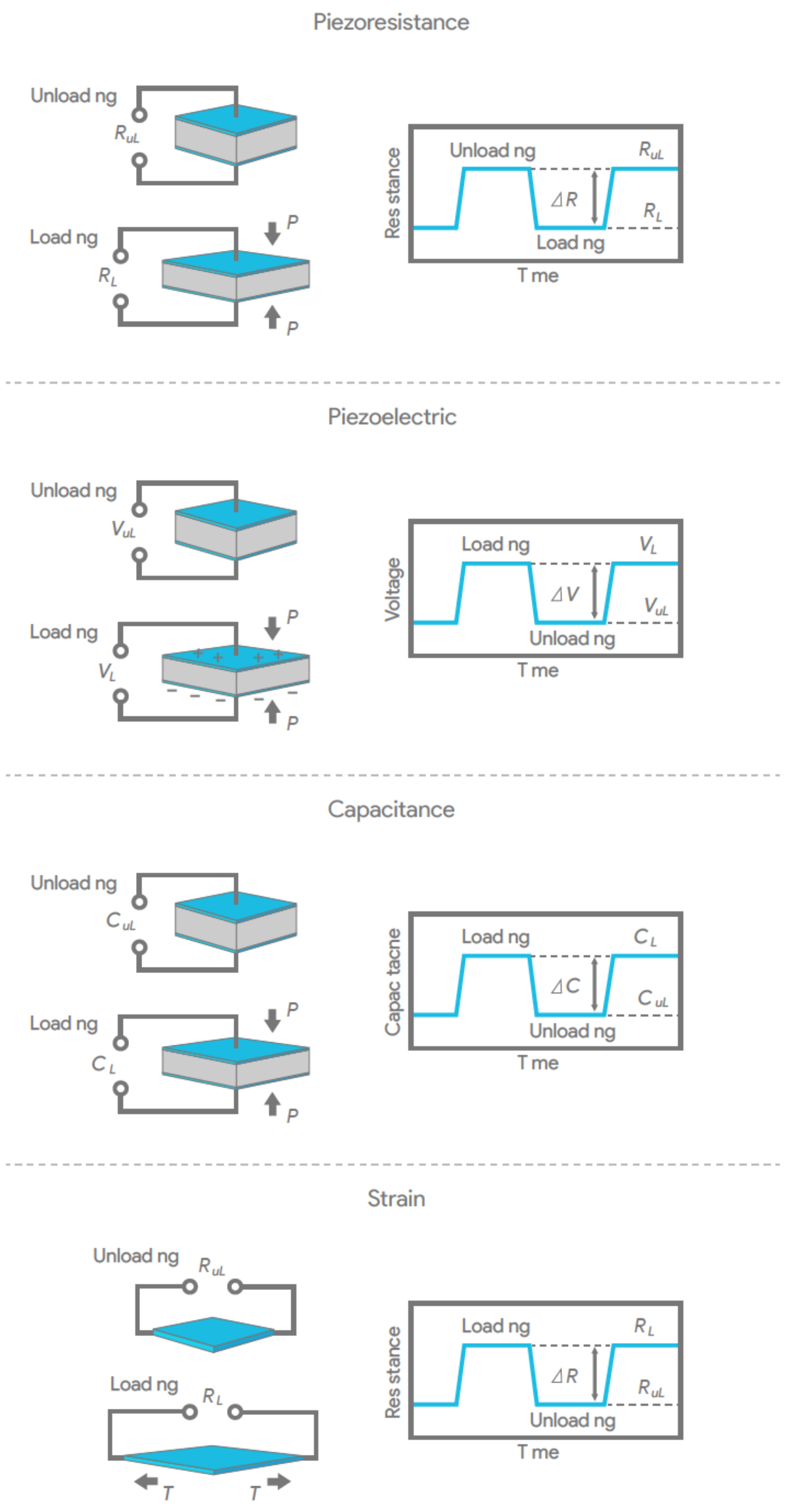


Figure 11 - force sensing principles overview

Piezoresistance

A sensor that uses the piezoresistive sensing principle is constructed by two conductors which are connected by a material holding the piezoresistive properties. Several different arrangements of conductive plating and piezoresistive materials exist and are elaborated further as understanding purposes for this thesis.

Sensor structures

The variety of structures can be devided into single-point structures and matrix arrays. Matrix arrays have the added benefit over single-point structures to capture pressure distribution over an area by creating a grid of sensing points, allowing for tactile mapping. This can also be realised by an array of single-point structures. This thesis confines the possibilily of sensor structure to the following structures:

(a) A single-point sandwich structure consisting of two parallel opposing plates sandwiching a piezorisitive material.

(b) A single-point interdigital structure with interlocking traces. A large variety of designs exist based on the same principle.

(c) A matrix structure created by opposing perpendicular traces, creating a grid of sensing points.

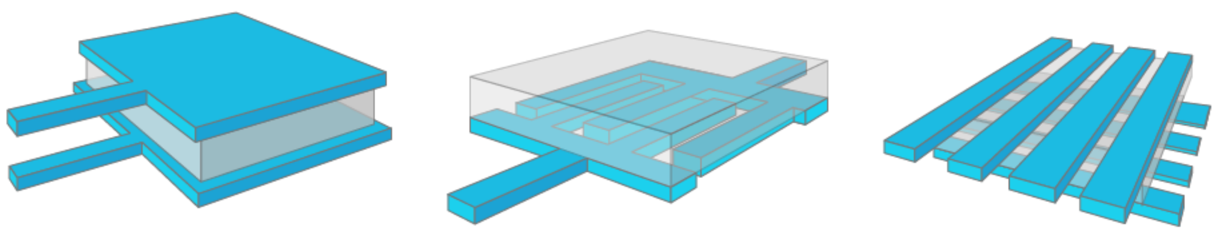
Piezoresistive materials

Materials that carry piezoresistive properties are found in a variety of forms. Due to lack of a commercial application, few piezoresistive materials are produced for the commercial market. However, due to the antistatic properties of the materials it is also used as electronics packaging. Currently the following piezoresistive materials are (commercially) available:

Piezoresistive thin films: These rubber-like plastic sheets consist of a conductive polyethylene plastic film, which is carbon-filled to give it piezoresistive properties. The technology manufacturer 3M offers such a piezoresistive thin film, called velostat [15].

Piezoresistive foams: Although no commercially available piezoresistive foams exist, these foams can be produced to function as a piezoresistor in force sensing applications as described in several studies [18, 36]. These Piezoresistive foams consist out of a porous-like material, infused with carbon. Polydimethylsiloxane (PDMS) is often used to function as the porous-like material and is infused by graphene nanoparticles to give the material piezoresistive properties.

Piezoresistive fabrics: These fabrics are produced by using individually coated fibres (doped polypyrrole, PPY) to weave a fabric which is electrically conductive. Since the piezoresistive effect still has little applications in wearable application, the commercially available Piezoresistive fabrics are still limited.



(a) Single-point sandwich structure (b) Single-point interdigital structure (c) Sensor matrix structure

Figure 12 - overview of possible sensor structures

Capacitance

A sensor that is based on the capacitive effect is constructed by two separated opposing conductors. When a voltage is applied, a change in voltage potential across the two conductors is induced and changes when the separation distance is changed. The change in separation distance can be created by a variety of methods, which are elaborated further in this section. Furthermore, a necessary circuit design is discussed to be able to accurately measure the voltage potential to be used to derive a applied tactile force.

Dielectric

Variable distance between the two conducting plates is the most widely used approach for pressure measuring [16]. There are a variety of different structures and materials that can function as a dielectric and/or provide the needed deformation properties to allow for this variation in separation distance. A review study posted in the advanced materials technologies journal [16] identifies the following selective designs of dielectric materials:

Air dielectric: separating the conductive plates without any insulating material, instead use merely air/vacuum as insulation. Most used mechanism for making use of air as dielectric is a cantilever style structure, in which one edge is fixed while other sides are free to move.

Porous material dielectric: using a material which has an internal structure consisting of air gaps which makes them highly compressible and able to regain their original thickness after compression. These materials, like porous elastomers, foam or sponges, separate the conducting plates and compress when a force is applied.

Wrinkled dielectric: the conducting plates are separated by a dielectric material which has a wrinkled structure. This wrinkled structure gives them spring-like properties, while making them able to compress and move back to original form when force is applied.

Capacitive measuring

Methods that provide the most accurate reading of capacitance make use of circuits like RC timer circuits (using a 555 IC) or op-amp integrator circuits to create an analog capacitive measuring circuit. Output for these kinds of circuits is mostly based on frequency shift or attenuation of the analog signal. A more simplistic method of capacitive sensing also exists, by measuring how long the capacitor takes to charge and discharge by a RC circuit construction.

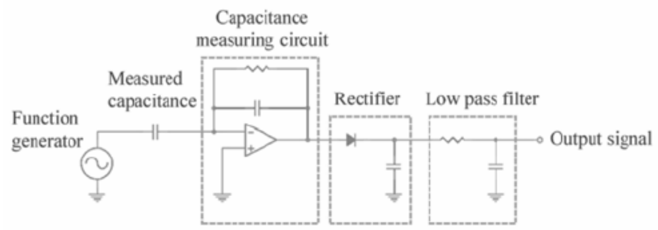


Figure 13 - proposed capacitive readout of study [21]

The design of a capacitive measuring circuit that accurately measures the capacitive state of the tactile sensors in a matrix of capacitors need to account for noise inside circuit to provide accurate measurements. A study describing the design of a elastic capacitive tactile array pressure sensor system (ECTAPSS) [18] shows a viable method of capacitive measuring of matrix arrays.

Comparison

To prepare for the selection of a sensing principle and gain more insights in the functional aspects of the principles, a comparison is made between the piezoresistive and capacitive principle, and looks at the aspects of sensing characteristics, fabrication methods and main trade-offs of the principles.

Characteristics

An excellent study looking into stretchable absolute pressure sensors [19] defines and compares the characteristics of the two analysed sensing principles, and is based on referenced literature. It identifies 3 main advantages of piezoresistive sensing over capacitive sensing, namely excellent linearity, simple interface electronics and low fabrication costs. Capacitive sensing exceeds in better accuracy and resolution.

Fabrication

Looking at a comparison of fabrication methods for sensing principles as defined in a review paper on novel tactile sensor technologies [20] shows a low complexity, cost and high robustness for a piezoresistive based tactile sensor, while a capacitive based sensor shows low robustness.

Moreover, it is interesting to note the review paper is identifying rapid 3D fabrication as most viable among the studied fabrication methods of bulk machining, moulding/ imprinting and thus rapid 3D fabrication.

Trade-offs

Several studies that compare sensing principles in tactile applications [20-22] identify additional trade-offs that are identified in the application op sensing principles. Tradeoffs that needs to be accounted for are the introduction of stray capacitance or cross-talk, complex readout circuitry's and significant hysteresis. Tradeoffs identified for piezoresistive based applications include a non-linear response and signal drift.

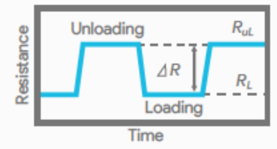
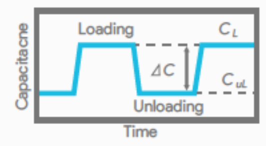
Piezoresistive sensing	Capacitive sensing	
		
Characteristics [19]		
Good	Fair	*Linearity*
±1%	±0.2%	*Accuracy*
1 part in 10^5	1 part in 10^4 to 10^5	*Resolution*
~1600 x 10 ^{6} / °C	~4 x 10 ^{6} / °C	*Temperature error*
Rapid 3D Fabrication [20]		
Low	Low	*Complexity and Cost*
High	Low	*Robustness*
Simp e	Comp ex	*Circuitry*
Trade offs [20 22]		
Exce ent repeatabi ity	Good sensitivity and accuracy	
Low cost and comp exity	Comp ex circuitry	
Non inear response	Introduction of cross ta k	
Large temperature error		

Figure 14 - comparison of piezoresistive and capacitive sensing principle [29-32]

3.3 3D printing overview

Additive manufacturing (AM), better known as 3D printing, has been a breakthrough technology in modern innovation and has seen increasingly growing interest and application. It finds its way into every field of innovation by adding benefits like low-cost production, ability towards ultra-personalised products and rapid development.

Based on ISO standards (*ASTM F42*), additive manufacturing can be classified in these 7 classifications and are summarised in figure 15. Recent developments in the technology of 3D printing made the technology capable of geometric fabrication of increased shape complexity, material complexity and functional complexity. Advancements in the technology with regards to new additive materials, new fabrication methods and techniques and multi-material capabilities allows the 3D printing technology to have enormous design freedom and fabrication possibilities, from rapid prototyping to the end-of-use product manufacturing process.

In more recent developments involving AM, 3D printing is being utilised to fabricate electronics by making use of conductive and insulating materials. Electrical components and materials are being applied to 3D structures to embed electronics into fabrication and allows for fabrication of integrated circuitry on flexible and stretchable substrates by the deposition of conductive materials. The technology of 3D printing electronics allows for new possibilities in fabrication like embedding electronics, 3d structural electronics, or stretchable electronics.

The following section will go deeper into two 3D printing technologies which are able to be applied to the field of printed electronics and fall within the scope and research for widely accessible 3D printing technologies. These technologies are material jetting and material extrusion.

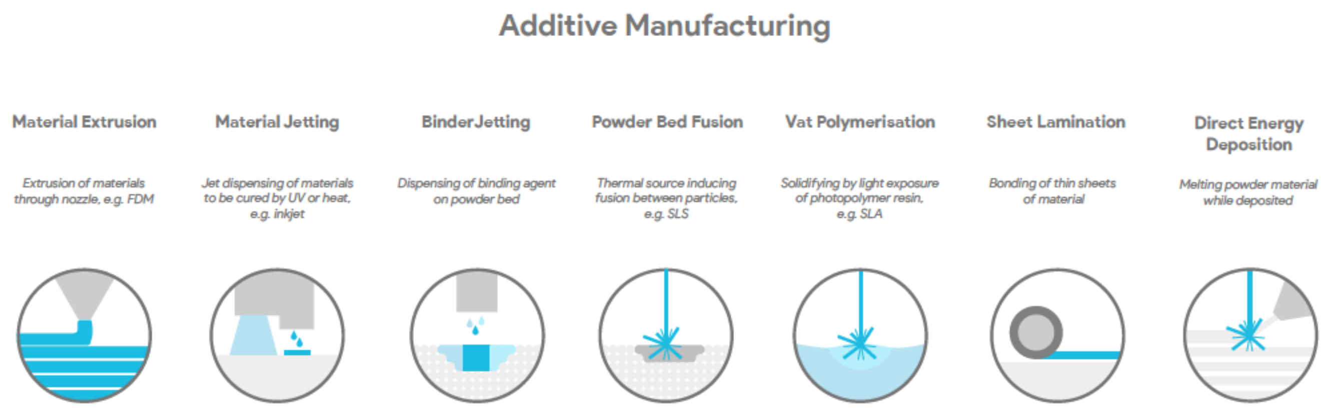


Figure 15 - overview of addtive manufacturing clasifications (ISO ASTM F42)

Material jetting

Material jetting is the most conventional technique to be applied in the fabrication of printed electronics, while the manufacturing technique imposes several advantages for the fabrication of electronics over other traditional techniques. These advantages include a highly automated process resulting in reproducible results and a stable process, little to no wastage of material inks used, and the fact that the process does not require contact with the substrate enabling for more variety in substrate selection.

The technology of inkjet printing dispenses droplets of ink by a control signal. A schematic representation of how this is achieved can be seen in figure 16. In the researched application of printed electronics, the inks mostly consist of conductive or insulate inks. These inks are mostly based on solvent-based nanoparticle inks and use these nanoparticles to give the ink its specialised conductive or insulate properties. When dispensed, an external energy source, mostly UV or heat, needs to cure the inks by evaporating the solvent.

Substrates

Selecting a material to use as substrate for material jetting is important to the functioning of the circuit in the application of printed electronics. The right substrate can be used to create specialised printed electronics like flexible electronics with a flexible substrate, or wearable electronics with a fabric substrate.

Selecting a material to be used as a substrate for material jetting heavily depends on the physical properties of the substrate material including dimensional stability, thermal stability and solvent compatibility, as defined in thesis on the fabrication and testing of flexible electronics performed at the McGill University, Montreal [23].

Providers of these inkjet printing technologies provide some preferred substrates, which are tested and proven to work with their technology. These substrate materials include FR4 and Kapton.

Focusing on the research of printable flexible electronics, additional substrates can be explored to function as substrate. Often referred polymer materials used as flexible substrate are materials like Polydimethylsiloxane (PDMS), Thermoplastic polyurethane (TPU) and Polyethylene terephthalate (PET). These materials provide excellent dimensional stability, solvent resistance and ink adhesion, have a high glass temperature and provide the desired flexible properties.

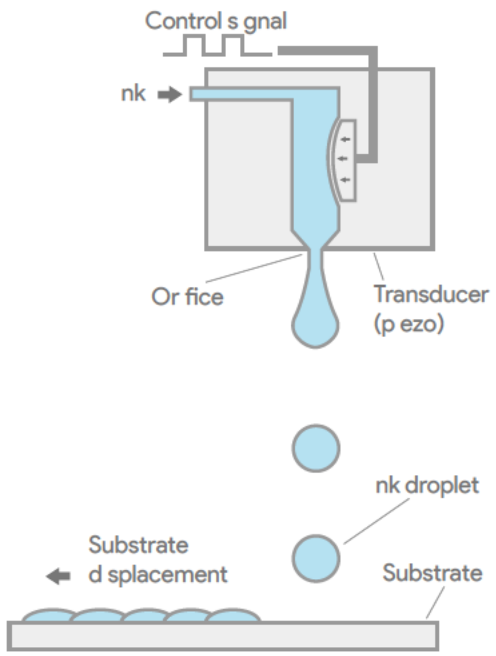


Figure 16 - inkjet printing technology

Material extrusion

Material extrusion is undoubtedly the most accessible and widely applied advanced manufacturing technique. The technology of material extrusion has seen tremendous advancements in recent years, evolving as a technology which has progress in nearly every application field of research and development. The development of advanced filaments gives the technology the ability to provide new ways of manufacturing and fabrication techniques. These advanced materials include thermoplastics with electrical properties (e.g., conductivity), mechanical properties (e.g., increased toughness or flexibility), chemical properties, (e.g., chemical resistance) or aesthetic properties.

Advanced filaments

A few filaments that can contribute to the design of printed electronics and are explored in this research:

TPU, or thermoplastic polyurethane is a type of plastic that has flexible properties. In the field of printed electronics, it can be used to fabricate flexible dielectrics. It has a shore hardness of up to 85A, making it extremely flexible. The most common TPU on the market is NinjaFlex [24]

Conductive PLA is a filament which is a carbon infused PLA plastic. It can be used to create low-voltage circuits in complex 3D geometry. A popular filament is Protopasta's composite PLA [25]

Conductive TPU is a plastic which carries both the properties of a flexible material and is electrically conductive.

Fabric substrates

While 3D printing is a technology which is explored and applied in a large variety of fields, 3D printing is also widely explored in the field of wearables and textiles. We can use fundamental techniques to explore opportunities towards printed wearable electronics.

To allow for incorporation of 3D printed geometries on fabrics, a method is needed to bond the extruded thermoplastic to the fabric and use the fabric as a carrier substrate for the 3D print. To allow for 3D printing on a fabric as substrate and create a sufficient bond between the two materials, 3 different design directions are defined. These directions include:

Meshed: A perforated structure allows the thermoplastic to bond with itself through the holes of the fabric. The print gets locked into the structure of the fabric, creating a bond between the two materials.

Intertwined: intertwine the two materials by perforating the fabric using a laser cut structure into the fabric. By printing a structure on both sides of the fabric, the perforated structure in the fabric allows the two 3D printed sides to fuse to each other, sandwiching the fabric and incorporating the fabric into the 3D printed structure.

Chemical bonding: using specific chemical properties of materials to fuse the materials. This approach fuses the materials chemically. When using a fabric which is coated with a material which chemically bonds with the thermoplastic which is used as the filament for the 3D print, the printed geometry bonds to the coating of the fabric, letting the coating act as a binder between the fabric and 3D print material.

3D printers

This research focusses on the fabrication of 3D printed electronics involving the following two 3D printers: Voltera V-One (see figure 17a) and Botfactory SV2 (see figure 17b). These commercially available 3D printers are specially designed to aid in the fabrication of electronics on a variety of substrates.

Voltera V-One - Ink dispensing

The Voltera V-one [26] is a desktop 3D printer which can print electronically conductive traces on selected substrates like a PCB or flexible materials. The printer uses a syringe-like nozzle which holds the conductive material, which is ejected by a screw inside the syringe. The nozzle ejects the conductive material by a turning motion of the screw, creating traces on the substrate. The deposited conductive material is an ink, which needs to be cured in order to properly function and last and is done by the incorporated heated bed of the Voltera v-one. Substrates for the fabrication of the circuit can be a conventional material like FR4, but different substrates, like flexible materials or thin films can be explored.

Botfactory SV2 - Ink jetting

The SV2 desktop 3D printer [27] is an electronics printer built by company Botfactory. It uses the AM technology of material jetting and uses thermal ink jetting to lay down conductive traces on a selected substrate. Substrates can include both rigid and flexible materials, like FR4 or Kapton. The deposited ink needs to be cured using the incorporated heat bed, or by additional heating options like a heat-oven or even room temperatures. The Botfactory is able to print both insulating and conductive material by the use of different ink cartridges, allowing for multi-layer PCB printing.

(a) Voltera V-One

(b) Botfactory SV2

Figure 17 - 3D printers used in project exploration [24-25]

4 LIST OF REQUIREMENTS

This chapter will define the goals for the development of a sensor and lists the requirements for the explored sensors. It provides a solid foundation for the progression of the project.

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4.2 Sensor Requirements 34

4.1 Sensor goal

The exploration and development of a 3D printed tactile sensor needs to follow some clear requirements and goals in order to steer the results into a desired outcome. These goals are defined according to results of research and analysis. A sensor goal is defined according to two aspects, fabrication and performance.

Fabrication

The goal on sensor fabrication can be defined according to the aspects of repeatability, adaptability and cost.

The goal for the fabrication of the sensor is largely aimed at an adaptable design. The exploration needs to focus on a fabrication method which is significantly adaptable in its design. This should make the fabrication of the design easy to be applied to a variety of application fields by a universal design and be adaptable to allows for personalised products. Repeatability of the sensor fabrication also plays a large role in the fabrication goal of the sensor. The fabrication of the sensor needs to be easy to replicate and provide the same results. The aspects of costs is less of a factor in the fabrication goal, although still kept as a factor while fabrication of the sensor needs to be accessible by the use of available 3D printing technologies.

Performance

The goal on performance of the sensor is largely defined according to 3 aspects, Repeatability, resolution and accuracy. A definition is important and given in the glossary page of this thesis.

The performance of the sensor is mainly assessed according to its repeatability. The most significant aspect that the sensor needs to show according to the project scope is the ability for the sensor to provide a repeatable outcome when met with the same environment, thus providing a consistent readout when the same load is applied. >

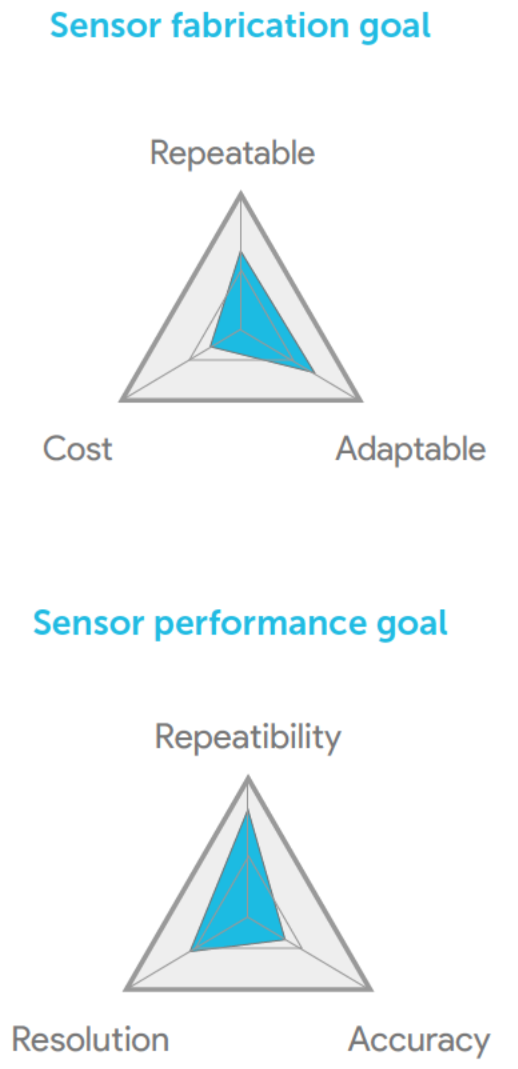

Figure 18 - sensor goals

The resolution of the sensor also plays a role in the assessment of the sensor, although more limited, while the ability to distinct in small deviations of applied loads is desirable, but not decisive for the performance of the sensor. The accuracy of the sensor is less significant to the performance of the sensor, while the performance of the sensor is less dependent on how it performs in an absolute sense. Closely resembling a real-world value or its recognised standard is not within the scope of this exploration. the application of these sensors is not used as pressure instruments but used as inputs for tactile mapping or machine interactions, making the need for accurate readings out of scope.

While it is significantly important to have a sensing principle which gives a repeatable and stable readout of its pressure sensing, focus of the exploration that is performed in this thesis is focussed on the exploration of opportunities 3D printing can have on the development of tactile sensors. Therefore, this exploration does not focus on the development of commercially viable sensory conditions and only needs to prove a level of significant repeatability and stability, not measurement accuracy. The explored fabrication method of 3D printing provides far less fabrication accuracy and ideal materials compared to traditional sensor manufacturing methods. A commercial level of accuracy is not viable nor the scope of this research while the focus lies on an exploration of a new field of fabrication techniques which cannot match current industrial fabrication standards. Figure 19 shows these industrial fabrication standards for the design of commercial tactile sensor according to design guidelines, as defined in a journal on advanced MEMS technologies, and used as reference. [28]

Major Guidelines for Design of Tactile Sensor

	Parameter	Requirements
Force	Force variation	Orthogonal and transversal
	Force sensitivity	1–1000 g wt
	Force dynamic range	0.01–10 N
Time	Temporal variation	Static and dynamic
	Time response	1 ms
	Sampling rate	100 Hz to 1 kHz
Space	Spatial resolution	1–2 mm
	Array size	5 × 5–10 × 10 points
	Linearity	Monotonic and stable response
	Hysteresis	Low hysteresis and repeatability
	Robustness	Sustain application defined load
	Cross-talking	Minimal cross-talk
Technological aspects	Shielding	Shielding from electrical/magnetic noise
		Simple mechanical integration
	Integration	Minimal wiring, low power consumption
		Low cost, compliance

Figure 19 - industrial fabrication standards for tactile sensor performance [36]

4.2 Sensor requirements

The development of a tactile sensor needs to follow certain requirements in order to guide the exploration into a desired outcome. The tables below sum up the requirements for the development of a tactile sensor. The requirements are set according to the acquired knowledge that is presented in chapter 3 – Research & Analysis.

To define the requirements for the development of a tactile sensor to be used in wearable and robotics applications, we can base our requirements on human tactile perception as a standard for tactile sensing. A widely acknowledged review by J. Dargahi studies these relations in his paper on human tactile perception as a standard for artificial tactile sensing [29]. We base our requirements on the findings of this paper, but limit it in required performance due to the explorative scope of this thesis.

1.0 General

1.1	The sensor should be able to respond to (a difference in) applied surface pressure (1 g)
1.2	The sensor should be flexible and be able to bend in both axis
1.3	Bending of the substrate should not affect the performance of the sensor

2.0 Performance

2.1	The sensor should be able to sense a minimum load equivalent to light touch (± 5 g) (Range)
2.2	The sensor should provide the same readout when equal loads are applied (Repeatable)
2.3	Readout can be non-linear but should have a monotonic function / follow a curve (Linearity)
2.4	Drift in the sensor should be non-existent, or be compensable (drift)

3.0 Fabrication

3.1	The sensor should be fabricated using conventional/accessible 3D printing methods (FDM, inkjet)
3.2	The fabrication and design of the sensor should be easily reproducible

4.0 Application

4.1	The sensor design should be able to allow for wearable applications
4.2	The readouts of the sensor should be usable for tactile imaging applications
4.3	The design of the sensor should allow for adaptability towards personalised products

5 CONCEPT

This chapter will describe the generation, selection and evaluation of a final single sensor concept according to an analysis of fabrication a performance.

5.1 Design drivers 36
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5.4 Evaluation 54

5.1 Design drivers

Leading from the performed research in a previous chapter, we can define some design considerations and options that can lead us to a concept design proposition. These design considerations are mostly based on different working principles and how to construct and fabricate these tactile sensors. Based on these design considerations identified in the research chapter, we can derive some design drivers which can fuel or concept generation. Possible design options derived from the research are defined in the tables to the right.

The exploration of possible design options, have identified several key design drivers which are used to create concept directions towards the design of a printed tactile sensor. These identified design options can be summarised according to the following points in figure 20.

Piezoresistance

Sensor structure	Matrix array - Interdigital - Single point
Piezores. material	Foam - Thin film - Fabric
Sensing layout	Matrix array - Single-point array

Capacitance

Conductor	Conductor/skin - conductor/conductor
Dielectric structure	Hinge - Wrinkled - Porous
Dielectric material	Air - Flex material - Foam

Fabrication

Technology	FDM - Inkjet
3D Printer	Ultimaker S5 - Voltera V One - Botfactory SV2
Material	Cond. PLA - TPU - Cond. ink - Flex ink

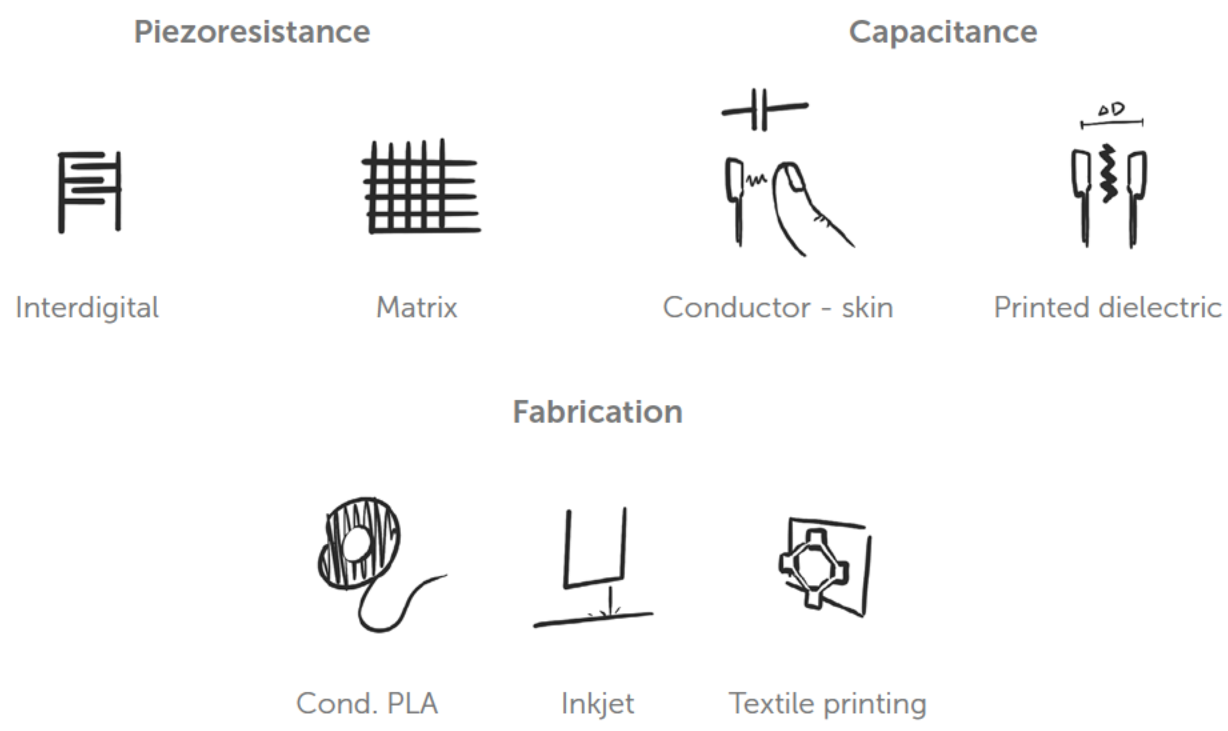


Figure 20 - identified design options

5.2 Generation

According to the design drivers that are presented in 5.1, a selection of design concepts are presented. These design concepts are generated according two main aspects, namely the sensor structure and method of fabrication. Below we elaborate on different concepts according to these two main aspects.

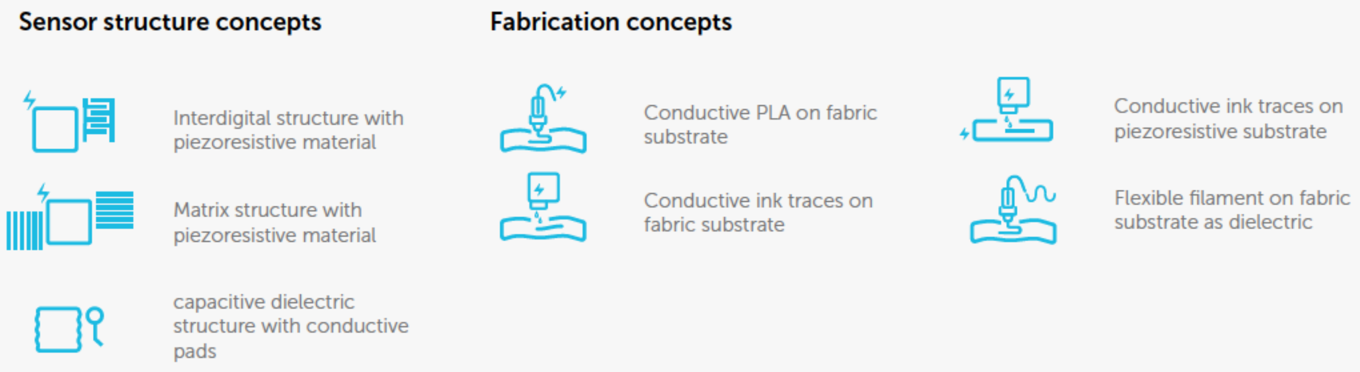


Figure 21 - concept generation

We synthesise these concepts into some envisioned concepts. This synthesis of concepts allows for some envisioned final sensors in the proceedings of the analysis of these concepts. Below are presented 4 different sensor synthesised concept designs.

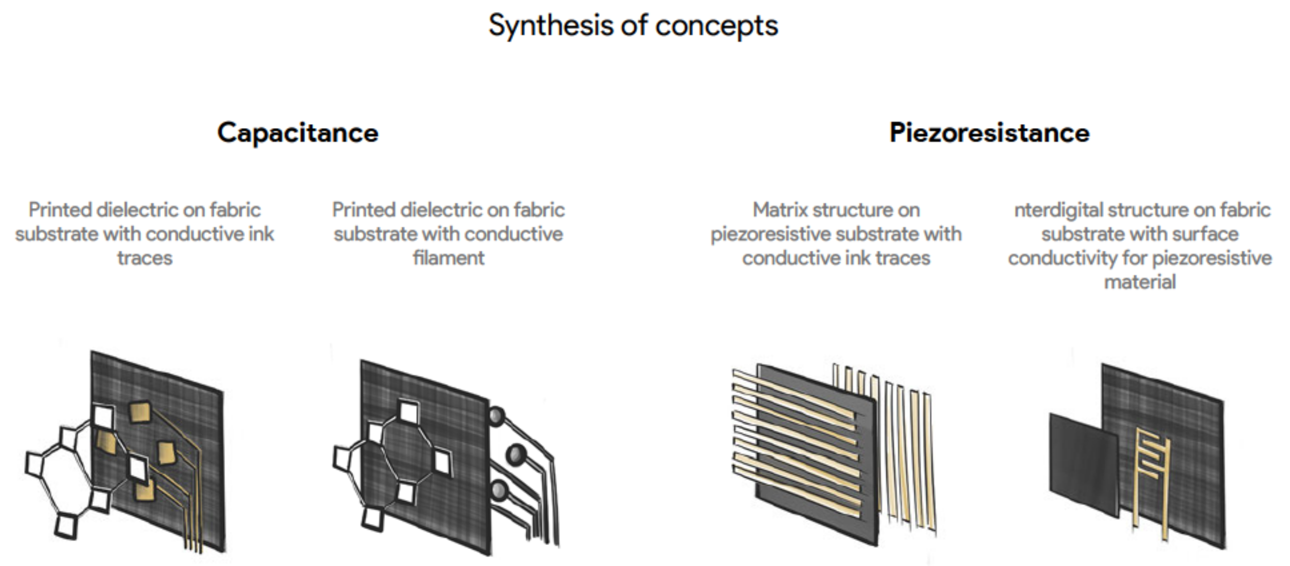


Figure 22 - synthesised concept designs overview

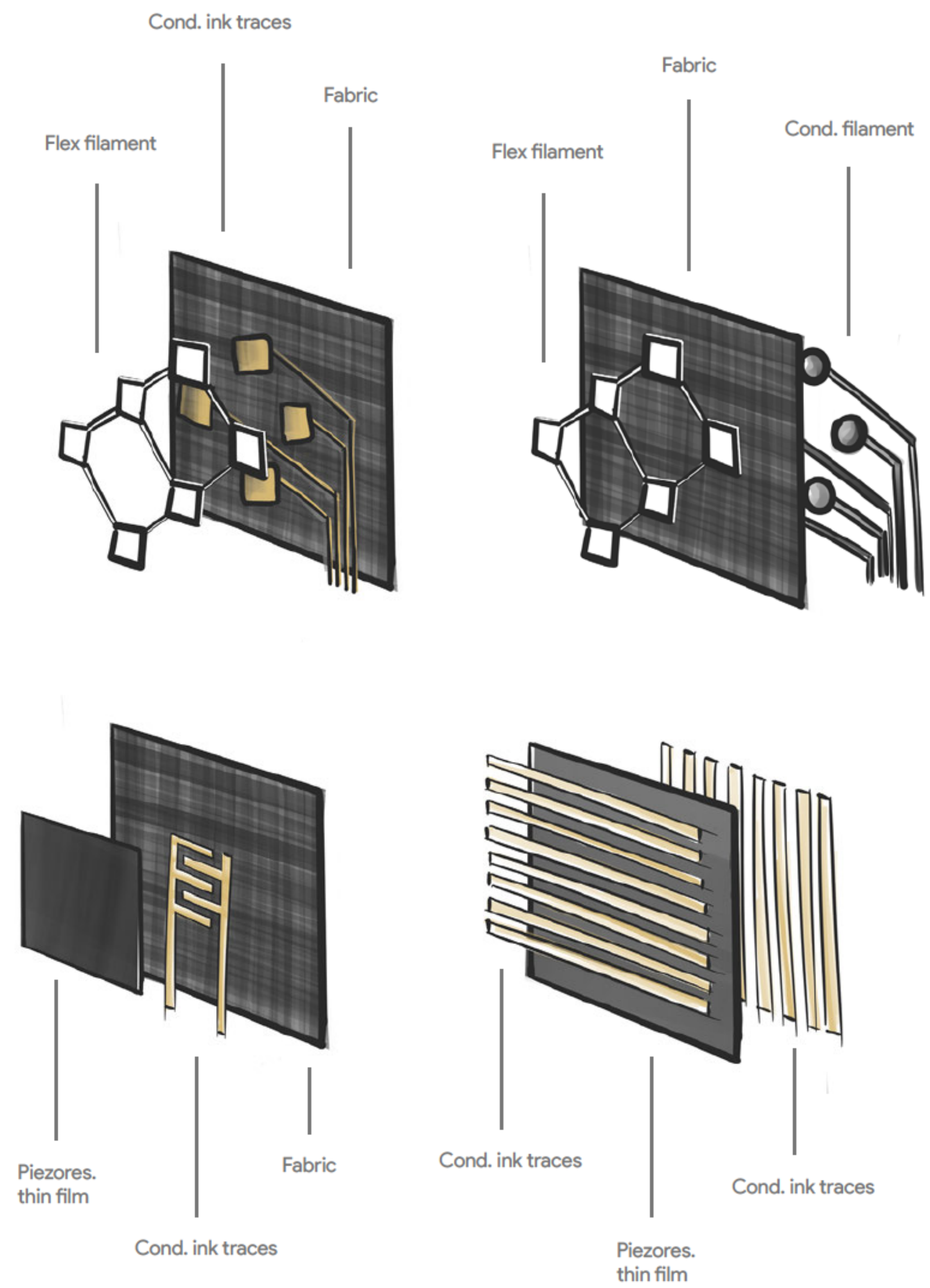


Figure 23 - synthesised concept designs construction overview

5.3 Selection

The viability of the presented concepts in 5.2 is explored further to select and provide proof of a viable fabrication method and performance. The following section will analyse these factors with regards to the set design requirements. The analysis is split into two sections, focussing on performance and fabrication. It will describe the testing that has been performed to create a solid base for the selection of the design principles.

Fabrication

A selection on the key fabrication principles of a sensor concept is based on a variety of exploratory tests. These tests and their insights are categorised into the following categories and are elaborated accordingly: Traces, substrate and printing.

Traces

Conductor: a variety of materials were tested to select a conductor which is 3D printable using accessible technologies and can function as the conductor in the sensing circuit. These materials include conductive PLA, conductive ink paste, flexible conductive ink paste and conductive solvent-based ink. The conductor selection is dependant on the printing technique.

Resistance: although a low resistance is less important to the application of sensing circuits, a stable resistance is necessary to provide accurate readouts. A variety of fabrication methods, like trace patterns and trace width (0.5mm - 1 mm) where tested for a stable trace and trace resistance.

Design: a variety of interdigital structures were tested on their sensing performance. Round structures proved more repeatable readouts while it provides equal resistance throughout the whole structure best. A second variable in the selection of a trace design was the durability of the traces, eliminating sharp corners and narrow traces.

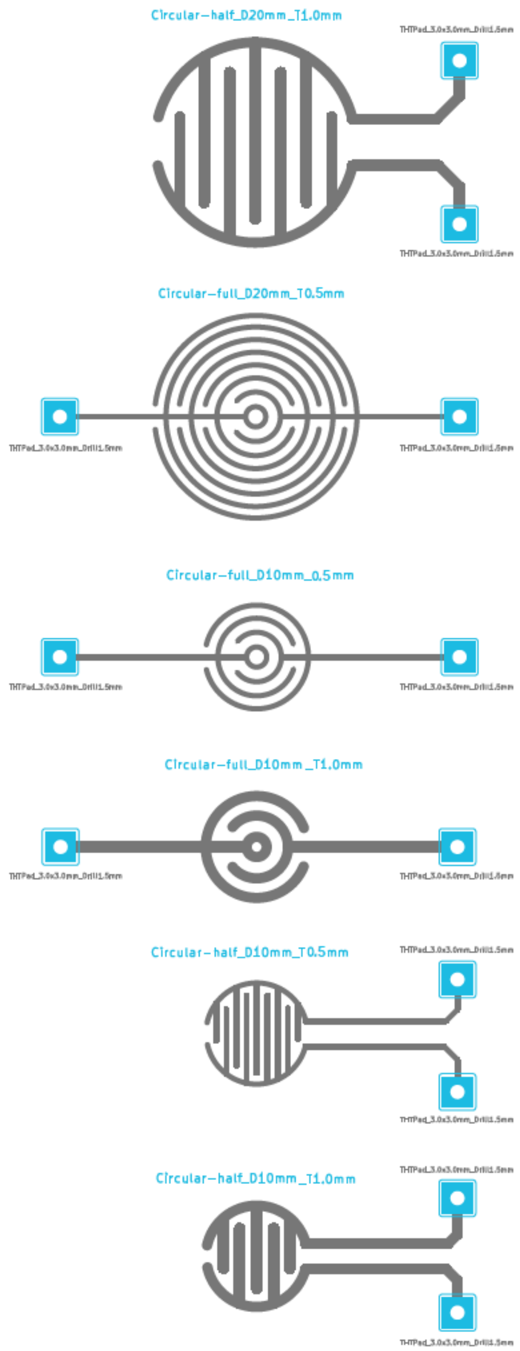
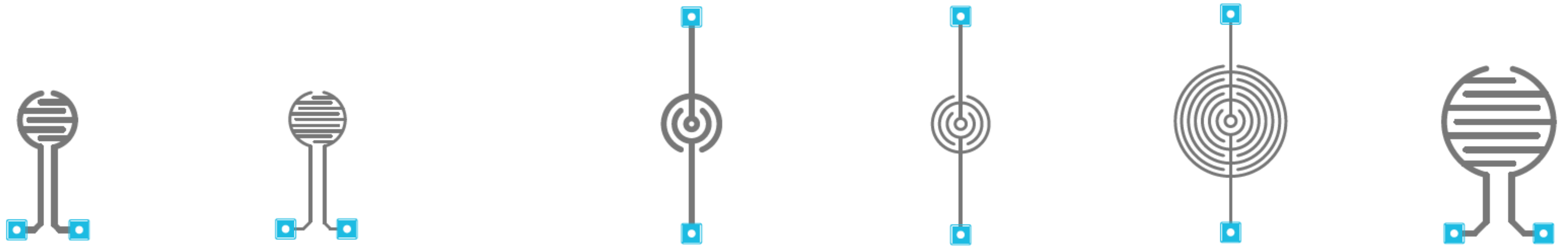


Figure 24 - traces fabrication selection samples

Figure 25 - fabrication testing



	Weight	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total
Conductance	30	8	240	3	90	**8**	**240**	3	90	3	90	8	240
Readout stability	20	4	80	4	80	**8**	**160**	8	160	8	160	4	80
Trace durability	20	4	80	4	80	**6**	**120**	6	120	3	60	3	60
Repeatability	20	6	120	4	80	**7**	**140**	5	100	4	80	4	80
Spacial Resolution	10	8	80	8	80	**8**	**80**	8	80	4	80	4	80
Total	100		600		410		**740**		550		420		540

Figure 26 - weighted objectives selection of traces fabrication

Substrate

To allow for wearable applications of the explored concepts, the fabrication of the sensors require a material which has flexible properties, like a thin film or textile fabric, and can also act as substrate for the identified conductive materials. The substrate needs to provide proper dimensional stability to prevent damaging the traces, thermal stability to withstand curing temperatures and solvent compatibility to provide a sufficient bond with the used conductive materials.

The substrate selection is based on testing with a variety of materials, like FR4, kapton, coated nylon, TPU and (piezo-resistive) thin films.

The exploration of different substrates resulted in the discovery of a material which suits the needs for a large variety of sensor designs in the field of printed electronics. This material is commercially available and has a variety of applications in the textile field with water-resistant and heat-sealable properties. The material can be sourced online at specialised fabric manufacturers, extremtextil [30]. The nylon fabric material is coated with a TPU layer, giving it a variety of interesting properties. The material is especially useful in the scope of this research while it serves as an excellent substrate for both TPU 3D printing (chemically bonding to the substrate) as conductive inkjet printing (TPU serves as excellent inkjet substrate), and additionally has flexible properties. An additionally interesting property is the ability to heat-seal to itself by chemically bonding the TPU layers.

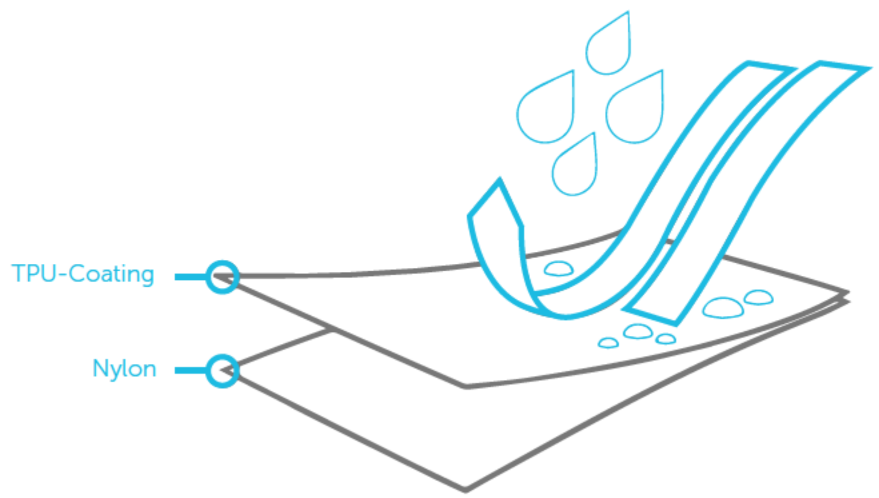


Figure 27 - overview of TPU-coated nylon substrate

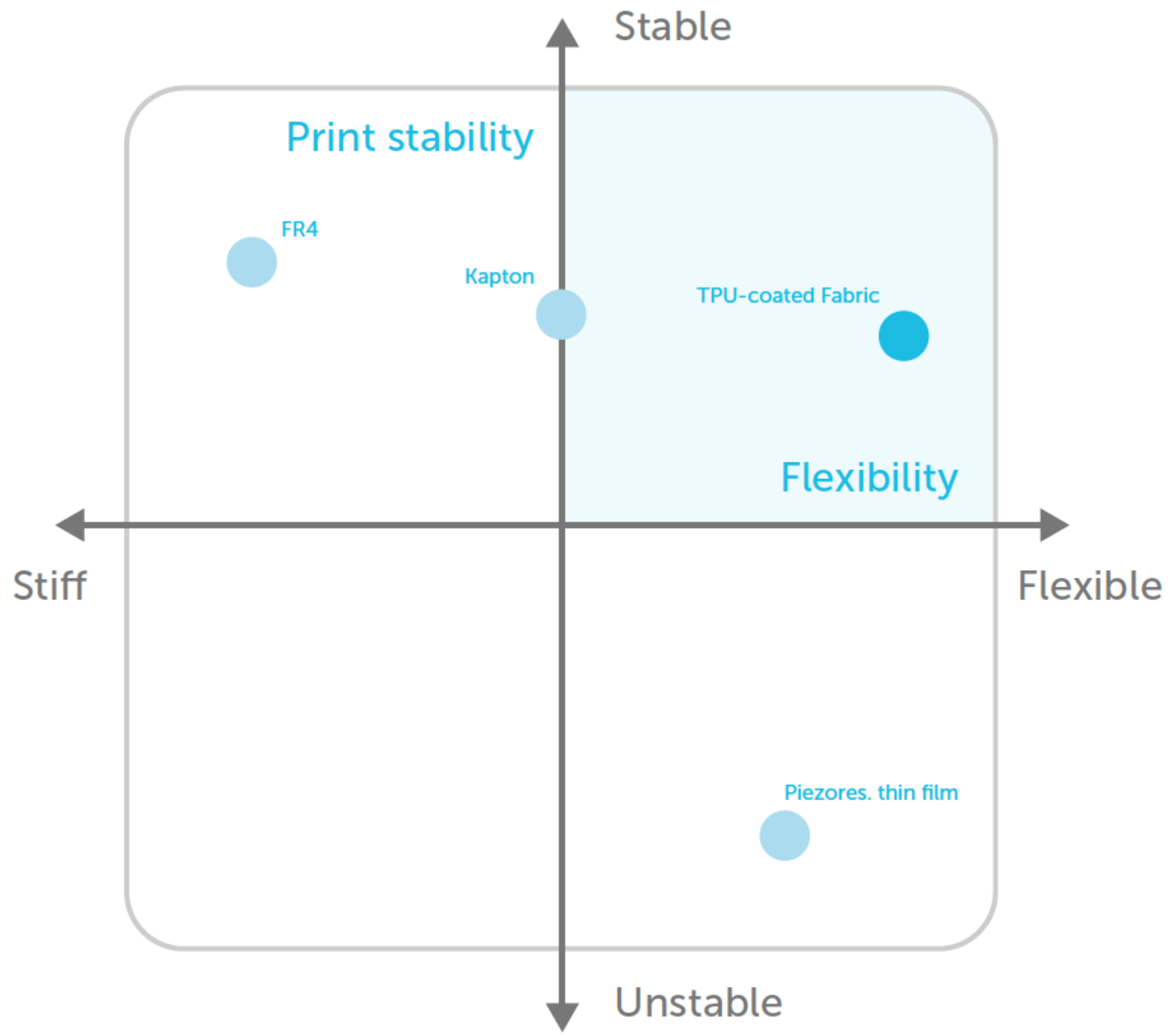


Figure 28 - C-Box selection of substrate

Printing

printing technology selection needs to result in the best method of available printing techniques in combination with the selected substrate.

Ink jetting: A variety of designs where printed using the Botfactory SV2, and tested aspects like optimal curing time, printing repetitions and ink resolution. The tests showed reasonable results, but lacked a repeatable fabrication method while resistance and traces stability varied significantly.

Ink dispensing: The Voltera V-One was also tested on its performance with the selected substrate and showed more repeatable fabrication and stable traces. The selected trace design always shows a stable conductivity with a resistance readout of around 0.8 ohm throughout the sensing circuit.

FDM: Additional testing was performed to assess the possibility of using conventional FDM printing to create sensing circuits. A variety of sensing structures were printed using the Ultimaker S5 and conductive composite PLA. The circuits showed significantly promising results but lacked in providing flexible properties for wearable applications.

Figure 29 shows a harris profile selection which weighs the merits and demerits of the printing technologies.

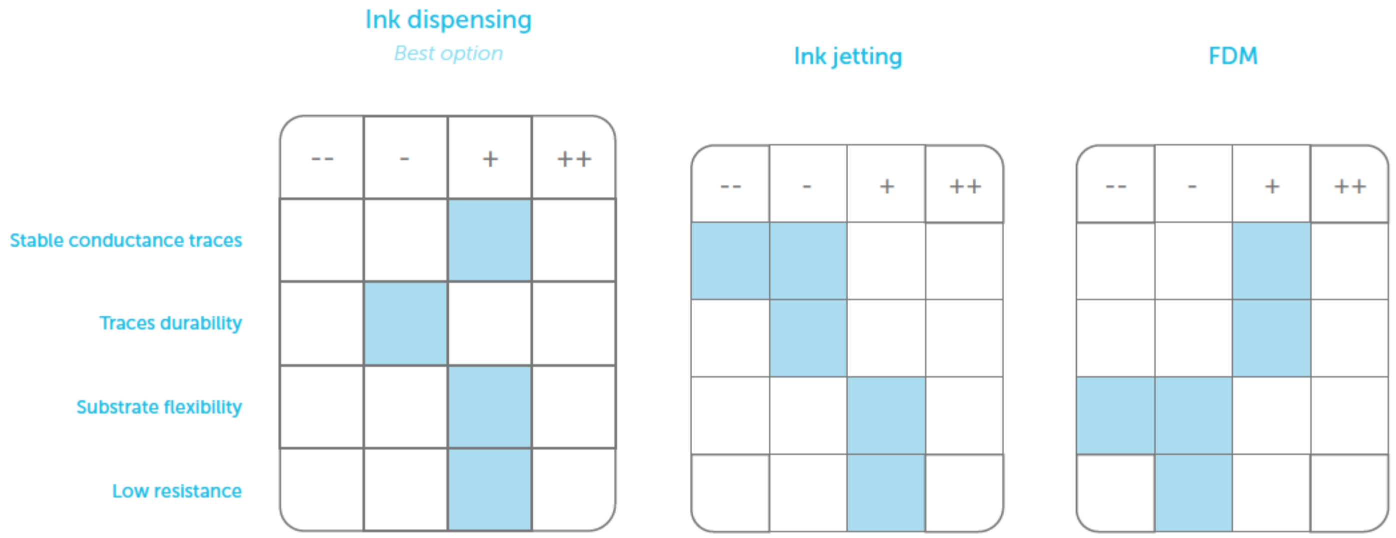


Figure 29 - harris profile selection of printing technologies

Figure 30 - Printed traces using the Voltera V-One showing a standard resistance of 0.7 ohm

Performance

The analysis is performed by the use of a custom built setup to compare the readout of a load cell to the readout of the sensor samples. While it's the industrial standard for measuring weight, we can use it as our benchmark for analysing the readouts of the sensor samples. A HX711 load cell amplifier applies a signal to the load cell, and amplifies its readout to be measured by a microcontroller.

A schematic representation of the setup can be seen in figure 32. The load cell is mounted to a baseplate by the use of a 3D printed mount, and allows the load cell to bend, introducing strain in the load cell when a load (force) is applied. The other end of the load cell is fitted with a 3D printed mount for the sensor sample to be placed on. The readout of this sensor sample is sent to a microcontroller to measure the sensors readout. A fixed load is applied on the surface of the sample.

The setup needs to analyse a variety of different sensing principles and variations on these principles. The different sensor samples can be seen in figure 31. The sensor samples are all inkjet printed circuits on FR4 using the Botfactory SV2. The samples include the following sensing principles:

- Interdigital structure small, piezoresistive sensing
- Interdigital structure large, piezoresistive sensing
- Matrix structure, piezoresistive sensing
- A multitude of different TPU printed dielectrics, Capacitive sensing

  - Porous thin dielectric
  - Porous thick dielectric
  - Wrinkled dielectric
  - Solid dielectric

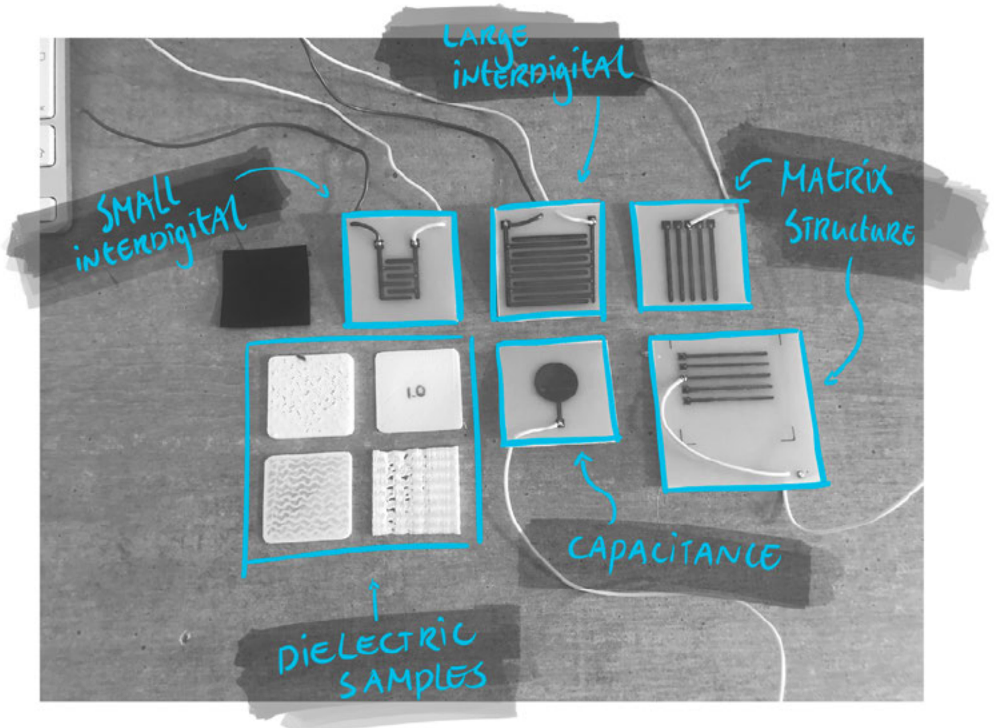


Figure 31 - performance analysis sensing principle samples

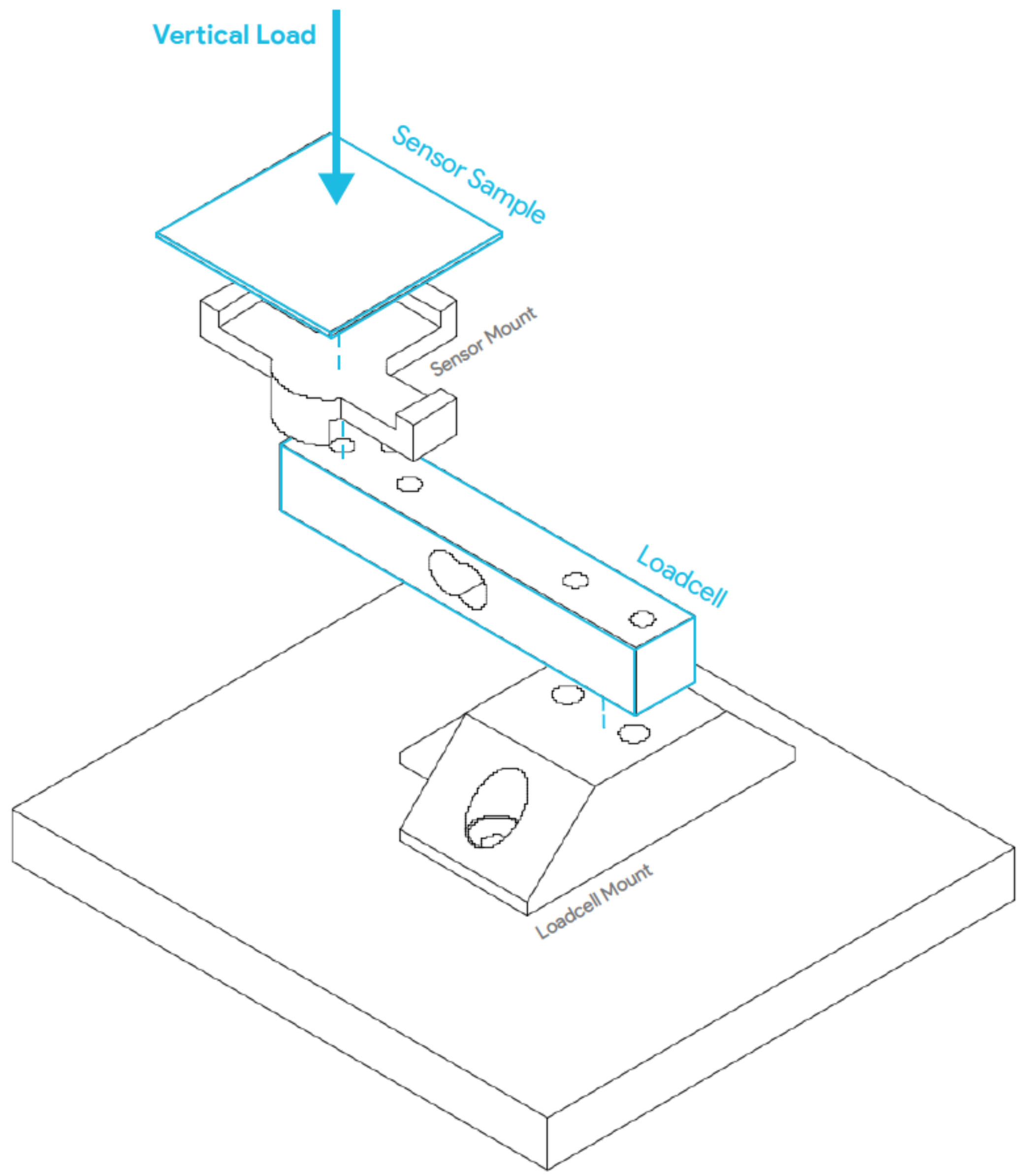


Figure 32 - performance analysis setup

Measurements

The sensor samples based on the piezo-resistive sensing principle are measured on their readout by sensing a voltage potential on one of the printed traces in the circuit. When a force is applied, the resistance in the circuit changes by the piezoresistive thin film layer on the circuit, making an increased measurable voltage drop in the circuit. The microcontroller converts this analog voltage to a digital signal using its built-in ADC. Using a voltage divider setup, together with a basic ohms law formula the digital value is converted into a resistive value of the sample sensor. The voltage divider is constructed using a reference resistor, which resistance is defined by closely matching the internal resistance of the sensor sample. This provides the most accurate conversion.

The sensor samples based on the capacitive principle are measured on their readout by measuring the charge-discharge trough a resistor-capacitor setup. A printed dielectric is placed on a printed conductive pad. When a force is applied by a second conductive pad (or finger using the conductance of the skin) on the dielectric, a capacitor is created between the two conductors. An increase in pressure also increases the capacitive state by the deformable dielectric. A microcontroller measures this change by the changing charge-discharge time.

The samples are analysed by comparing the readouts of the sample sensors to the readout of the load cell, and looking for a comparable outcome, stability and repeatability of the sensor. A plotter allows for visualising the two readouts and compare them to each other. The analysis focuses on the sensory aspects of repeatability, range, stability and resolution. A definition of these aspects is important and are given in the glossary page of this thesis.

▶ *Glossary*

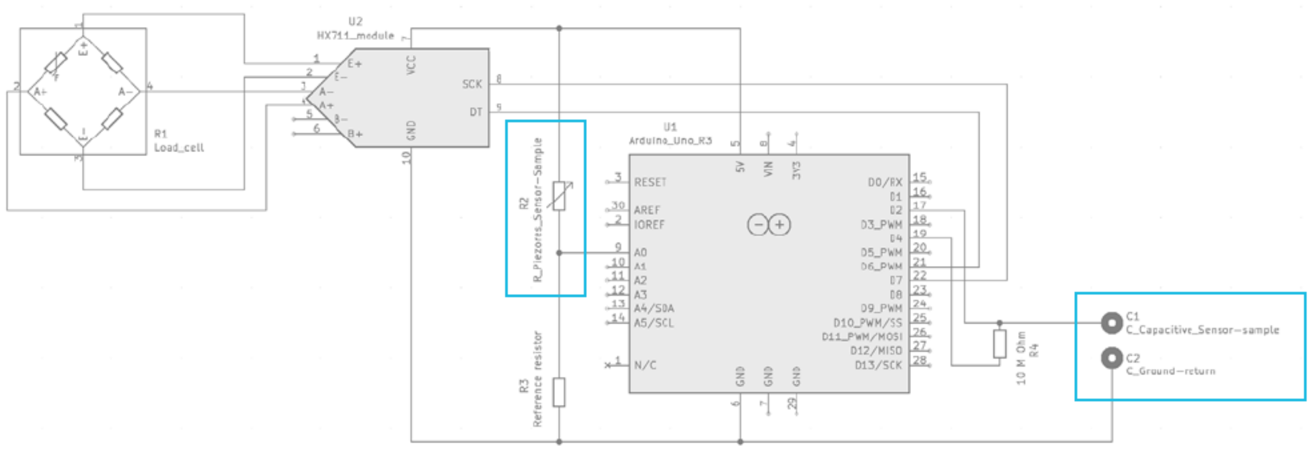


Figure 33 - performance analysis circuit schematic

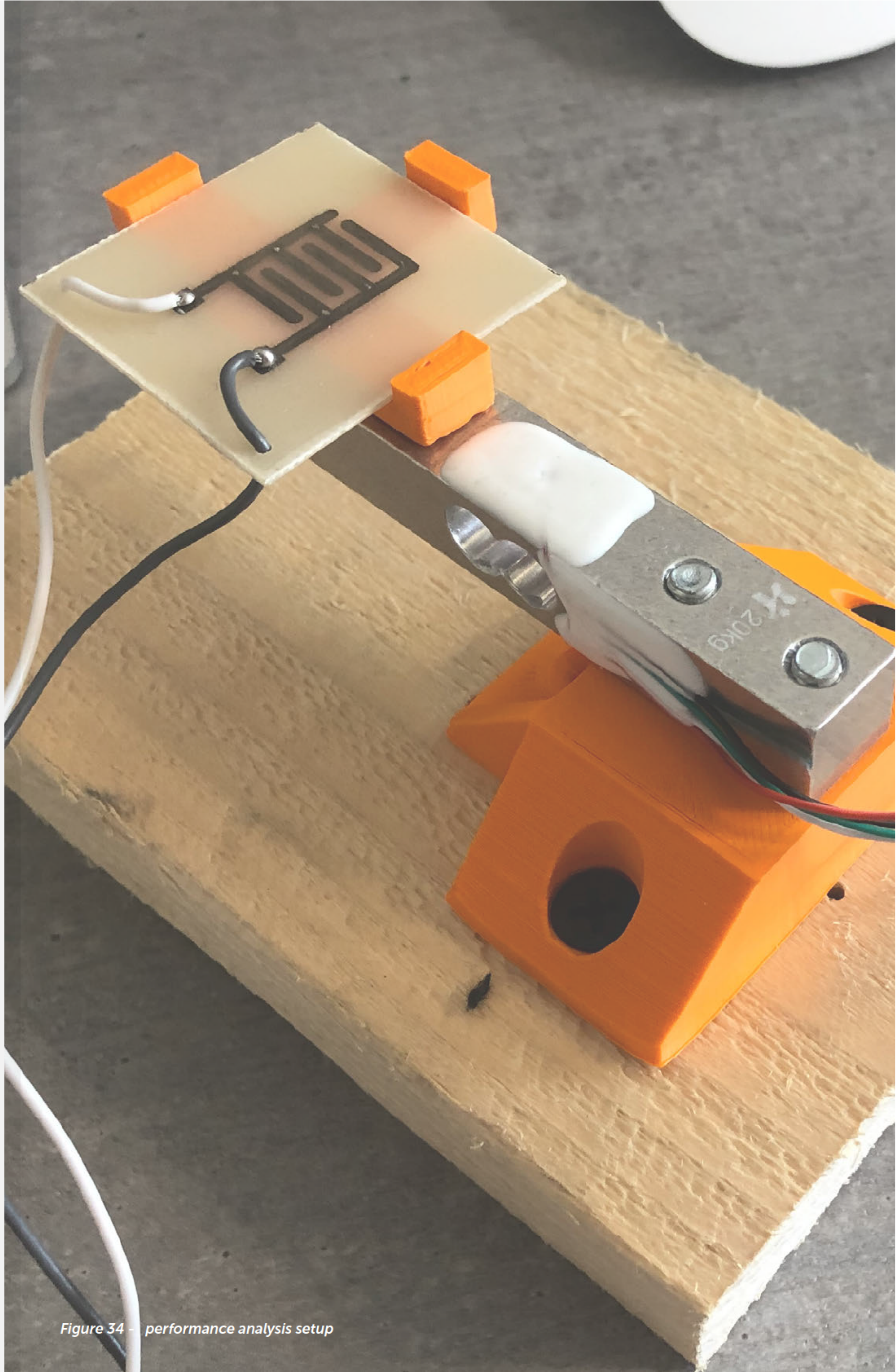


Figure 34 - performance analysis setup

Results

Figures 35-38 show the results of the sensor samples. In the graphs, the readout data of the sensor samples are plotted against the data of the benchmark data of the loadcell. It gives an overview of the accuracy of the sensor principles. Raw data of the analysis can be found in appendix D.

▷ *Appendix D*

First, the sensor is applied with a force by pressing on it from light touch to reasonable force (0g to ±1200g). Then, the sensor is loaded by a fixed weight up to 3 times (30g).

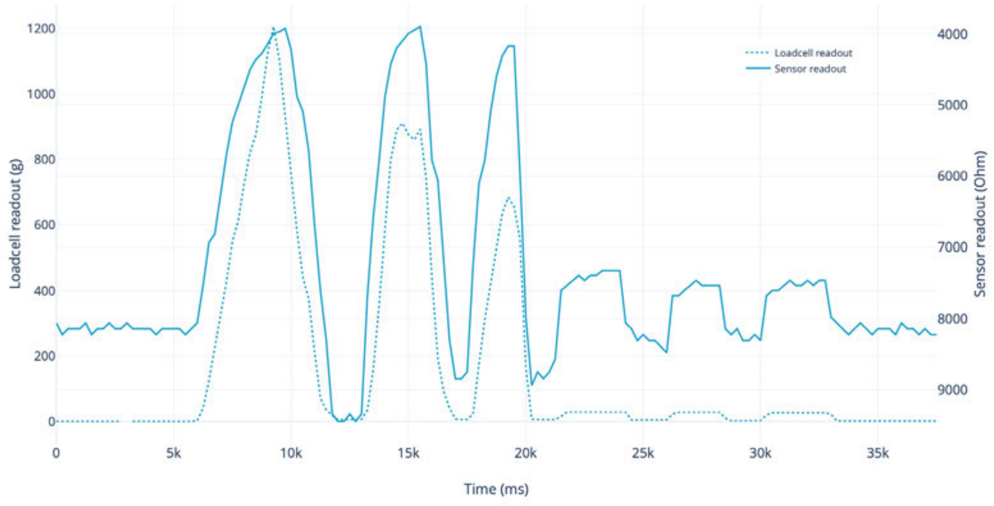


Figure 35 - readout interdigital structure small

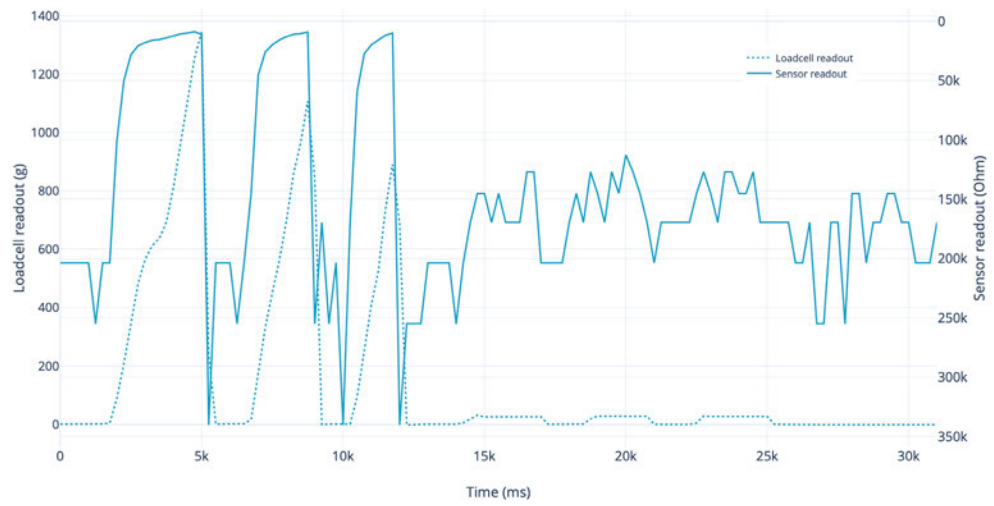


Figure 36 - readout interdigital structure large

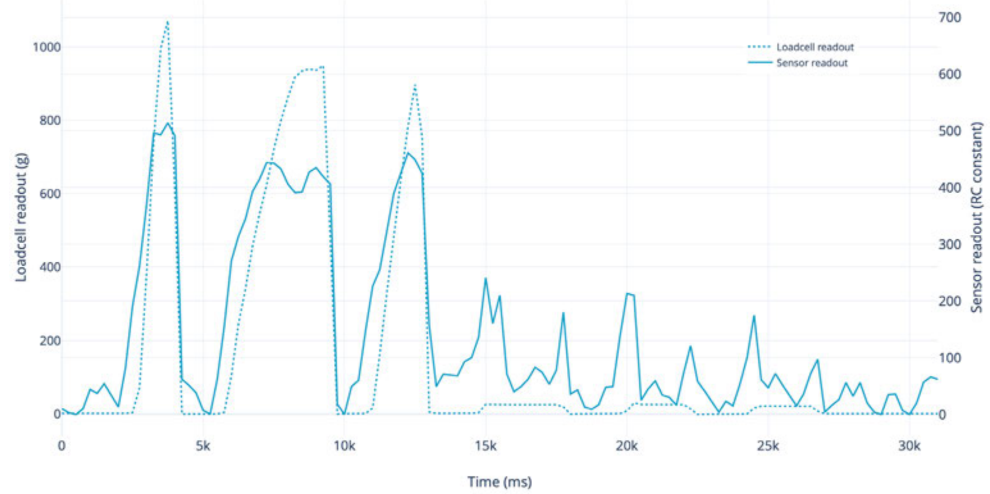


Figure 37 - readout capacitive wrinckled dielectric

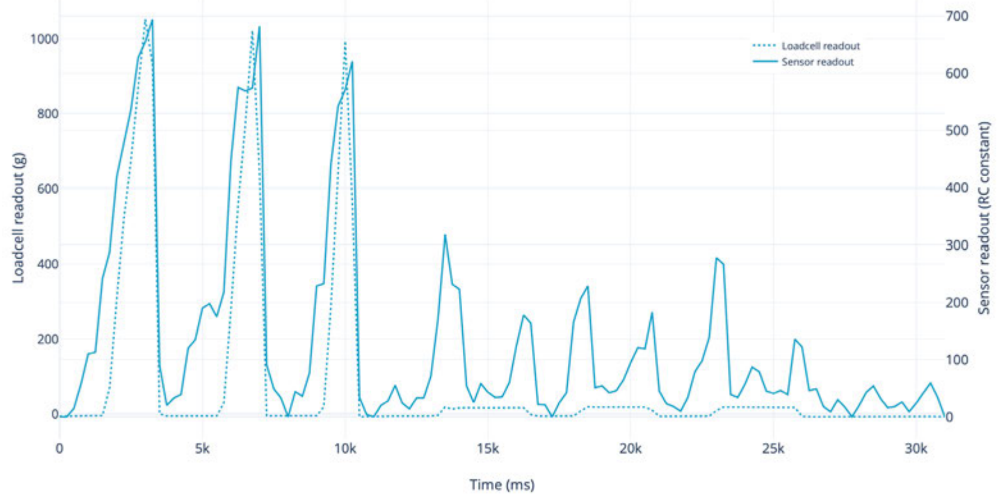


Figure 38 - readout capacitive porous thin dielectric

Figure 39 - analysis of performance sensing principle samples

Analysis

The readouts of these samples, analysing them and comparing them to the readout of the load cell, gives very good insight in the performance of these sensing principles. Below we state the insights that came from this analysis and is based on the results of all sensor samples included in the appendix.

- deviations in the surface area and location in which the pressure is applied changes the readout of the sensor significantly
- Smaller structures give a more repeatable readout, while a decrease in sensing area of the structure means less deviation in applied pressure area and pressure location, giving a more repeatable outcome.
- Round structures give a more repeatable readout of the sensor while the circuit has less structural differences, making a change in location of applied pressure have less impact on the repeatability.
- A large number of external factors can negatively influence the sensing capabilities of capacitive sensing by introducing stray capacitance in the circuit.

To conclude on which of the principles is most suitable for the use in the progression of the development of printed tactile sensors, we look at how the sensor samples behave in relation to the defined sensory aspects of repeatability, stability and resolution. We sum up the key insights in relation to these main sensory aspects. Additional analysis of raw data can be found in appendix D.

▷ *Appendix D*

- Small interdigital structure:
shows a significant repeatable outcome while readout follows load cell readout well. Sensor can differentiate in the two different weights therefore showing significant resolution. Stability of readouts is reasonable; readouts show slight drifts in the measurements. Readouts show an acceptable response time.

- Large interdigital structure:
shows significantly repeatable readouts and acceptable resolution but shows shows significantly less stability while introducing more drift and less stability in readout.

- Capacitive porous thin dielectric:
sensing principle shows difficulty sensing small loads. Moreover, stability and drift is introduced in readouts. Spikes are introduced by stray capacitance.

- Capacitive wrinkled dielectric:
readouts show significant issues in stability and do not significantly resemble the readout of the loadcell. Stability of the readout is low.

5.4 Evaluation

According to the tests performed in the selection section 5.3, this evaluation will conclude the findings from the selection and derives a solid base for the formulation of a final concept. The evaluation is based and split on the performance and fabrication tests and is elaborated accordingly.

Fabrication

The following findings from the selection tests can be derived and used in the formulation of a final sensor concept:

Traces

The selection tests showed a viable width of the traces to be 1 mm and total diameter of sensing structure around 10 mm. lowering trace width would significantly decrease conductivity on the selected substrate. Additionally, the performed tests showed a smaller sensing surface diameter to give more stable readouts. A diameter of 10mm showed the best balance between repeatable readings and stable readings.

Ultimately a round interdigital design, elaborated in 5.5 – concept design, will be chosen for the progression of the sensor design. This design showed best performing readouts, while it provides equal resistance throughout the whole structure best.

Substrate

From the substrates that were tested, only one showed both viable print stability and flexible properties (see 5.3 selection), essential in the fabrication of flexible sensors. TPU-coated fabric showed excellent performances as substrate for the tested conductive inks and provided significant flexible ability for wearable applications, while also providing additional benefits like heat-sealing and chemical resistance.

Printing

The 3D printing technique of ink dispensing using the Voltera V-One showed excellent performance by showing repeatable fabrication and stable traces with the selected fabrication specifications and will be used in the progression of the sensor development.

Figure 40 - final trace fabrication design

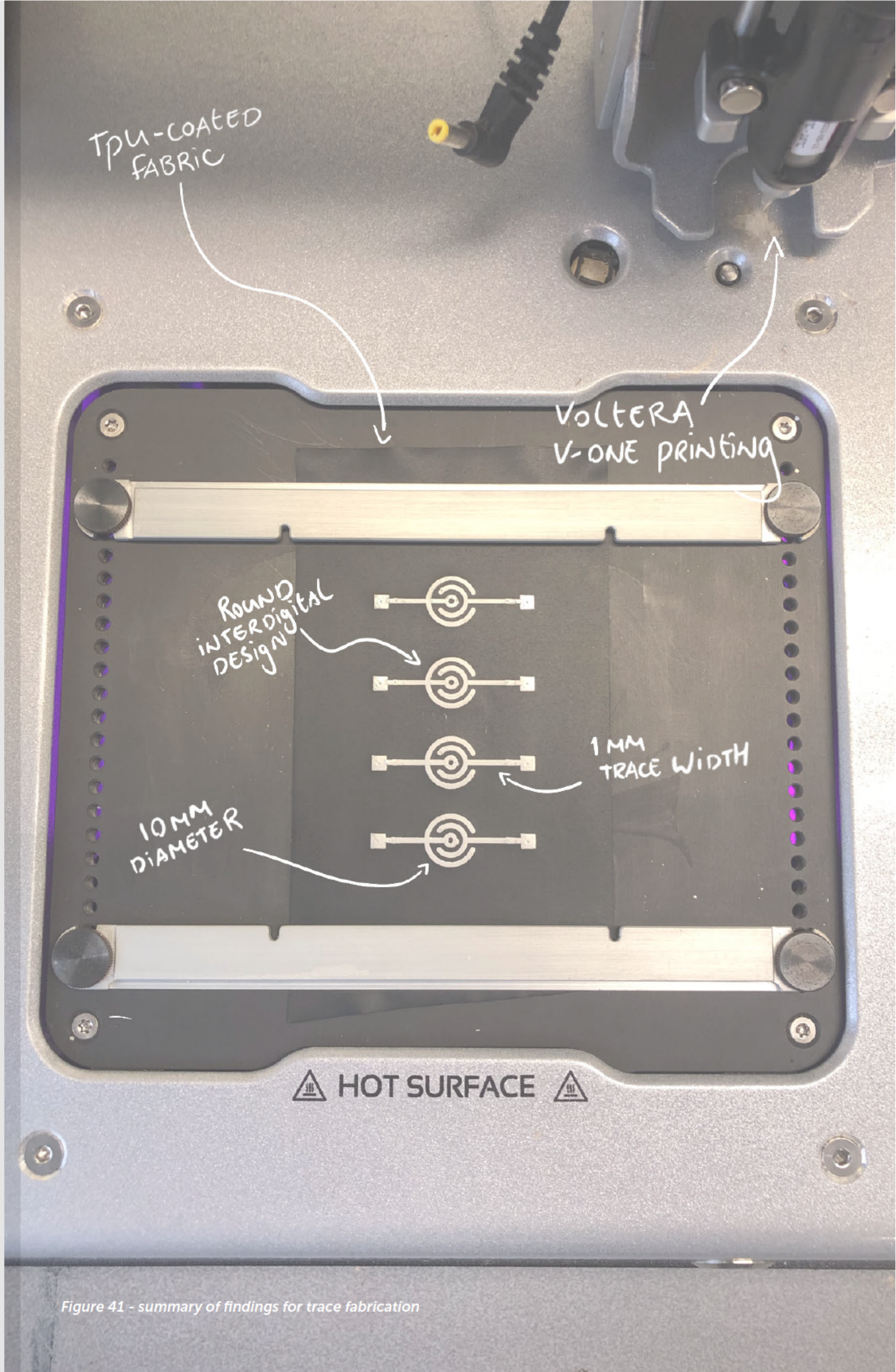


Figure 41 - summary of findings for trace fabrication

Sensing principle accuracy

Small interdigital pizeoresistive structure

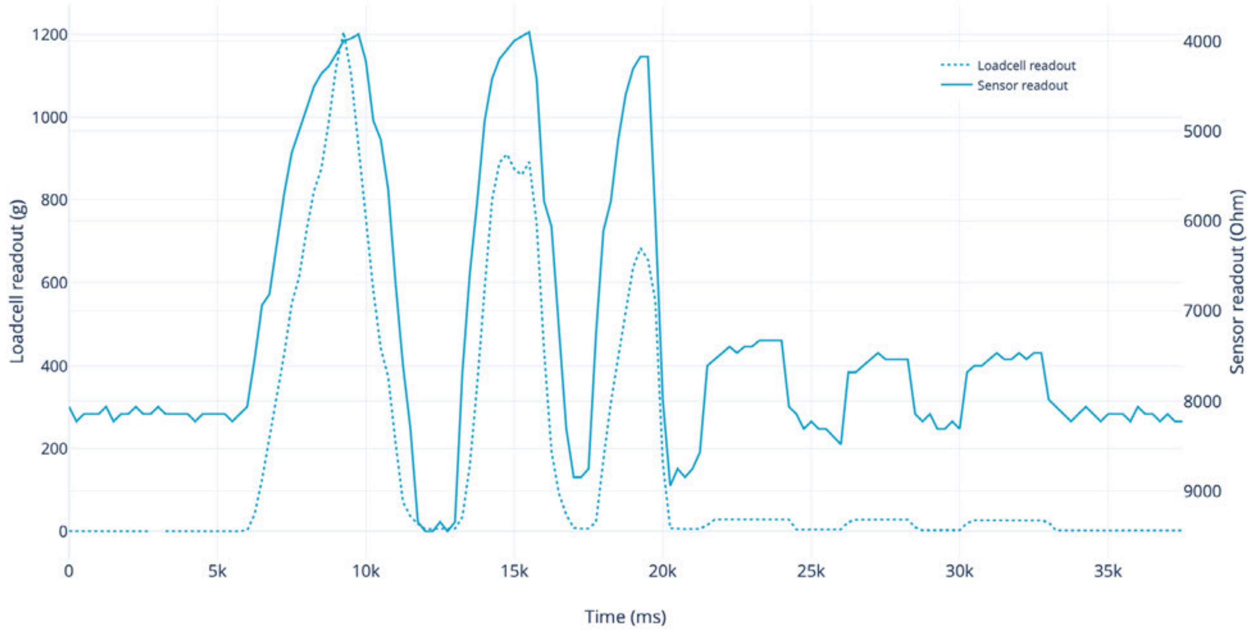


Figure 42 - readout accuracy of small interdigital structure sample

Sensing principle linearity

Small interdigital pizeoresistive structure

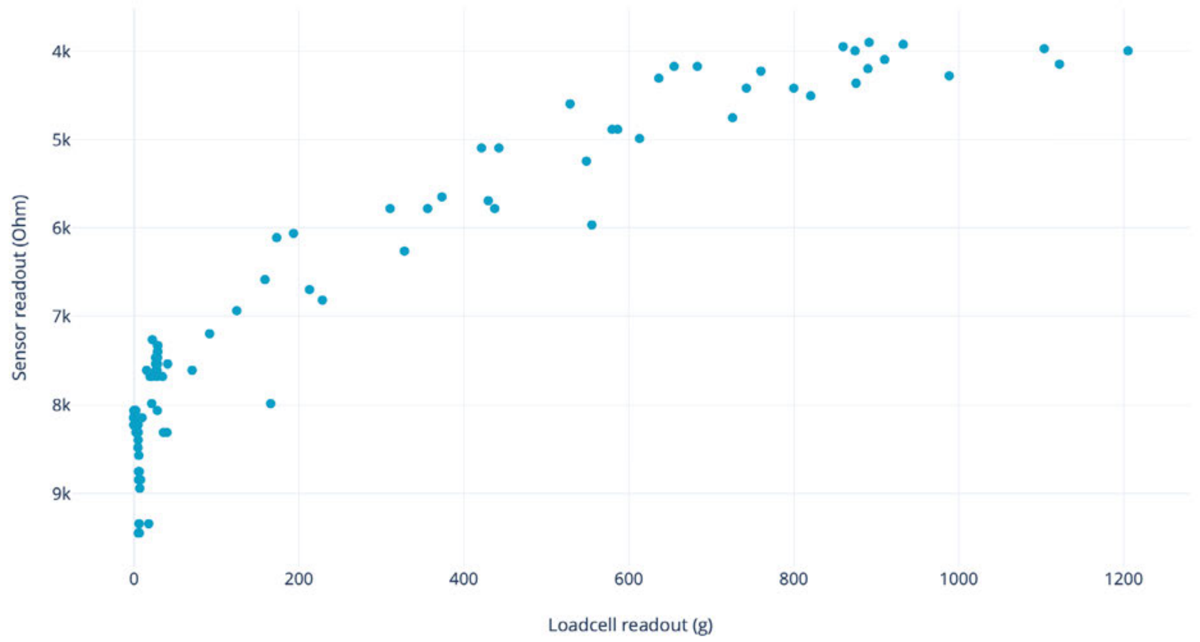


Figure 43 - readout linearity of small interdigital structure sample

Performance

Takeaways

According to the insights given by the performed analysis on the sensor samples, some takeaways can be defined which are used in the progression of the exploration and development of 3D printed tactile sensors. These takeaways conclude the followings aspects:

• Sensing range and resolution of capacitive sensing principle is very much dependant on the printed structure of the dielectric, and therefore needs to be researched further when proceeding with this principle.

• The piezo-resistive principle shows significant repeatability, resolution and stability to progress with the exploration and development using this principle.

• Deviations in applied pressure and pressure-area will be neglected in this research. This thesis will analyse repeatability according to a fixed area and location. The exploration of 3D printing as method of fabrication makes it significantly difficult to reach commercial level repeatability. This research will merely focus on an exploration of possibilities.

• Making slight adaptations to circuit structure can increase the repeatability of the sensing circuit, by making the footprint of the circuit round instead of squared and decreasing the total sensing area.

Sensing principle

The sample tests selected and analysed previously shows a small interdigital, piezoresistive structure as optimal sensing mechanism. This principle shows the best performance in stability, resolution and repeatability.

Figure 43 shows the linearity of the data which was gathered in the tests with the sensor samples. It shows how closely the sample follows the control measurements. While the sensing principle does not shows a linear readout, it does have a definitive curve (monotonic function).

6 EMBODIMENT

This chapter will elaborate on the proposed design by an embodiment of the sensor and a validation of this sensor. It proceeds to briefly explore the possible applications for the validated sensor.

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6.2 Fabrication 62
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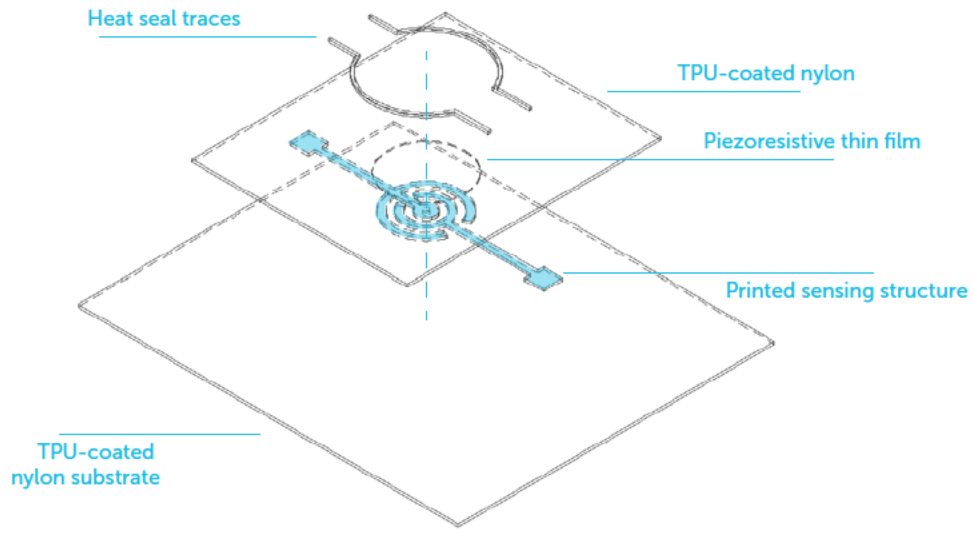

Figure 44 - overview of single sensor embodiment design

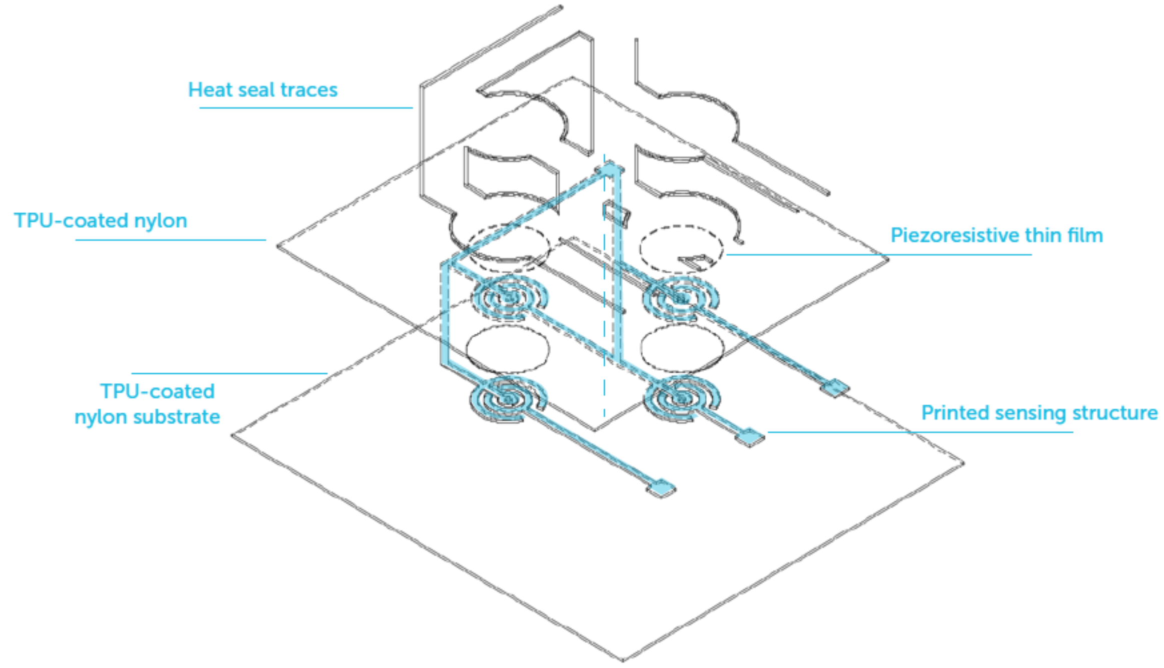

Figure 45 - overview of sensor array embodiment design

6.1 Design

To conclude on a final concept design, we elaborate the design proposal of a printed flexible tactile sensor, which is used in the embodiment and application of this project. The design is based on the exploration and findings performed and described throughout this thesis, and is constructed using the selection of fabrication and sensing principles. The design is elaborated according to its design and its fabrication.

The final design proposal is based on the piezoresistive sensing principle, while the selection and evaluation in 5.4 showed a sensor design using the capacitive effect needs additional dielectric structure testing in order to provide a repeatable readout. A small elaboration of a capacitive tactile sensor design is provided for the purpose of possible future work.

Piezoresistive tactile sensor

The proposed design using piezoresistive sensing uses a TPU-coated fabric as substrate for the sensor design. A small round, interdigital structure is printed on this substrate using conductive ink by ink paste printing. On this interdigital structure, a sensing material is placed, in this application consisting of a piezoresistive thin film. The sensor is fixated and protected by a second layer of TPU-coated fabric by chemical bonding. This results in a single sheet of sandwiched nylon fabric with embedded sensing capabilities. The possibility and fabrication of embedding the sensing circuit into sheet fabric is explored further in chapter 6 - embodiment. When the surface is loaded with a force, the resistance of the embedded traces changes, giving the ability to the fabric to sense a load. An overview of the design can be seen in figure 46a.

Tactile sensor array

To provide the embedded sensor sheets with tactile imaging capabilities, an array of single sensors can be fabricated in order to give an increased number of sensing points. An overview of this design can be seen in figure 46c. A relatively simple circuit can provide sensing capabilities for every sensing point, by loading the structures with a voltage on one side of the sensing point and multiplexing the readouts of all individual single sensor.

Capacitive tactile sensor

The proposed design using capacitive sensing consists of a TPU-coated fabric substrate. The conductor is printed on the substrate using conductive ink by ink paste printing and consists of a single conductive pad. A dielectric 3D structure is FDM printed using TPU filament, providing a compressible material to function as dielectric. The FDM printed TPU chemically bonds with the TPU-coated substrate while the FDM prints at glass temperature of the coating. A capacitive state is created in the sensing circuit when a second conductive material is placed opposing of the conductive pad and dielectric and varies according to the force applied to the compressible dielectric. This second conductive material can include skin conductivity in wearable applications. An overview of design can be seen in figure 46b.

To act as viable tactile sensor, additional exploration needs to be done in a dielectric structure design. Relevant studies into 3D printed structural behaviour can help with this in future work. [31]

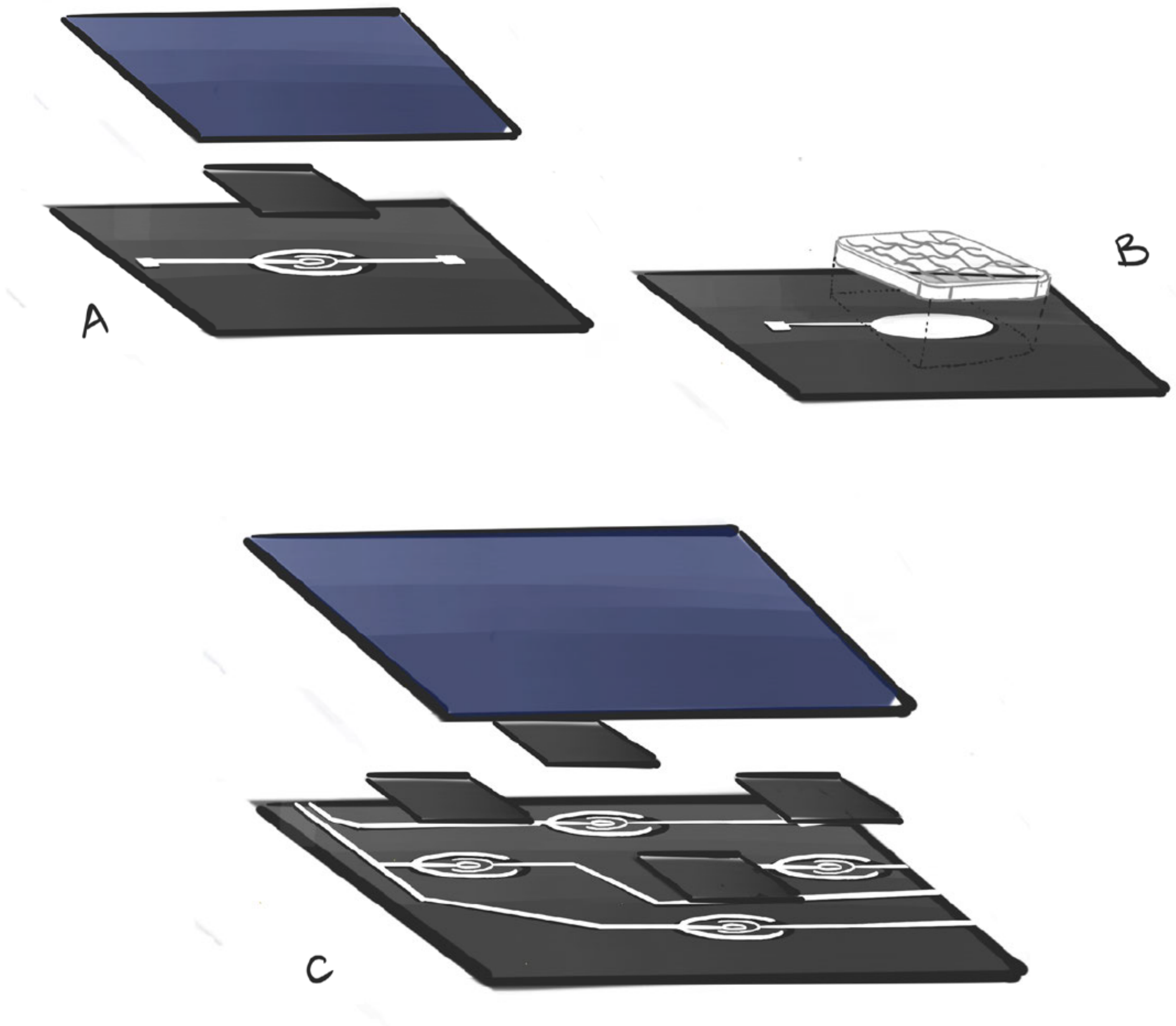

Figure 46 - concept designs

6.2 Fabrication

The fabrication of the piezoresistive tactile single sensor is acquired according to the following specifications:

Substrate
The substrate used is a TPU-coated nylon fabric, providing a flexible substrate with stable ink paste printing and heat-sealable properties. Sourced at 'extremtextil' [30].

Printing
The conductive traces used in the sensor are printed using the Voltera V-One, by dispensing conductive solvent-base ink paste on the selected substrate. The ink is cured using a temperature of 60 degrees, below glass temperature of the substrate, for 40 minutes. Curing is done using the heated bed of the Voltera printer.

Conductive ink
The ink used in the fabrication is flex 2 ink from Voltera, a conductive ink paste with special properties to allow for extra strain in the traces without losing conductivity. The ink is dispensed by the Voltera V-One.

Structure
The sensing structure which is printed on the substrate is a round, interdigital structure, composed of 1 mm traces and a sensing diameter of 10 mm. An interlocking, circular design is proposed providing excellent stability and repeatable readings.

Construction
The sensor is constructed by a piezoresistive thin film, velostat, and sandwiched by two sheets of TPU-coated nylon fabric, one with a printed interdigital structure. These nylon fabric sheets are chemically bonded by applying heat to the surface, above glass temperature of the TPU-coating, at 200 degrees.

Circuit
A readout circuit Is composed of a microcontroller connected to the positive and negative terminals of the interdigital structure and loads a positive voltage to one of the sides. A voltage drop in the voltage divider setup is measured by the microcontroller and changes when a load is applied. The printed traces are connected by small copper wires, which are conductively connected (soldered) by a drop of conductive ink and cured at room temperature.

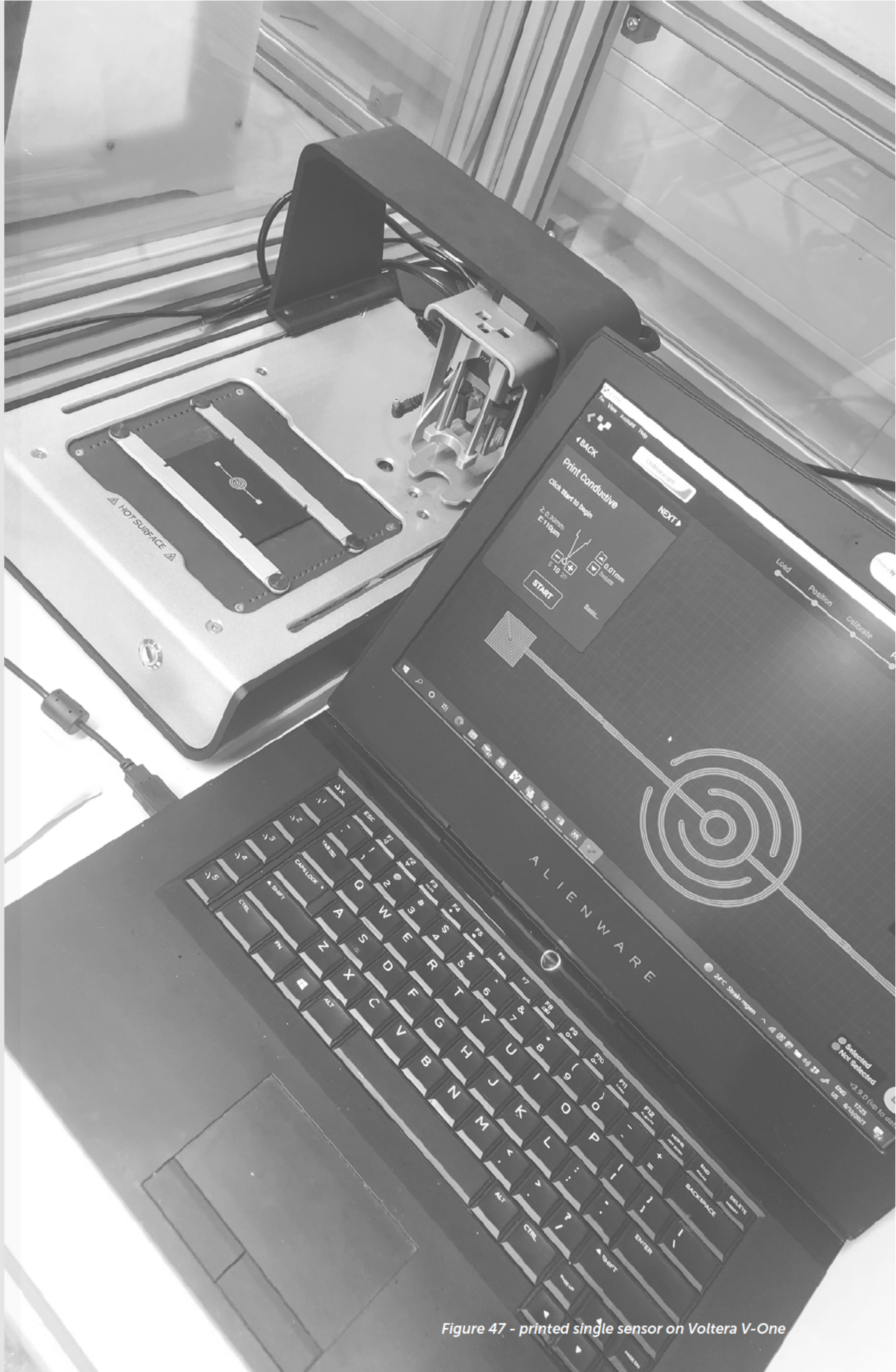

Figure 47 - printed single sensor on Voltera V-One

6.3 Validation

This thesis proposes the design of an embedded tactile sensor using explored 3D printing techniques. While a significant part of the performance of a sensor can be derived by the characterisation of a sensor, the validation of the explored sensor is analysed according to the aspects of the characterisation of a sensor

Setup

This validation of the explored setup is performed using a custom created test stand to apply a linear vertical load, directly in-line to a developed sensor sample. When a load is applied, the test stand is able to acquire readings of both the sensor sample, as well as a fitted loadcell. The loadcell is placed under the vertical load and is fixated along one side of the cell. When a load is applied to the sensor, the loadcell acts as a control measurement of the sensor and is used in the analysis of the sensor characterisation and performance. The test stand setup can be seen in figure 48.

Measurements

The readings of the loadcell and sample sensor are acquired by the use of a microcontroller (Arduino uno), and uses a loadcell amplifier (HX711) to amplify the loadcell voltage changes,

The sensor is read by applying a voltage to one terminal. The opposing terminal is connected using a voltage divider setup and includes a reference resistor matching the stable internal resistance of the sample sensor. a microcontroller reads the potential difference on the voltage divider, and with a ADC readout provides a digital signal. A code, attached as appendix E, converts this digital signal into a resistance value using ohms law.

▶ *Appendix E*

The loadcell is read by a loadcell amplifier, which converts the small potential differences caused by the strain in the loadcell and provides an analog reading. These readings are calibrated by using the library calibration function and uses a known weight to set a calibration factor.

The characterisation of the sensor is largely based on an excellent sensor terminology documentation posted by NI [32]. A description on terminology can be found in the glossary section of this thesis.

▶ *Glossary*

The linearity curve is measured by applying a variety of loads on the sensor for 6 repetitions. The readout of the sensor is then plotted against the loadcell control measurements.

The sensor accuracy is analysed by applying both a fixed a variable load to the sensor, and comparing the readouts by plotting the readouts against time.

A hysteresis curve is plotted by applying and release of a single load to the sensor, and plotting the readouts against the control measurement. A rising and a falling curve is created.

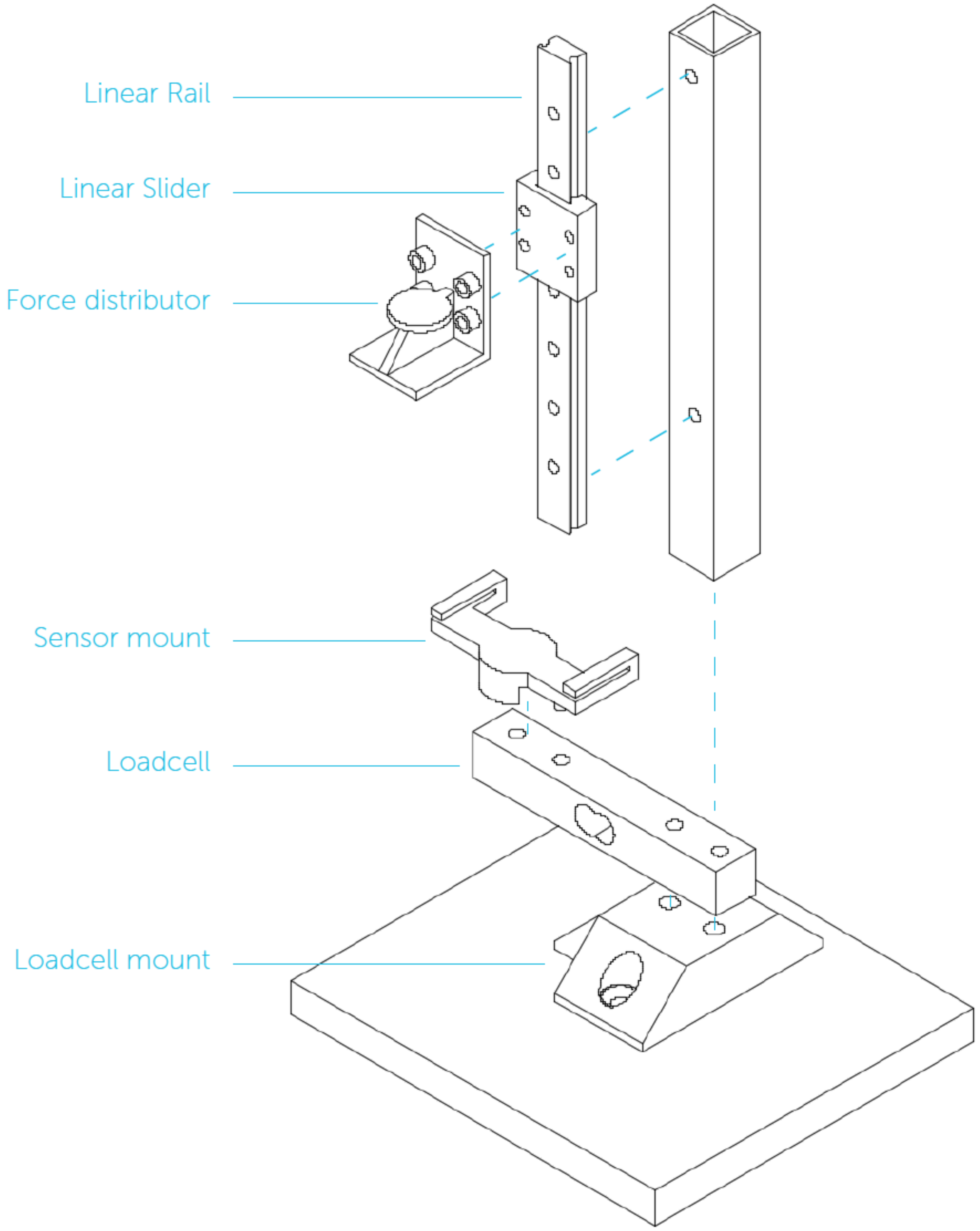

Figure 48 - validation setup overview

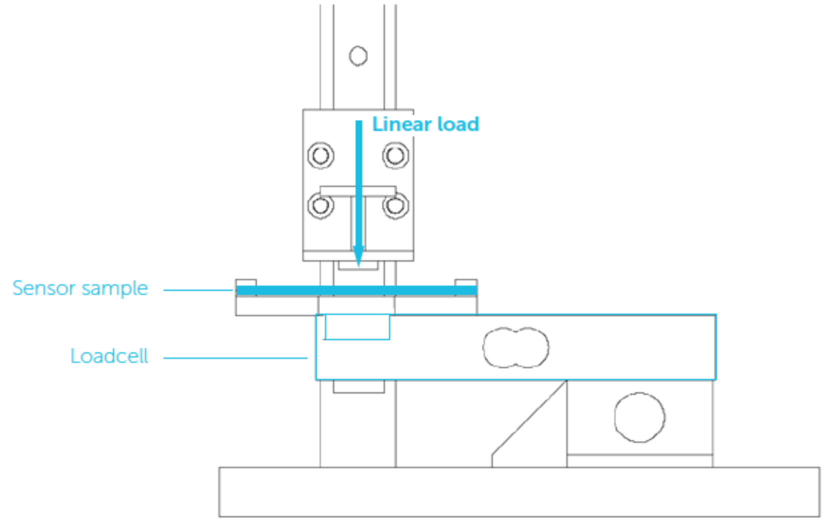

Figure 49 - validation setup load overview

```
int Vin = 5;
float R1 = 4000;

raw = analogRead(A0);

if(raw){
  buffer = raw * Vin;
  Vout = (buffer)/1024.0;
  buffer = (Vin/Vout) - 1;
  R2= R1 * buffer;
}
```

Figure 50 - code converting ADC to resistance

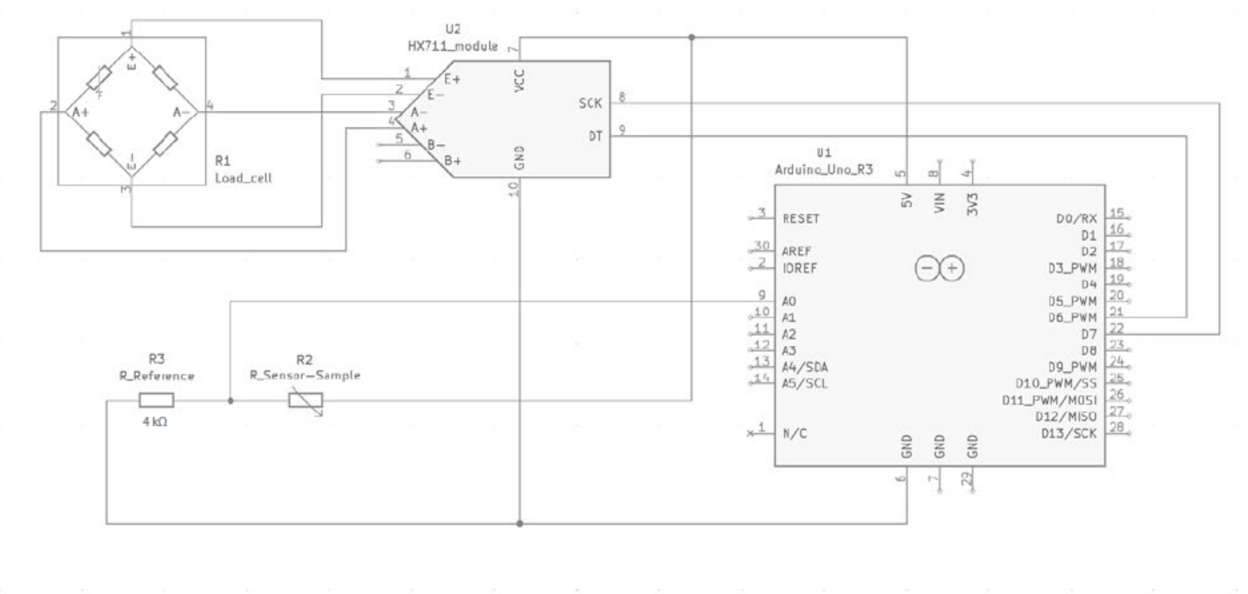

Figure 51 - validation setup circuit schematics

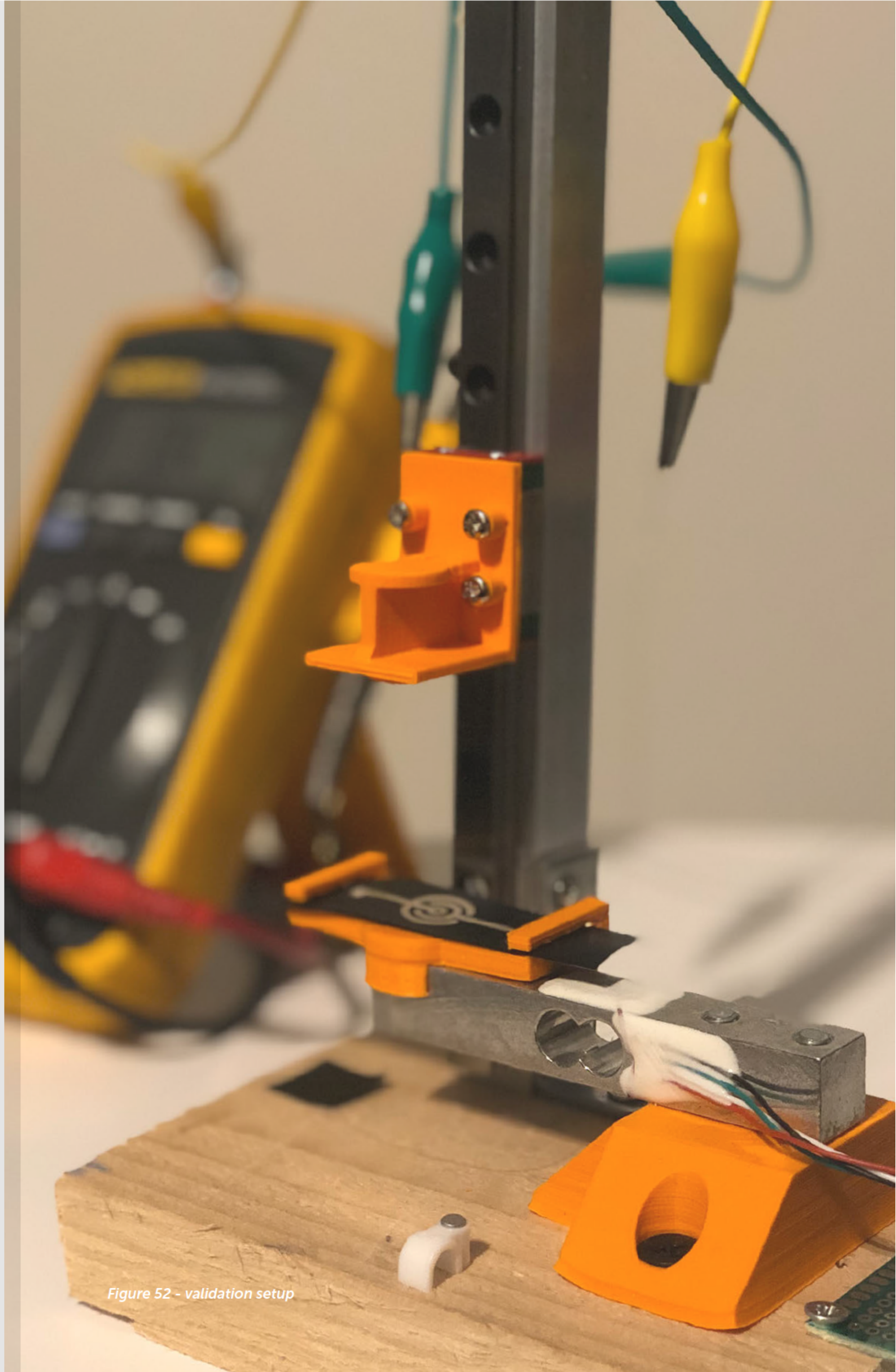

Figure 52 - validation setup

Characterisation

The resulting plots, as seen in figures 53-56, show the performance of the developed sensor, and can be used to characterise the sensor. Here, we define the characterisation of the sensor according to the following 3 aspects: Linearity, sensor characteristics and hysteresis.

Linearity

To analyse the performance of the developed sensor, figure 53 shows the plotted readouts of the sensor, used to analyse the linearity of the sensor.

Measurement curve: A measurement curve can be derived form the readouts of the validation test, which can be seen in figure 54. While the sensor does not shows an ideal linear measurement line, it does provide reasonable readouts that follow a curve. This result provides proof for a repeatable performance of the sensor. Deviation from the measurement curve is only minimal, again showing proof of repeatability.

Non-linearity: The nonlinearity of the analysed sensor can be, according to IEC standard [33], defined according to a 'best fit straight line' (BFSL). Plotting a BFSL line in the graps shows a significant non-linearity error of around 20% F.S. Nonlinearity however can be compensated for by a number of methods, including look-up tables or linearised equation. [34] Through linearisation, a nonlinear response curve can be converted into a straight line, improving the sensor accuracy.

Sensor linearity
Final embodied sensor

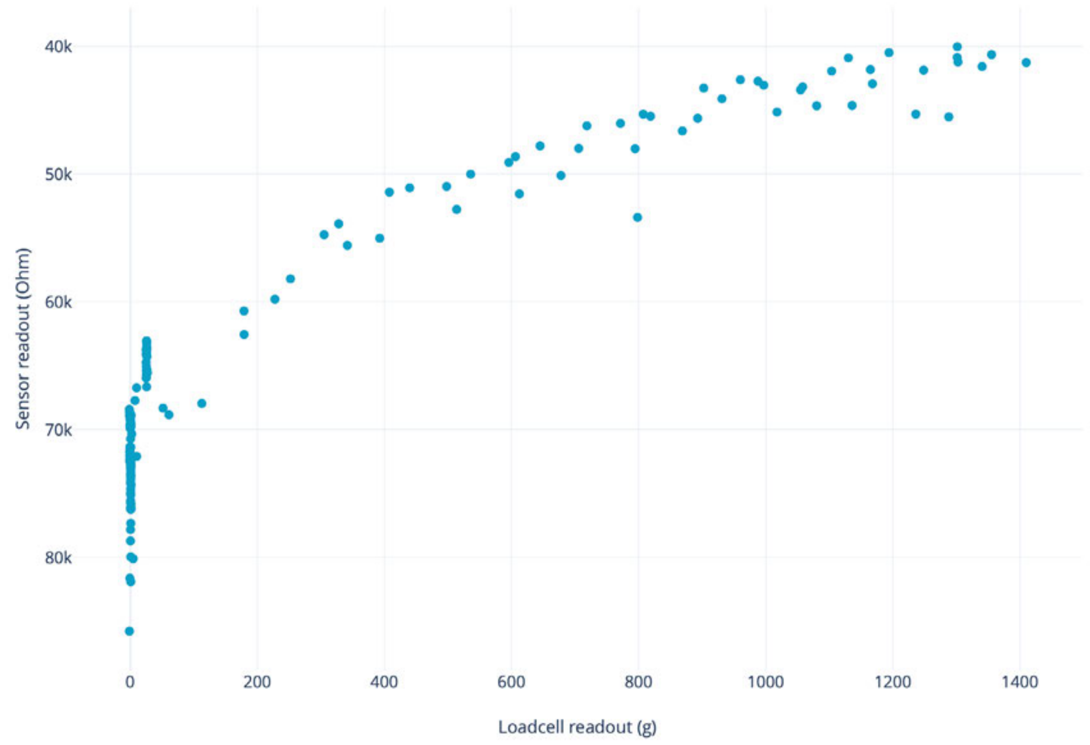

Figure 53 - readout linearity of final embodied sensor

Non-linearity
Final embodied sensor

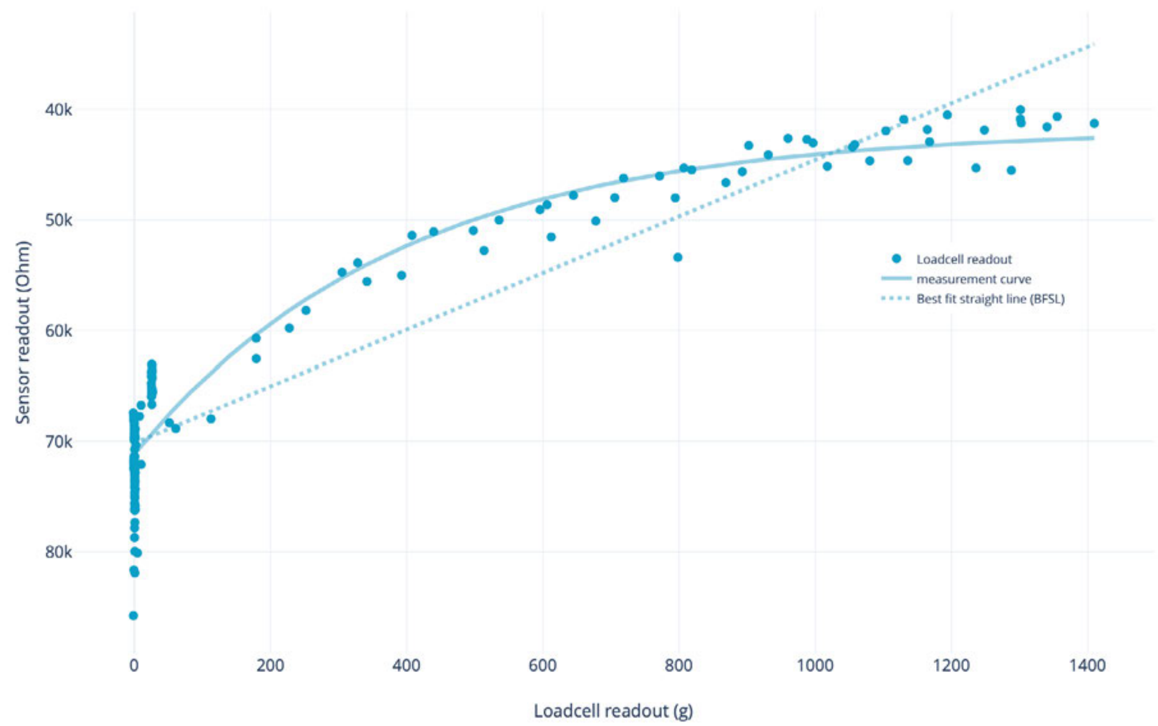

Figure 54 - nonlinearity of final embodied sensor

Sensor accuracy
Final embodied sensor

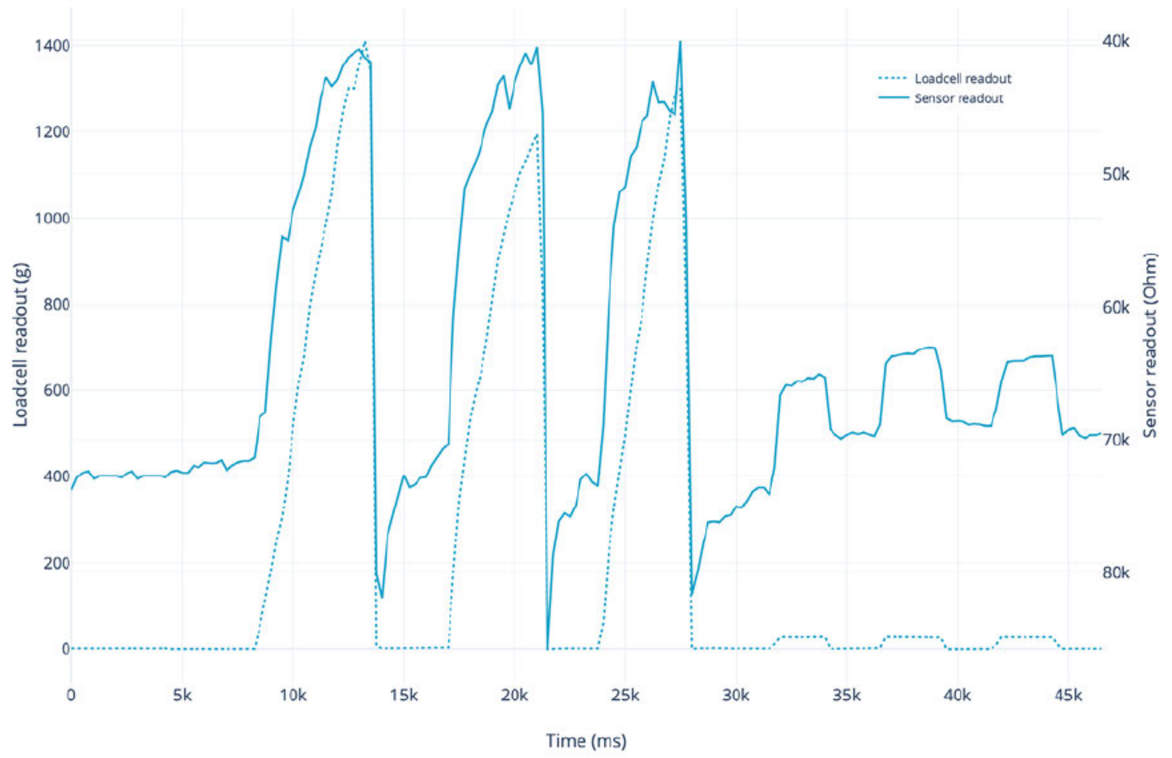

Figure 55 - readout accuracy of final embodied sensor

Sensor hysteresis
Final embodied sensor

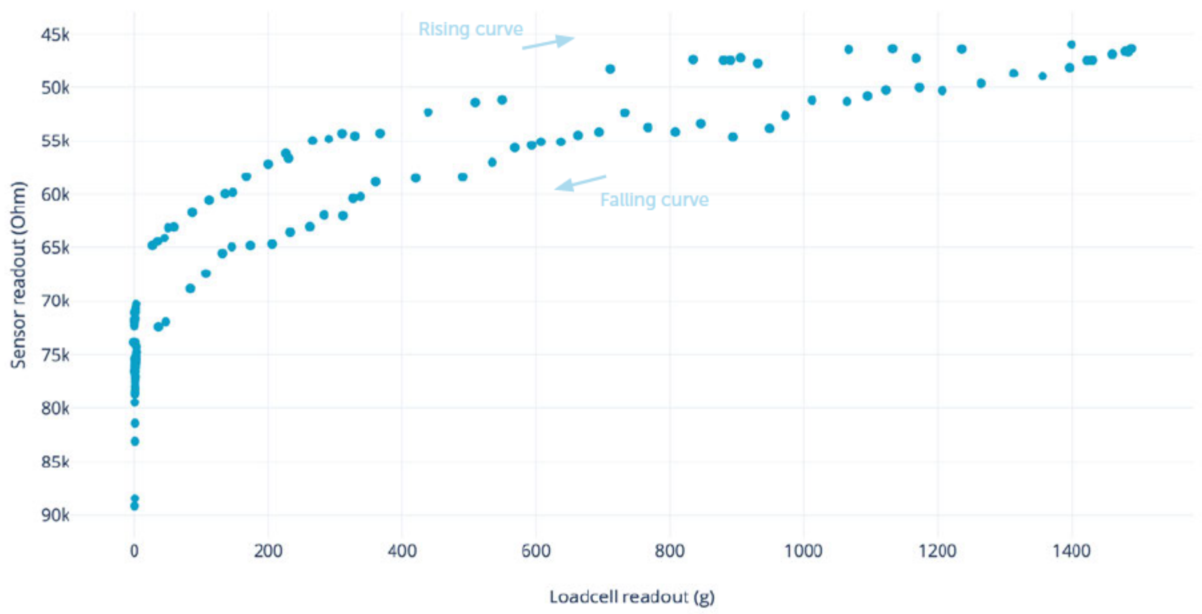

Figure 56 - readout hysteresis of final embodied sensor

Sensor characteristics
The characteristics of the sensor are analysed by comparing the readouts of the sensor against the readout of the control measurements of the loadcell. This data is plotted in figure 55.

Accuracy: comparing the plots gives better insight in the accuracy of the sensor. While the sensor readout does follow the control measurements so some accuracy is reached, still a lot of deviation is observed in the readouts.

Resolution: The sensor is able to differentiate between the two different loads. however, smaller differences in loads (<100g) are difficult to measure, as seen by the difference of readouts at the first two peaks.

Drift: Some drift can be observed in the readouts, while the stable state resistance drifts from around 73KΩ to around 70 kΩ. during the test.

Interference: Analysing the falling curves shows some undershoot in readout. It is expected these observations have to do with interferences of the skin when applying a load.

Hysteresis
Plotting the sensor readout against the control measurement for a single load and unload cycle shows the difference in rising and falling curve of the sensor. This difference is the hysteresis error of the sensor. Figure 56 shows this hysteresis curve. Analysing the curve shows a significant hysteresis error.

6.4 Sensor embedding

The previous chapter describes a final concept of a single sensor. Here, we elaborate how this concept can be embodied into a wearable sensor by fabrication of sensors on fabric. The embodiment focuses on a fabrication technique and assembly to allow for the embedding of wearable sensing and tactile imaging.

Embedding

The proposed sensor concept includes a TPU-coated nylon substrate. Using the nylon as substrate allows for, by making use of its flexible properties, applying the sensor concept onto wearable applications.

By chemically bonding two sheets of nylon, a sensing structure can be embedded into the sheets. A method of heating the surface of the TPU-coating can be applied to chemically fuse the two TPU-layers to each other.

Embedding the printed circuitry allows for physical and environmental protection of the traces and provide a clean aesthetic when applied to wearable applications like clothing.

Figure 57 - embedded single sensor with visualisation overlay of internal structure

Heat sealing

While this substrate shows excellent stability for ink dispensing printing, it also allows for additional fabrication possibilities using its special properties. When heat is applied to its surface and reaches the glass temperature (200 degrees for 3 seconds) of the TPU layer, its fuses with the second layer of TPU. This heat-sealing property can be used to embed the sensing circuit into the fabric sheets.

Additional testing of heat sealing showed heating the full surface of the nylon is not possible, while the piezo-resistive thin film loses full conductivity when heating it above 50 degrees.

Therefore, a method of targeted heat sealing was explored to fuse the layers. This method involves only sealing the perimeters of the sensor structure. This is reached by creating a tracing G-Code with decreased travel speed for any FDM printer and heating the nozzle to the TPU glass temperature. The nozzle traces the sensor and seals the nylon sheets. Unloading any filament is required.

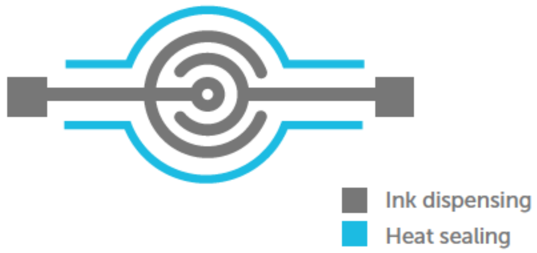

Figure 58 - sensor embedding overview

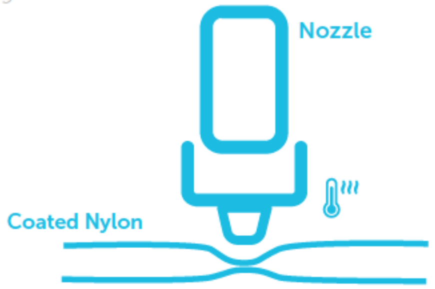

Figure 59 - heat sealing overview

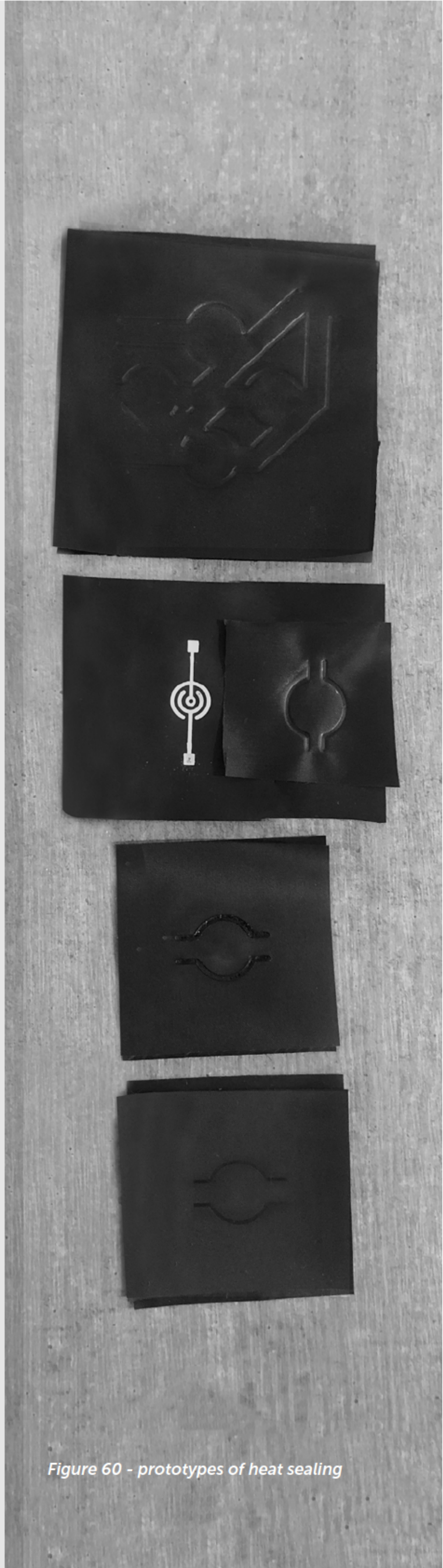

Figure 60 - prototypes of heat sealing

Wiring

To interface with the sensing circuit, a specific 'soldering' technique is used to conductively connect to the traces. This technique is used as prototyping method in this research.

While the dispensed ink traces can be damaged by heat of traditional soldering, additional ways of interfacing are explored.

A proven way of interfacing is using a thin copper wire, which is connected to the pads by a droplet of conductive ink. This ink is cured by room temperature and ensures a conductive connected between the wire and silver traces.

The wire is held in place and protected by physical movement by a drop of ordinary two-component glue on either side of the connection.

For future fabrication of the explored sensors, additional methods are required to be explored. The described technique is not viable for (small scale) production. Ink dispensing solutions using 3D printers may have potential.

Figure 61 - wire connection through microscope

6.5 Sensor application

Part of the defined scope is the exploration how the developed tactile sensor can be used in certain applications , specifically tactile imaging. This section will look at the possibilities and opportunities that the developed sensor can bring to applications for these embedded, wearable tactile sensors.

Sensor array

To allow for any application other than the ability for single measurements, the sensor design needs to have a bigger spatial dimension by having more sensing points. To give the sensor design this capability, an array of sensors can be designed. This array of sensors can be adapted and scaled towards the needs of the application. Here, we shortly explore these sensor arrays by developing a sensor array consisting of 4 sensing structures.

The terminals of the individual sensing structures are connected by a trace. The positive, voltage loaded side can be connected to a single pad. The negative terminal is hooked up to its individual pad to allow for reading its measurements, its internal resistance.

Multiplexing

While scaling the array might increase the amount of measuring terminals significantly, a method of multiplexing can be used to scan the individual pads. This method showed excellent performance, as been explored in tested in an earlier tactile mapping prototype and has been documented in appendix C.

▶ Appendix C

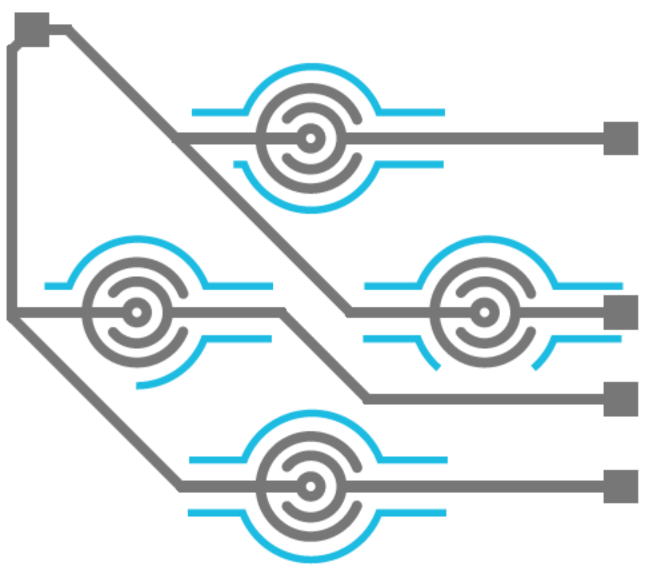

Figure 62 - traces and heat seal pattern of sensor array

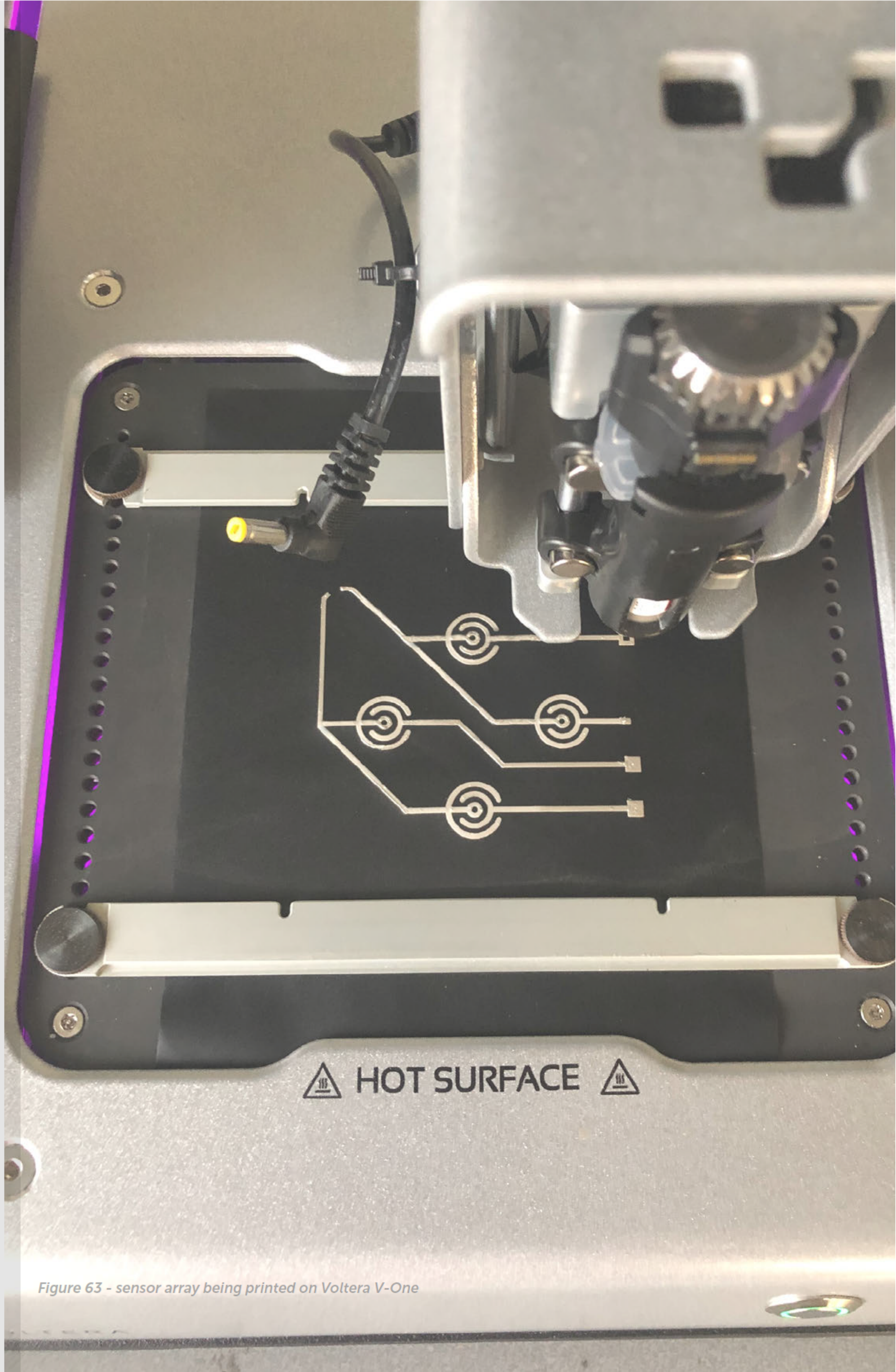

Figure 63 - sensor array being printed on Voltera V-One

Universal application

The explored and developed design of a flexible 3D printable tactile sensor allow for a variety of applications in the field of wearables and robotics. The flexible substrate allows for the application to curved geometry or the human body, making it applicable for bodily tactile measuring or robotic sensory input.

The explored possibility of creating a scalable array of sensing allow for a range of applications involving tactile imaging or pressure area measurements. These applications can include ergonomics studies, body pressure mapping or pressure distribution visualisations.

Additional exploration into embedded sensor design allows for integration into sheet fabric, allowing for wearable product integration like gloves, braces or foot-soles.

This research thesis can be used as foundation for designers and researchers to further explore opportunities in the application of wearable embedded sensors in smart products using these methods.

Significant additional work needs to be performed to allows for a universal application of the designed tactile sensors, while physical durability is an important factor to the application of the explored sensor This research commences the exploration of these possibilities and give new insights in the use of 3D printing as fabrication technique in sensor development.

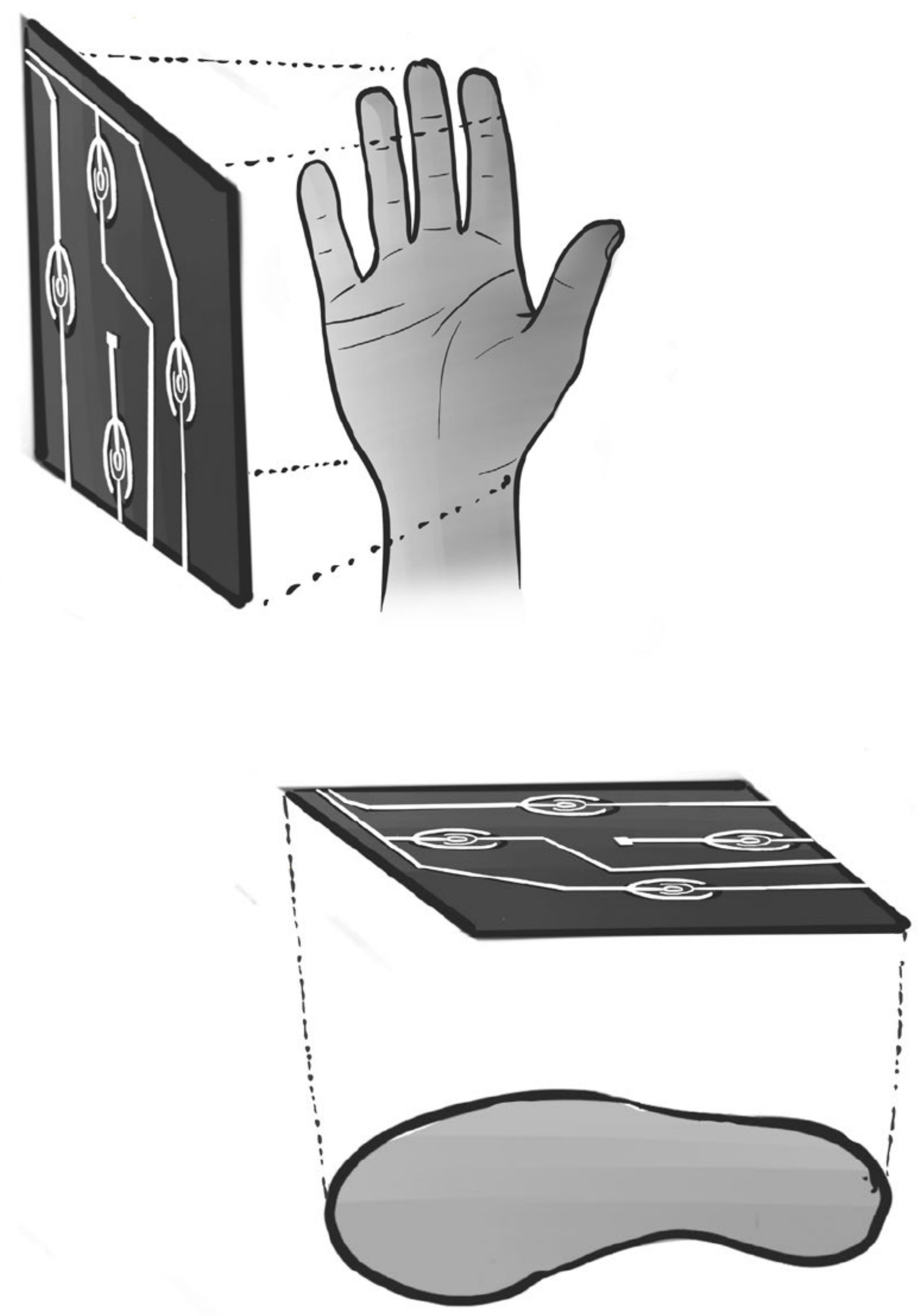

Figure 64 - two examples of universal application for sensor array design

7

CONCLUSION

This chapter will conclude the exploration and development of this research thesis by summing up and discussing the final results and insights from the research, and give insight for possible future work.

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7.1 Results

This thesis describes an exploration of 3D printing fabrication techniques in the field of printed electronics and uses this to develop an embedded tactile sensor to be used in a variety of (wearable) applications.

The research that has been performed in this thesis resulted in the following results and insights:

Exploration
An exploration of fabrication techniques which resulted in new opportunities regarding 3D printed electronics.

TPU-coated nylon substrates for conductive ink circuits - The use of a treated fabric material as substrate for 3D printing electronics provides a flexible and stable way of producing fabric embedded sensors.

Heat seal printing - Making use of the TPU-coating properties, heat sealing allows for the development of intricate circuits and assemblies and embed this into sheet fabric.

Development
The exploration of fabrication techniques was used in the embodiment of a sensor and resulted in the development and proof of concept of:

A repeatable single sensor embedded into sheet fabric - The embodiment of a sensor concept making use of the newly explored fabrication techniques.

An embedded sensor array for wearable tactile mapping - Using the development of a single sensor concept, a sensing array was explored to provide tactile imaging capabilities to wearable applications by embedded sensing arrays in sheet fabric.

Conclusion
The research performed in this thesis can be seen as an exploration and foundation of knowledge towards the use of widely researched and developed technologies of ink jetting/-dispensing to develop embedded sensor to be used in a large variety of tactile sensing/imaging applications. It can be used as reference for a new way of applying the fabrication techniques of easy and accessible technologies, to develop easy to apply sensing structures to flexible, wearable applications.

7.2 Discussion

While the final presented sensor is the result of an exploration of the use of a new fabrication method, the sensor and therefore performance of the sensor are still on a prototype level. The proposed sensors only perform under a controlled environment and its fidelity is still too low to be applicable to real world (wearable) products or other study applications. A significant amount of future work needs to improve and study the knowledge and insights of the explored fabrication techniques.

Excessive stress on the substrate or conductive connection negatively influence the results and readout of the sensor significantly.

The research done in this thesis does not result in a new sensor ready for application into future research and products. It can be seen as a foundation of a new way of looking at the application of 3D printing as fabrication method for embedded circuits and provide new knowledge of printing on flexible substrates.

7.3 Future work

The results of this research leave room for a number of work that may improve or create further knowledge on the described topic and scope, or can expand the performance and fidelity of the explored and developed single sensor.

While the concept chapter discontinued the exploration of a capacitive sensing principle concept, an interesting additional study can explore the potential of capacitive sensing concept, by an exploration of how the structure of the dielectric can provide the best sensing linearity.

To improve the proposed sensor, additional work needs to look into the improvement of reliability of the fabrication technique.

The sensor needs to show better physical durability of the traces on the substrate, as weel as improved reliability of the connections.

Finally, additional work can be performed to study how the proposed sensor can be applied into (wearable) products by exploring new and better ways to embed the sensing structures and a better interfacing of the circuit with wires and electrical components/ controllers.

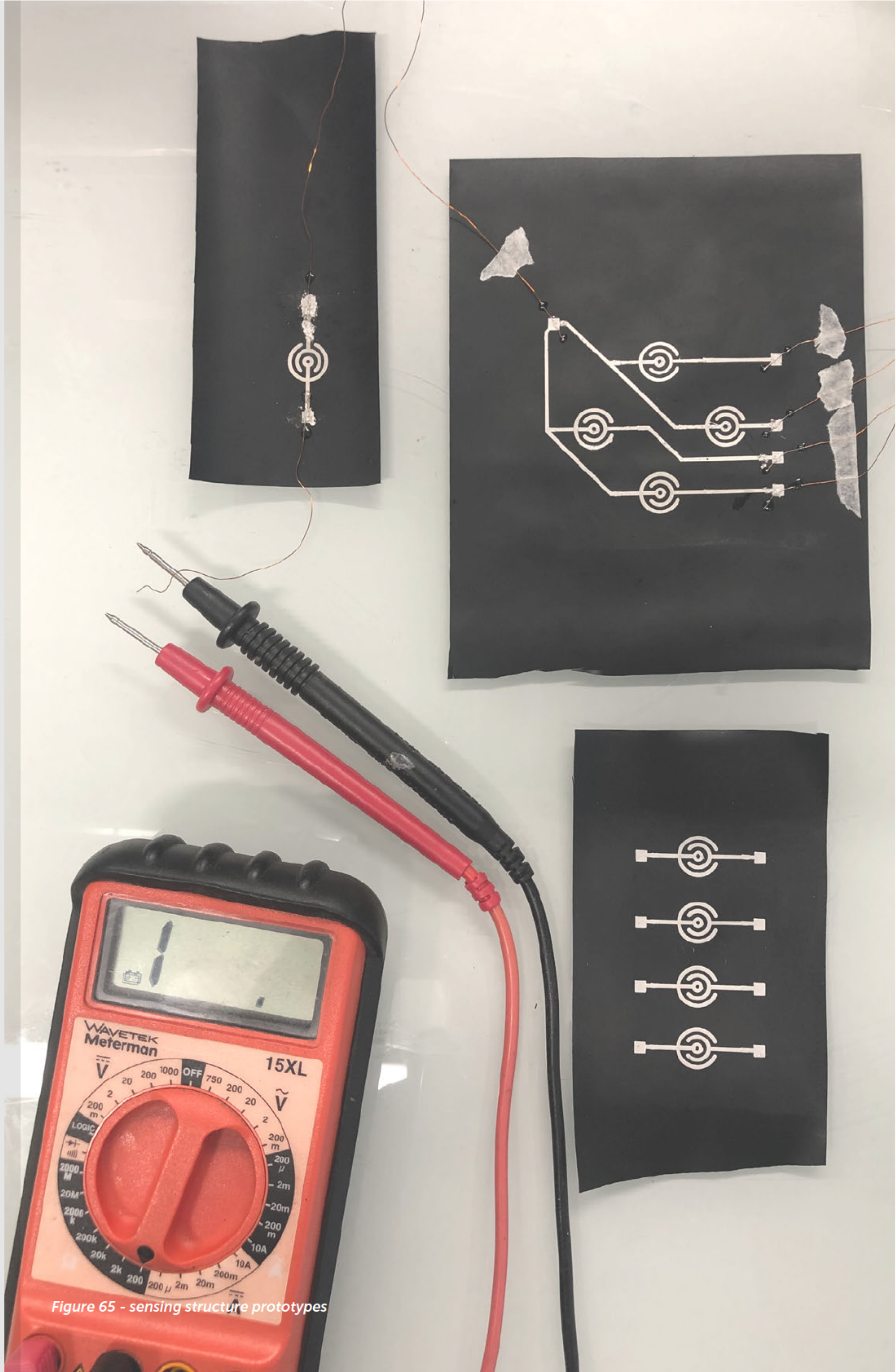

Figure 65 - sensing structure prototypes

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TABLES

Table A
3D printed tactile sensor studies

Table B
Tactile sensor integration studies

Table C
Tactile imaging key applications

Table A

3D printed tactile sensor studies

3DP Technology	Sensing Mechanism	Loads	Printable Materials	Materials Shape	Printed Component	Ref.
PolyJet	Piezoresistive	Pressure	Photocurable TangoPlus	Photopolymer, photopolymer composites	Sensor body	[131]
	Piezoresistive	Pressure	Conductive photocurable TangoPlus/MWCNTs composites		Sensing element	[131]
	Piezoresistive	Pressure	Photocurable VisiJet composites		Sensor body	[132]
DLP	—	—	UV curable EAA/AUD stretchable elastomer		Substrate/Sensor body	[133]
FDM	Piezoresistive	Pressure	Conductive PCL/CB composite	Filament	Sensing element	[134]
	Piezoelectric	Pressure	Thermoplastic elastomer		Sensor wavy substrate	[153]
	Piezoresistive	Tensile strain	Conductive TPU/MWCNTs nanocomposites		Sensing element	
	Capacitive	Pressure	Thermoplastic elastomer		Dielectric layer	[135]
	Piezoresistive	Pressure	Supporting structure: TPUSensing element: TPU/MWCNTs composites		Supporting structure, sensing element	[137]
	Capacitive	Pressure	ABS		Molds for microstructuring sensing element	[138]
Electric poling-assisted FDM	Piezoelectric	Tensile strain	Piezoelectric PVDF polymer	Filament	Sensing element	[139]
	Piezoelectric	Pressure	Piezoelectric PVDF polymer	Filament	Sensing element	[140]
	Piezoelectric	Pressure	PVDF/$BaTiO_3$ composites	Filament	Sensing element	[140]
Direct ink writing	Piezoresistive	Pressure	Sensing layer: 68 wt % Ag/silicone ink Electrode layer: 75 wt % Ag/silicone ink Substrate layer: silicone elastomer Supporting layer: 40% pluronic ink	Inks	Fully 3D-printed tactile sensor	[141]
	Piezoresistive	Tensile strain	Composite dough materials: NH_2-MWCNTs/GO/SIS composites	Ink	Sensing element	[142]
	Piezoresistive	Tensile strain	Gallium-indium alloy	Ink	Sensing element	[143]
	Piezoresistive	Pressure, tensile strain	Elastomer, gallium-indium alloy	Ink	Fully 3D-printed tactile sensor	[144]
	Capacitive	Pressure, temperature	Thermo-responsive hydrogel	Inks	Ionically conductive layer	[145]
Embedded direct ink writing	Piezoresistive	Tensile strain	Suspensions of CB in silicone oil	Inks	Sensing element	[151]
Multicore-shell direct ink writing	Capacitive	Tensile strain	Conductive layer: ionically conductive ink composed of glycerol, NaCL, and PEG Dielectric/encapsulation layer: modified silicone elastomer	Inks	Fully 3D-printed tactile sensor	[152]
electrohydrodynamic printing	Piezoelectric	Pressure	Piezoelectric PVDF polymer	Polymer solution	Sensing element	[153]
	Capacitive	Finger touch	20 wt %–35 wt % Ag nanoparticles/triethylene glycol composite	Composite solution	Conductive electrode	[154]

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Table B

Tactile sensor integration studies

Table 3: The list of tactile sensors that have been integrated with robot hands. Number of tactels (No.), spatial resolution (Res.), sensitivity (Sens.), dynamic range (Range) and data acquisition rate (Rate) are provided where possible.

Tactile sensor	Robot Hand	No. of tactels	Res./Sens./Range	Rate
Piezoresistive sensors				
FSR [56]	Robonaut data glove[106]	19	5mm/0.1N/20N	1 kHz
Fabric sensor [60]	Sensor Glove [54]	56	$34mm^2$/(0.1–30N)	-
Rubber-based [49]	Schunk gripper [108]	8x8	6.25mm^2/-/250kPa	100 fps
Rubber-based [39]	High-speed 3-fingered hand [101]	17x19	3mm/-/-	10 kHz
Weiss Robotics [53]	Schunk sDH [109]	(14x6)and(14x7)	3.5mm/-/250kPa	800 fps
3D-shaped sensor [34]	Shadow Hand	12	5.5mm/0.03$\frac{N}{cm^2}$/10N	$\sim$ 1 kHz
Rubber-based [35]	Universal robot hand [35]	102 on tip	3.6 mm/ 1N/-	50 Hz
Gifu hand sensor	Gifu Hand III [110]	624	~4mm/-/22$\frac{N}{cm^2}$	10 Hz
Tekscan [57]	Shadow Hand [94]	349	4mm/-/345kPa	200 Hz
FSR [41]	Southampton hand [41]	15	-	-
ATi Nano17 sensors [61]	Shadow hand [98]	5 per finger	-/ 3.26mN/12N	833 Hz
Weiss Robotics [58]	Fluidic FRH-4 hand [111]	14x6	3.5mm/-/250kPa	230 fps
Capacitive sensors				
Icub sensor [103], [44]	iCub Humanoid robot	12 per tip, 48-palm	$7mm/2.5\frac{fF}{kPa}$/150kPa	25-250Hz
PPS sensors [66]	PR2 robot grippers [38]	22	$4mm$/6.25mN/7kPa	24.4 Hz
PPS RoboTouch [66]	Allegro robotic hand [64]	24	25mm^2/7kPa	30-100Hz
Dynamic sensor [9]	Robotiq Gripper [112]	132	-/-12N	300 Hz
Combined sensor [113]	Parallel jaw gripper [113]	16	10 mN	up to 35 kHz
PPS RoboTouch	Barrett Hand [114]	120 per finger	$5mm$/6.25mN/7kPa	30-100Hz
Piezoelectric sensors				
PRes. [58] + PVDF [24]	8 DoF Fluid Hand [70]	4x7	3.5mm/-/250kPa	≥1kHz
PRes. ink + PVDF [88]	SKKU Hand II [88]	24 on fingertip	0.5mm/-/-	-
Tactile skin [115]	DLR Hand [116]	in	process of	development

[11] Zhanat Kappassov, Juan-Antonio Corrales, Véronique Perdereau,Tactile sensing in dexterous robot hands — Review, Robotics and Autonomous Systems,Volume 74, Part A,2015, Pages 195-220,ISSN 0921-8890, https://doi.org/10.1016/j.robot.2015.07.015.

Table C

Tactile imaging key applications

Proposed application industries with key areas and challenges.

Application industry	Key utility and application areas	Design challenges
Robotics	Dexterous manipulation Tele-robotics Service robots Exploration robots Rescue robots	Arrayed sensors Discrimination and classification algorithms Repeatability, wear resistance and wide dynamic range Customization Characterized response over wide temperature range High frequency response
Biomedical	MIS tools Tele-robotic operations Diagnostics tools Rehabilitation medicine Dentistry Patient care Gait analysis systems	Biocompatibility Rugged to withstand sterilization process Cost due to their disposable nature Characterization and classification algorithms Wireless interfaces Power consumption High frequency response Electrocutaneous feedback mechanisms Safety and reliability Ergonomics
Sports	Posture analysis Sports training	Conformable and customizable sensors Durability Wiring and power constraints Wireless interfaces
Agriculture and food processing	Service robots, such as for fruit picking	Adaptability to unstructured environments Toxin and allergin free construction Hygiene and cleanliness Safe for food handling Dexterous movement Soft grippers Unexplored application area
Aerospace and automobiles industry	Safety studies Safety devices Diagnostic tools Acceleration optimization systems Navigation interfaces for mobile devices	Device centered sensor design Safety and reliability Rugged to withstand high shear, tensile and normal forces Unexplored application area
Consumers products	Healthcare products such as intelligent toothbrushes Service Robots for elderly Textile and clothing	User acceptance Wear resistance and reliability Cost, so that it can target wider application market Rugged to bear abuse

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APPENDIX

Appendix A
Project reflection

Appendix B
Sensing principles explorative prototypes

Appendix C
Tactile mapping explorative prototype

Appendix D
Performance selection results

Appendix E
Validation setup code

Appendix F
Initial project brief

Appendix G
Midterm evaluation

Appendix H
Showcase poster

Appendix I
Project summary

Appendix A
Project reflection

Looking back at the thoughts I had when starting this research project, the scope of the project was an overwhelming idea. The setup of the project, by using design thinking to research and develop a technology field, was something I hadn't had significant prior experience with. My goal for the project was to show my interest and expertise in the fields of 3D printing and electronics, and provide proof on concept on the acquired skills on the application of design thinking. Working on the research project has developed me a lot in applying my design skills in the research of new technological advancements, and has learned me how to apply the skills acquired during my study years in the a more scientific approach of research and development.
At this point of writing, looking back at the results of the project gives a satisfactory feeling. A lot of time and dedication has gone in creating a master thesis that documents the project well, and im happy with the results.

The project showed much more challenges than originally thought. While little to no prior studies was performed in the scope of my thesis, the development of a flexible 3D printable tactile sensor needed to be initiated from the ground. The exploration to find a technique to allow for the embodiment of such a sensor took some time, giving me significant challenges to develop a 3d printed flexible sensor which was able to have pressure sensing capabilities.
Since a lot of challenges made the start of the embodiment difficult, some originally defined objectives in the project brief were left out. The development of a smart sensing glove showed way to much challenges to fit in one project, while substantial work needed to be done on the fundamentals of a 3D printed tactile sensor and its fabrication.

I had great enjoyment working on a project which exactly fits my interest in the field of design. Applying my developed knowledge in electronics through my years of study, and combining this with my interest in the rapid growing field of 3D printing and the implications this technology can have on the field of design, has kept me excited for working on the research throughout the whole final master project.

It was a honour working with my supervisory team and gave me great insights and guidance during the project. I thank them for their time and devotion during a time were the working conditions by a global pandemic was increasingly difficult. Looking back at the project, I would have liked to involve my coaches more in the project to improve on the outcome of the research. During these times I found it increasingly difficult to plan consistent meetings while distant communication made it hard to talk on a regular basis.

I happy to conclude my years of developing myself in becoming an industrial design engineer by presenting this master thesis focusing on the expertise areas I have developed myself in the most during my studies and enjoy the most.

Appendix B

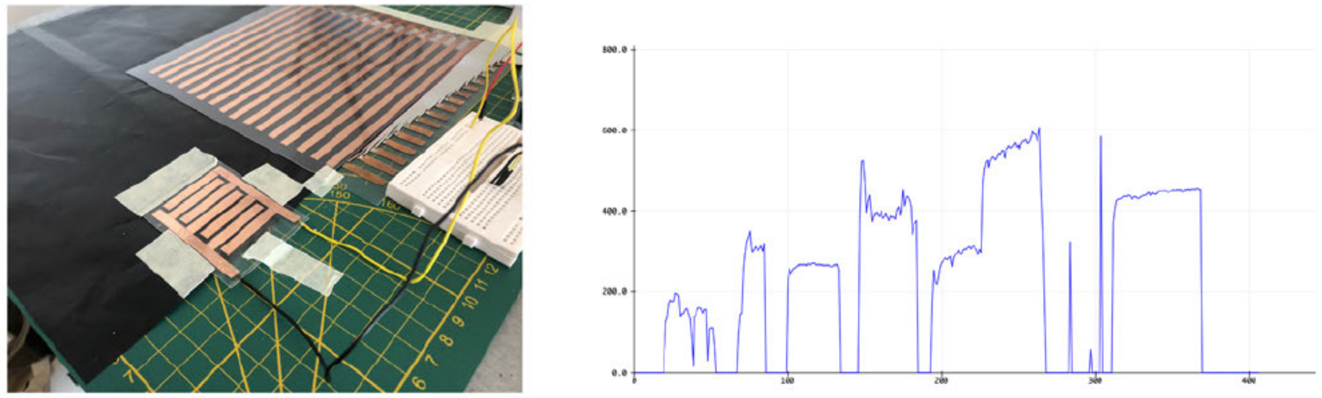
Sensing principles explorative prototypes

Piezoresistive sensing

To get a feel for how a piezoresistive material behaves and to test if the piezoresistive material can sense a measurable difference in applied contact pressure, a low-fidelity interdigital sensor structure, with a piezo resistive material was analysed. The structure is connected to a microcontroller (Arduino Uno). The microcontroller can measure the change in resistance of the piezoresistive material by measuring the voltage drop by the positive and negative trace of the interdigital structure.

Measurements/results

The prototypes show the sensing circuit can sense the contact pressure that is being applied on the surface. Additionally, there is a measurable difference in magnitude of applied contact pressure, which is shown by the graph seen in figure [17-b]. Analysis of the accuracy and repeatability of these sensor readings are analysed in a more in-depth test setup described in the chapter 5 – concept.



A B

Figure B1 - low-fidelity prototype piezoresistive principle

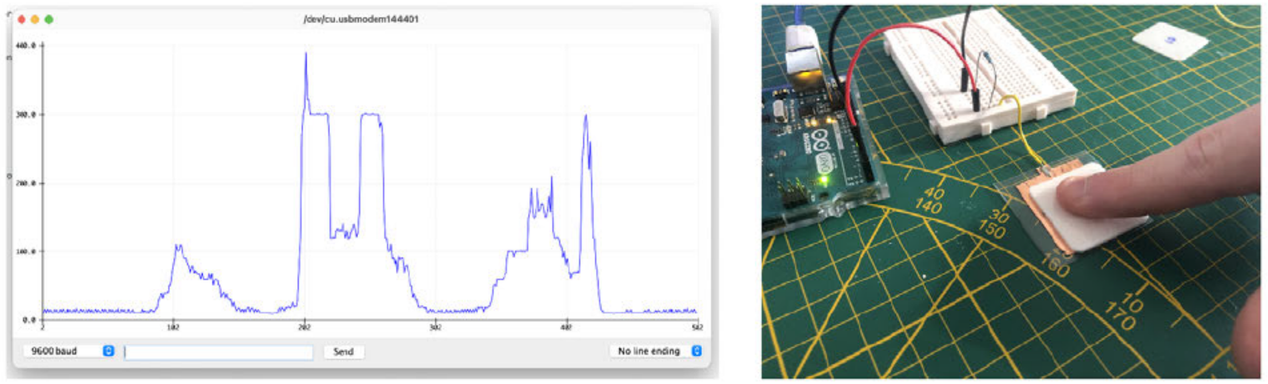
Capacitive sensing

To explore the possibilities of a printed dielectric and the use of skin conductivity as capacitive effect, a low fidelity prototype was used to analyse the capacitive sensing principle.

The prototype needs to show if the design consideration of 3d printing the dielectric can be used, while specially looking at if a difference in applied pressure can be measured. To test this, a simple setup is created by using a microcontroller (Arduino uno) and capacitive sensing library (Capsense) to measure the capacitive state when a light and hard press by a finger is applied to the surface of the dielectric. Figure [18-b] shows the described setup.

Measurements/results

When looking at the graph shown in figure [18-a], the setup shows the use of a 3d printed dielectric in the fabrication of a tactile sensor can measure and differentiate between a difference in the applied pressure on the surface of the dielectric. Moreover, the use of skin conductivity is shown to be viable in creating a tactile sensor. Further testing on the accuracy and reliability is analysed further in chapter 5 – concept.



A B

Figure B2 - low-fidelity prototype capacitive principle

Appendix C

Tactile mapping explorative prototype

Matrix array

to broaden the knowledge and explore the field of tactile sensing and mapping, the exploration phase was kicked off by the development of a low-fidelity and explorative prototype. The prototype applied the knowledge extracted from theory research.

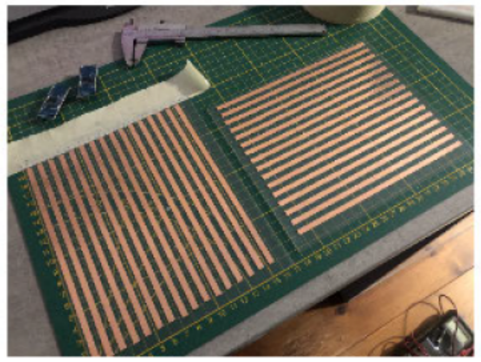
Setup

The prototype consists of two thermoplastic sheets, and are equipped with 16 conductive traces created by copper tape. The two sheets are offset by 90 degrees from eachother, and sandwich a sheet of piezoresistive thin film (3M Velostat). Resulting is a matrix grid of sensing circuits.

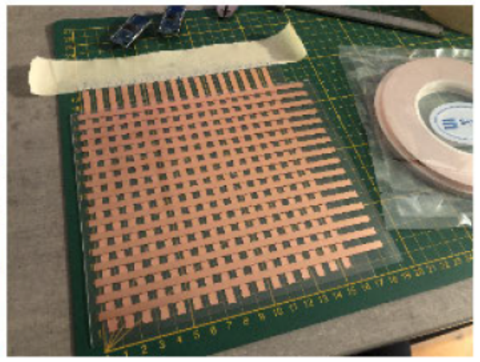
A readout circuit is constructed using two 16-channel multiplexers, which scan the grid of sensing circuits and readout the resistance within these traces. A microcontroller (Arduino Uno) processes this data and sends it to a processing file, visualising the readouts of pressure in a 2D grid.

Results

The resulting prototype showed excellent tactile mapping abilities. The prototype provided an excellent start at exploring the requirements for tactile sensing and mapping. The prototype showed piezoresistive sensing as good option for further exploration. Additional work needs to shows flexibility, ease of fabrication and better scalability.



A



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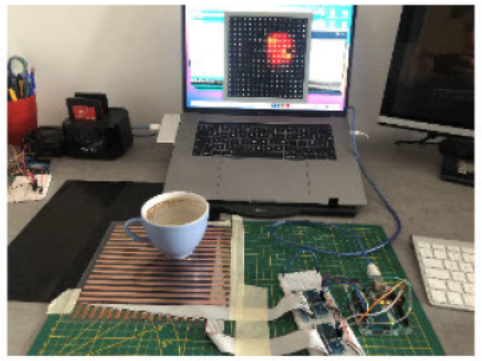

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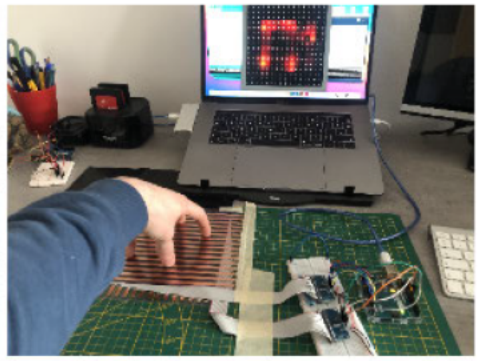
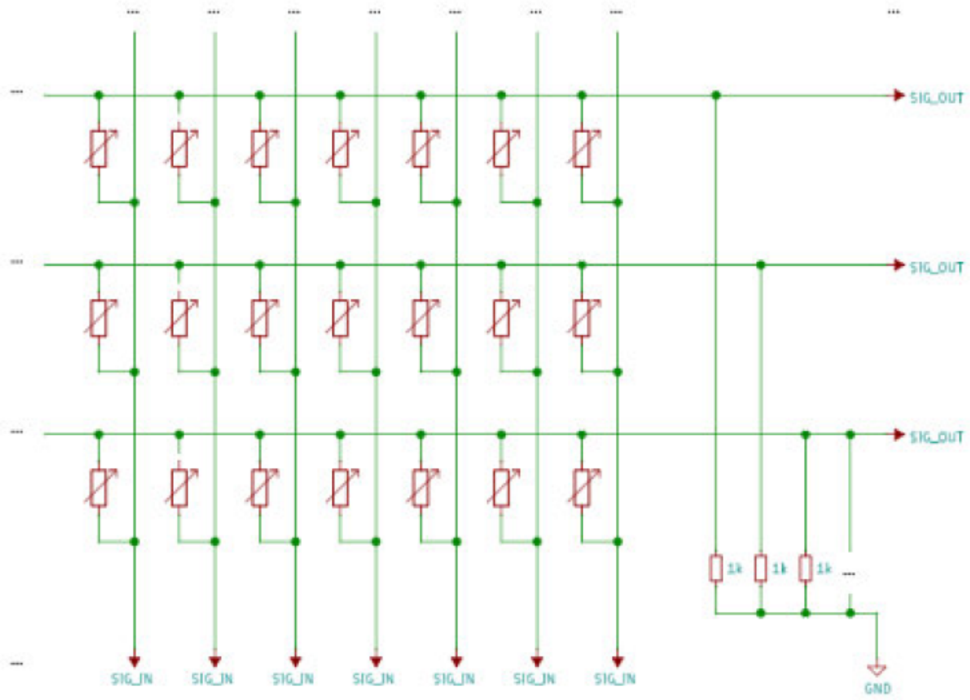
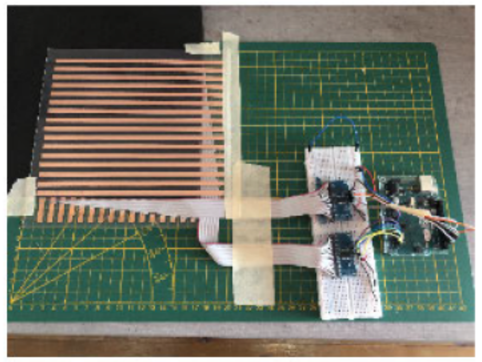


E

Figure C1 - low-fidelity prototype matrix array



C



F

Appendix D

Performance selection results

Results

Figures D1-D6 show the raw data of the performed selection tests. The results shows the plotted data of the readouts of both the sample sensor (top graph) and load cell (bottom graph).

Analysis

To conclude on which of the principles is most suitable for the use in the progression of the development of printed tactile sensors, we look at how the sensor samples behave in relation to the defined sensory aspects of repeatability, stability and resolution. Below we sum up the key insights in relation to these main sensory aspects.

Sample 1 | *small interdigital structure*
Shows a significant repeatable outcome while readout follows load cell readout well. Sensor can differentiate in the two different weights therefore showing significant resolution. Stability of readouts is reasonable, readouts show slight drifts in the measurements. Readouts show an acceptable response time.

Sample 2 | *large interdigital structure*
Much like sample 1, sample 2 shows significantly repeatable readouts and acceptable resolution. Readout does shows slightly less stability while introducing more drift and less stability in readout.

Sample 3 | *matrix array structure*
Shows, like the previous samples, repeatable readouts and significant resolution by differentiating in weight. However, this sample shows a slight decrease in stability. This stability however can be corrected when necessary by using a running average.

Sample 4 | *porous thin dielectric*
The readouts of this sample show a significantly repeatable outcome. Resolution of the sensor however is lacking since differentiating in applied weights is difficult. Readout is reasonable stable, slight fluctuation in readout, but can be accounted for.

Sample 5 | *porous thick dielectric*
This sample shows some level of repeatability and resolution. The sensor is able to differentiate between applied weights, but only in a limited amount. Stability of sensor is lacking because of lower resolution.

Sample 6 | *solid dielectric*
Shows non-usable readouts while resolution is low. Readouts are non-uniform and non-linear while variation in weight provides a sensor readout of only two states.

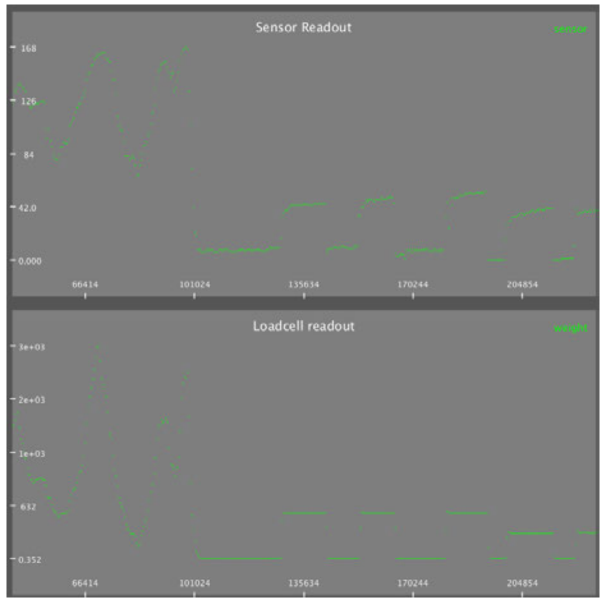


Figure D1 - raw data small interdigital stucture | sample 1

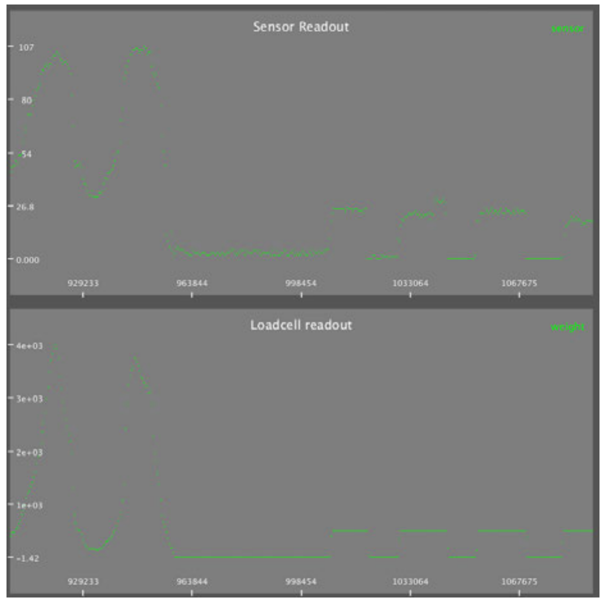


Figure D2 - raw data large interdigital stucture | sample 2

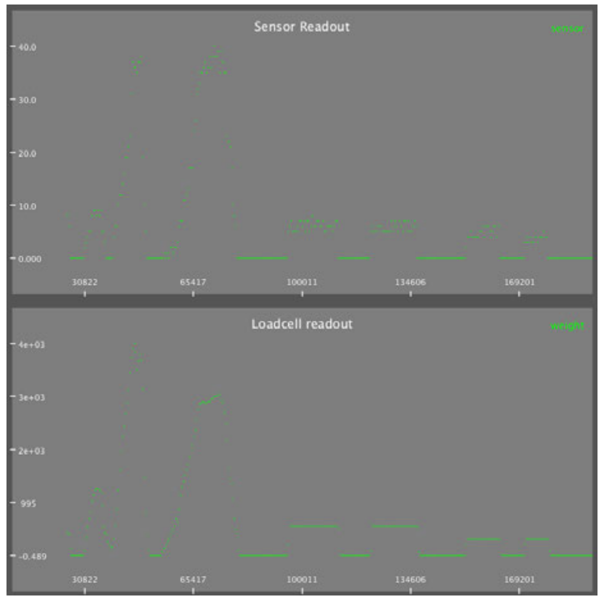


Figure D3 - raw data matrix array structure | sample 3

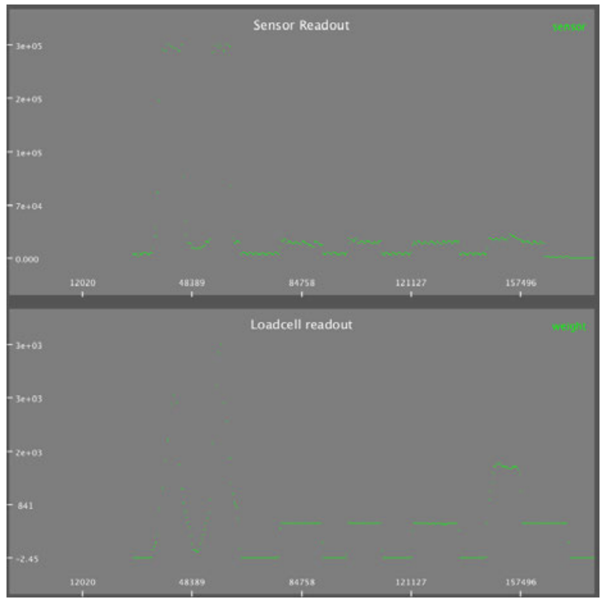


Figure D4 - raw data thin porous dielectric | sample 4

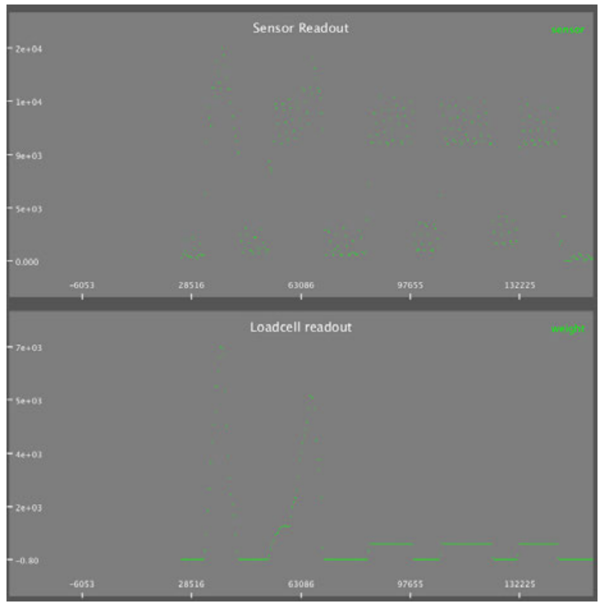


Figure D4 - raw data porous thick dielectric | sample 5

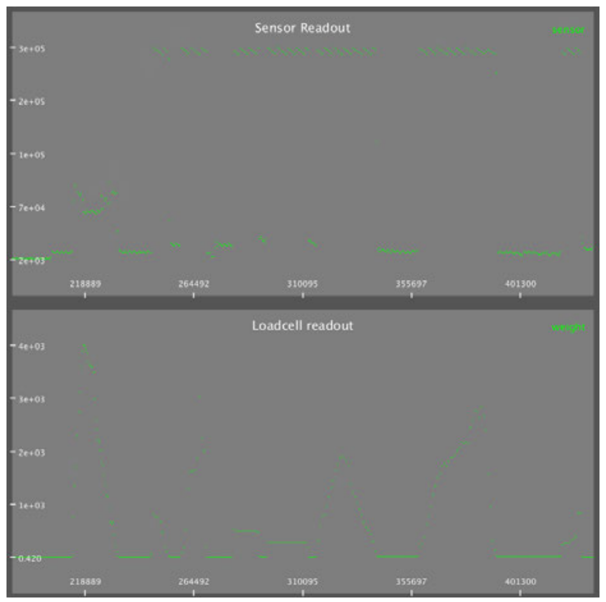


Figure D6 - raw data solid dielectric | sample 6

Appendix E

validation setup code

```
// Rick van de Ven, Sept 2021; IPD Master graduation
// Operating code for the test setup of a combination loadcell and sensor sample (variable resistor)
// to allow for sensor characterisation of the development of printed sensors

//ArduSpreadsheet plugin is used to record and append serial-data to CSV.
//REF: https://circuitjournal.com/arduino-serial-to-spreadsheet

#include "HX711.h"                  //include Loadcell amplifier library

HX711 scale;                        //Create instance of HX711

int raw = 0;                        //Var for storing raw value A0
float Vout = 0;                     //Var for storing measured Voutput of sample
float R2 = 0;                       //Resistance of sample
float buffer = 0;

int Vin = 5;                        //Vinput on sample
float R1 = 20000;                   //Resistance of reference resistor

float avg[4];                       //array for storing readouts
int index = 0;                      //readout number index
float average;                      //average of 5 readouts

uint8_t dataPin = 6;
uint8_t clockPin = 7;

uint32_t start, stop;
volatile float f;

void setup()
{
  Serial.begin(115200);

  scale.begin(dataPin, clockPin);   //Define data and clock
  scale.set_scale(107.9);           //Calibration HX711
  scale.tare();                     //Set HX711 to 0

}
```

```
void loop()
{

  f = scale.get_units(1);                //continuous scale 4x per second, append to var f

  raw = analogRead(A0);                  // Read analog pin A0 and append to raw

  if(raw){                               //calculation for converting ADC readout to resistance
    buffer = raw * Vin;
    Vout = (buffer)/1024.0;
    buffer = (Vin/Vout) - 1;
    R2= R1 * buffer;
  }

  avg[index] = R2;                       //append readout ot array
  index++;

  if(index == 5){                        //after 5 readouts, calculate average over readouts
    average = avg[0] + avg[1] + avg[2] + avg[3] + avg[4];

    Serial.print(f);                     //send loadcell readout over serial
    Serial.print(",");
    Serial.print(average);               //send sensor readout over serial
    //Serial.print(",");
    //Serial.print(raw);
    Serial.println();

    for(int x = 0; x < 4; x++)           //clear array
    {
      avg[x] = 0;
    };

    index = 0;
  }

  delay(50);
  //5 readouts x 50ms = 250ms
}

// -- END OF FILE --
```

Appendix F

Initial project brief

DESIGN FOR *our future*

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

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

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

[redacted]

Your master programme (only select the options that apply to you):

IDE master(s): IPD / Dfl / SPD

2nd non-IDE master:

individual programme: 01 - 09 - 2019 (give date of approval)

honours programme: Honours Programme Master

specialisation / annotation: Medisign / Tech. in Sustainable Design / Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Dr. Song, Y. — dept. / section: Mechatronic Design

** mentor: Dr. ir. Doubrovski, E.L. — dept. / section: Mechatronic Design

2nd mentor: Kooijman, A.

organisation: TU Delft IDE

city: — country:

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

comments (optional): 2 members from the section of mechatronics design, while the project would significantly benefit form coaches which have knowledge about the topic and have their expertise into 3d printing and customised products.

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

Procedural Checks - IDE Master Graduation

TU Delft

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair: Dr. Song, Y. — date: 01 - 04 - 2021 — signature: Y. Song (Digitally signed by Y Song, Date 2021.04.12 17:39:47 +02'00')

CHECK STUDY PROGRESS

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

Master electives no. of EC accumulated in total: 27 EC — YES: all 1st year master courses passed

Of which, taking the conditional requirements into account, can be part of the exam programme: 27 EC — NO: missing 1st year master courses are:

List of electives obtained before the third semester without approval of the BoE

name: J. J. de Bruin — date: 15 - 04 - 2021 — signature: J. J. de Bruin, SPA (Digitally signed by J. J. de Bruin, SPA, Date 2021.04.15 12:10:46 +02'00')

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **. Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: APPROVED / NOT APPROVED

Procedure: APPROVED / NOT APPROVED

Remarks:
- second mentor approved after explanation chair
- start date and end date are missing
- in title 3D printed instead of 3DP

comments

name: Monique von Morgen — date: 28 - 04 - 2021 — signature:

Initials & Name: R.H.C. van de Ven 4921 — Student number: 4615018

Title of Project: The design of 3DP pressure sensors for the application of a smart glove

Personal Project Brief - IDE Master Graduation

TU Delft

The design of 3DP pressure sensors for the application of a smart glove — project title

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

start date - -   - - end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

We see significant recent developments into pressure sensors as application into wearables. This graduation project focuses on how 3d printing technologies might add new opportunities towards developing wearable pressure sensors. The scope of this project aims at exploring and developing 3D printed wearable pressure sensors, and ultimately focuses to apply these sensors on the development of a electronics based, smart pressure sensing glove to demonstrate the opportunities of 3DP pressure sensors. This glove can function as a tool for designers and researchers to understand the human grasp. This can for example be used in the improvement of ergonomics of products by designers or research towards robotics able to manipulate objects. The contribution to the field of easily manufacturable pressure sensors with 3DP can be highly interesting for fields like health monitoring, human-machine interaction or prosthetics. Current opportunities are built upon MIT research that enables for the analysis of human grasping (see image), while still limited on the human aspect towards the feel and touch the prototype has. The main opportunity in this project is to use the technology (3D) printed electronics with flexible materials to enable a more thin sensor network incorporated into a glove.

space available for images / figures on next page

Personal Project Brief - IDE Master Graduation

TU Delft

introduction (continued): space for images

image / figure 1: MIT research on an electronic pressure sensing glove for human touch

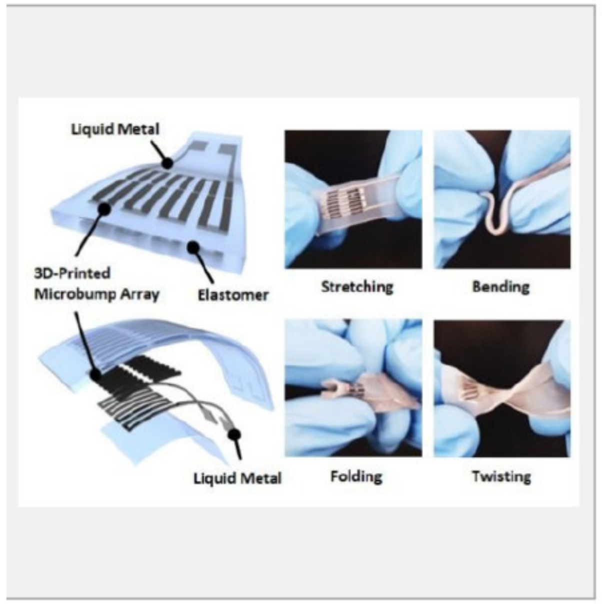


image / figure 2: 3DP technique of printing flexible pressure sensors

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The main challenge of this project is focused towards research into how we might be able to use the technology of electronics 3DP to manufacture pressure sensors, ultimately making a smart glove which is easily producible. The research into 3DP pressure sensing will also involve making the sensor network as thin as possible, as close to normal human grasp, to improve on the feeling of touch the person has on the object he is grasping. We aim to incorporate a pressure sensing circuit onto a flexible material with a voltera v-one / Bot factory electronics 3D printer. An additional challenge for the project will be to adapt the sensor network to fit the geometrics of a 3D hand model with the use of computational design.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

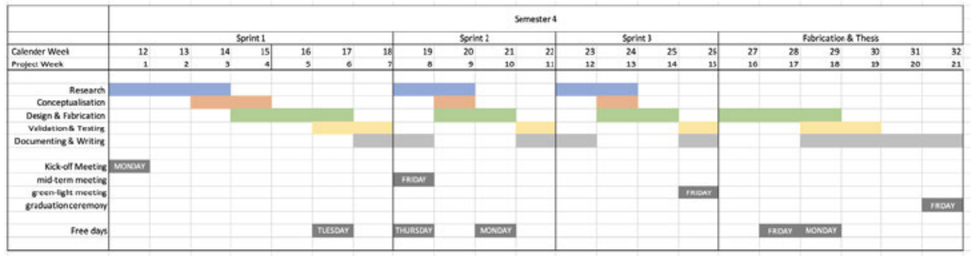
The graduation project will focus on researching and developing a final fabricated smart glove which is able to measure the grasp of a human hand, and is modeled to a P50 hand size. The glove will be fabricated by the use of an electronics 3D printer, using flexible conductive traces on a flexible rubber-like material fabricated into a wearable glove. The final glove needs to demonstrate the developments into a method of 3D printing pressure sensors to be used as wearable sensors.

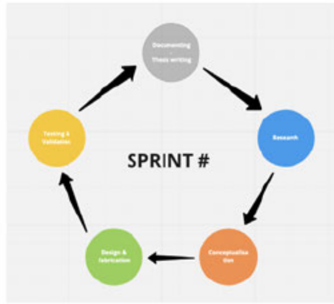
With regards to the focus areas of the IDE faculty, the project will mainly aim at the areas of human and technology. We try to explore the current developments into the state-of-the-art technologies of electronics 3DP and fabrication of wearable flexible pressure sensors into a smart glove by the means of a design thinking process, and apply a designers' holistic view to improve upon the human aspects around applying wearable sensors in a human-centered approach with regards to expressiveness, adaptivity and human feel. The human-centered approach focuses on minimizing infringement on human grasp of the user by minimizing interference like material thickness, material stiffness or cables.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date - -   - - end date





The project will be structured into 3 different sprints in which the research and development of the smart glove is explored by experimentation and extensive prototyping. Every sprint will be primarily focused on building a prototype to iterate on a final design, based on research into advanced electronic materials and printing techniques at the start of the sprint. writing and documenting the experimentation and research that is done in every sprint is done at the end of every sprint. The final 4 weeks are reserved for the fabrication of a final, fully functioning design.

Every sprint will have a focus towards the fabrication of a design concept of a smart glove. After each sprint, the goal is to have an design iteration of a final glove concept. Each sprint will apply the learning points from the exploration and experiences of the previous sprints, and improves on the issues.

Personal Project Brief - IDE Master Graduation

TU Delft

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

My main motivation for setting up the graduation project is the strong interest in the application of electronics in design and the use of 3D printing in the design process and as manufacturing method. I have a great ambition towards specialising into and combining the expertise areas of electronics and 3D printing. During my master track I have been developing myself into 3d printing and improving on my earlier acquired electronics skills, with this master graduation project I want to show my competences into these fields. additionally, I want to try and learn how I can combine these interests and competences by the use of 3D printing electronics and create in-depth knowledge on this expertise area.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30 Page 7 of 7

Initials & Name R.H.C. van de Ven 4921 Student number 4615018

Title of Project The design of 3DP pressure sensors for the application of a smart glove

Appendix G
Midterm evaluation

version May 2018

The Midterm Evaluation Form

>> Complete the form to prepare for the midterm evaluation, and send it to your supervisors, at least 3 days prior to your midterm evaluation session. <<

Name student	Rick van de Ven	
Student number	4615018	
Name chair	Y. Song	
Name mentor	E.L. Doubrovski, A. Kooijman	
Interim/In-between results		
Short description of realised interim results: *Exploration of 3D printing opportunities in the development of wearable tactile sensors and definition of 4 concepts to be realised into the final application of a tactile sensing glove.*		
Reaction on description of interim results: *There was a clear and elaborate study on the background including different principles, the potentials of different materials and manufacturing methods. Besides, student starts prototyping from day 1 and a series of experiment was conducted for exploration. The work looks good and in time considering both the scope and the details of the project. We are satisfied with the result.* *The report was well written and with clear structure. Some aspects could be improved and further deepened, e.g. the scope of the references, the use of references. Overall, it is a good step towards the final thesis.*		
Reflection[1] *<take the course's learning objectives as starting point when reflecting on the topics below [2]>*		
Reflection on quality	*Quality of interim results satisfies results according to the planning for the project. Developing tactile sensors with 3D printing initially was a hard challenge, the resulted exploration of the first half of the project resulted in significant knowledge, ideas and concepts to realise a tactile sensor array for a final application of sensing glove.*	*The supervisory team is happy about the progress. The scientific approach you took in the reporting is appreciated. All feedback are carefully considered and part of them are implemented. We also appreciate that you start to prototype from day 1.*
Reflection on planning	*Planning of the project is still according to plans of the initial project brief, although slight adjustments have been made to accompany the results of the exploration.* *Exploration resulted in a more universal approach for the conceptualised tactile sensors, focussing more on the development of these concepts and hereafter exploring the application of a smart sensing glove.* *The initial planning of the project brief to have several cycles on a finalised concept needs to be endeavoured more, creating more iterations on the final concept application*	*The projects runs according to the plan.* *As the project focus on research, considering the ambition of the set target, it is always possible to discuss and to adjust in different steps.* *In the rest of the project, the focus will shift gradually from research to embodiment. Considering the prototyping time, it is suggested to test and develop the concept asap following "small" cycles with "raw" prototypes, as this area is rather new in the faculty and more tries might be needed.*
Reflection on personal ambitions (if formulated in project brief)	*Current trajectory perfectly aligns with learning goal ambitions, while it allows me to demonstrate my expertise in the fields of electronics and 3D printing, while also developing myself more with regards to knowledge on the topic like circuit design.*	*Printed electronics is rather new in the faculty, the students took this project and we appreciate his endeavour for innovation. Please continue.*
Reflection on supervision and/or project context	*Would like to involve supervisory team more in the decision making of the project, specially in the fabrication of a sensing*	*The student is very independent, however, he always carefully listen to the feedback of the supervision team and implement in*

[1] A short indication of your thoughts and considerations with regard to the graduation project up till now.
[2] Learning objectives are to be found in the Course Manual, and in the IDE Study guide.

version May 2018

	glove. First half of the project focussed more on an exploration of possibilities and opportunities for the fabrication of 3d printing, proceding from the midterm focus would be more on making critical decisions to develop a sensing glove, therefore more interaction with the supervisory team on these decisions needs to have a focus.	*his work. Sometime the students might be too independent. The supervision team will be happy and ready to support throughout the process.*
Decision supervisory team concerning progress graduation project at this moment		
■ **Continue**	☐ **Adjust**	☐ **Discontinue**

Substantiate the decision:

The progress is good enough to continue. The project acts according to the plan. It is suggested:

1. To incorporate more references in the related work, e g. principle of sensors and manufacturing methods;
2. Sharpen the focus of the reports by addressing the challenges and research questions;
3. Calibrate wording according to the references, or define by yourself;

Adjustment of Project Brief: new arrangements

Proposal new arrangements based on this midterm evaluation:

The progress is good enough to continue.

Final arrangements

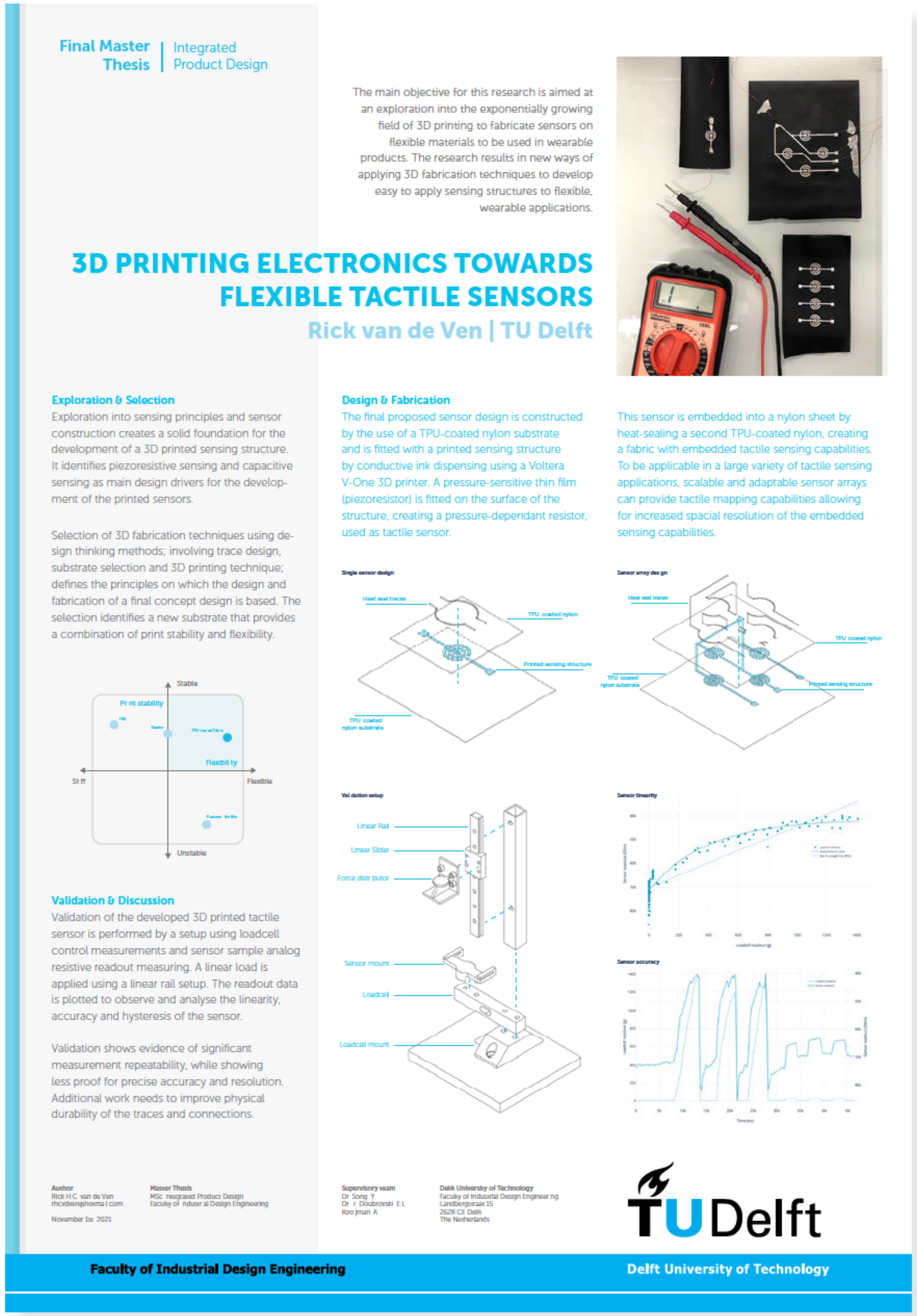
No significant change is needed at this stage

Signatures (name, date and signature of student, chair and mentor)

Name student: R. van de Ven **Date: 26/5/2021**	**Name chair:** Wolf Song **Date: 26/5/2021**	**Name chair:** E.L. Doubrovski **Date: 26/5/2021**	**Name mentor:** A. Kooijman **Date: 26/5/2021**

At the end of the Midterm Evaluation meeting: Please hand-in the filled-in form **on Brightspace,** upload to **'IDE Master Graduation Project'** organisation.

Appendix H
Showcase poster



Appendix I

Project summary

The research described in this thesis explores the field of 3D printing technologies in the fabrication of printed, flexible tactile sensors and explores new possibilities and opportunities in the fabrication. The research is aiming at new ways of applying 3D printing fabrication techniques to develop easily applicable sensing structures to flexible, wearable applications.

Exploration into sensing principles and sensor designs for the printed fabrication of these tactile sensors results in the main design drivers of piezoresistive sensing and capacitive sensing to act as sensing mechanism for the developed sensors.

Fabrication principles are selected according to design thinking methods, and select and evaluate the trace design, substrate selection and 3D printing technique used in defining a concept proposal.

The performed exploration and design selection result in the concept proposal of a 3D printed tactile sensor using a TPU-coated nylon fabric substrate and ink-dispensed sensing structure using a Voltera V-One 3D printer. The sensing element is embedded into the fabric using heat sealing. A scalable, adaptable sensing array is proposed to allow for embedded tactile imaging capabilities.

The developed tactile sensor is validated by analysing a characterisation of the sensor readouts. A validation setup using a loadcell and vertical load is used to allow for the plotting of the sensors' characteristics and linearity.

Validation shows evidence of significant measurement repeatability, while showing less proof for precise accuracy and resolution. Additional work needs to improve physical durability of the traces and connections.

The research concludes in a foundation towards the use of the 3D printing technologies of ink jetting/-dispensing to develop embedded sensor to be used in a large variety of tactile sensing/imaging applications.