3D printed Fluidic systems

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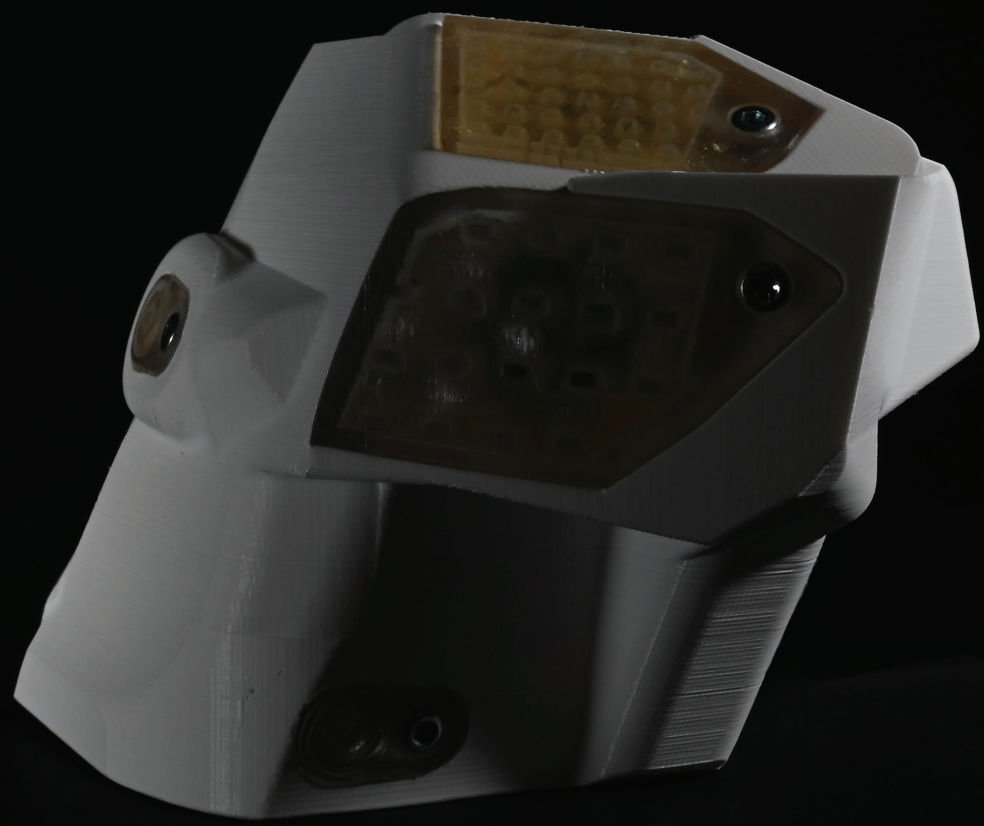

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Table of contents

1. EXECUTIVE SUMMARY

This research project departs from two novel concepts, 3D printing fluid, and fluidic interfaces.

With polyjet 3D printing, micro-droplets of different resin materials are ejected in layers and hardened instantly. Through this technology, complex 3D parts can be manufactured with up to 8 different materials, including flexible and rigid materials. This project departs from a research study in which a non-curing resin is used for the first time as one of the printed materials (McCurdy, 2016), which allows for 3D printed fluid geometries to be designed inside solid parts. However, the effect of fluid printing on the printed part quality is not mentioned beyond a list of design guidelines.

Fluidic interfaces is a novel concept, in which fluid is visibly displaced through small channels, as a result of deforming the flexible structure in which fluid is placed.

The main objective of this project is to discover whether combining the concepts of fluidic interfaces and the opportunity of 3D printing three-dimensional fluid structures, will create new forms of human-product interactions. Therefore, these two fields are researched, resulting in a haptic controlled with 3D printed fluid mechanisms.

Fluidic system structure research

Through low fidelity fluidic system prototypes, made from silicone it is researched how 3D fluidic systems need to be structured for creating new human-product interaction forms. From this, it is acknowledged that the design structure opportunities are based on an input (force), displacing the fluid, and an output (intended result) which can be visual, physical, or the combination of both.

With the different structure opportunities, a literature exploration is performed into existing developmental research prototypes within the established opportunities achievable with a fluidic system. With these findings, generated fluidic system ideas are rated in terms of viability, selecting dynamic textures as the idea to be developed into a concept, and demonstrate the design opportunities of 3D printed fluidic systems.

3D printing with fluid research

During the development of a dynamic texture concept, fluidic samples are 3D printed to observe the impact fluid has on the structural result. The effect of this is significant, as fluid spills between printed layers (during the print process), and severely weakens solid structures. In addition, flexible material printed in contact with fluid will deform greatly. Thus, solutions are exposed regarding the part printing alignment and the use of support structures to manufacture successful 3D fluidic structures.

It is anticipated that 3D printed fluidic parts are to be integrated into a concept, based on the deformation resulting from hydraulic pressure. Therefore an explorative analysis is carried out comparing finite element predictions to actual test results, creating a model for further mechanism predictions.

Concept design

Dynamic textures is chosen as the idea to be developed into a concept, thus the visual and tactile elements of texture are researched. As a result, 4 elements can be dynamically altered with a 3D printed fluidic system: surface colour, surface height, curvature and hardness. With this opportunity, a haptic feedback controller is selected as the idea to be developed into a final concept.

Human tactile variables play the role in receiving information from surface textures, from which fluidic mechanisms are designed. The mechanisms (roughness sensor and texture actuator), vary the perceivable surface roughness and height, with the use of deforming flexible membranes. These mechanisms are tested on three participants to obtain the design guidelines for optimal texture perception.

The final concept is based on the communication between the user and a product, through varying surface textures. This is tested with a proof of concept, on three participants concluding that the product opportunities of this concept lie in the implementation into immersiveness, or creating a new tactile language, however a longer testing duration will be needed for this validation.

2. Introduction

2.1 Context

Fluidic interfaces is a novel concept and approach of an interactive material utilising fluid channels. In these dynamic fluidic interfaces, fluid is considered as the medium to drive tangible information triggered by deformation of the flexible structure surrounding it, and at the same time, to function as a responsive display of that information. In the concept called 'venous materials' this has been explored, in which a set of elegant structures were designed, that respond to mechanical inputs from the user, and act as embedded analog fluidic sensors, dynamically displaying displacement through the flow of coloured liquids (Mor et al., 2020) (figure 1).

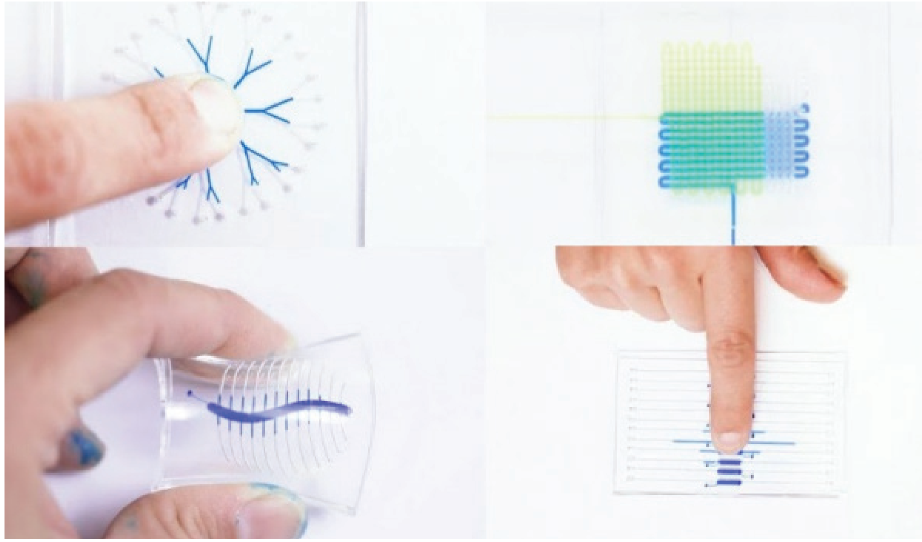


Figure 1: fluidic interface interaction demonstration (reference)

This existing concept reveals a programmable dynamic interface allowing products to change and adapt their appearance dynamically as a result of external influence. This is constituted of three thin silicon sheets, which need to be individually laser engraved, manually depositioned of internal fluids, and adhesives together (Appendix 1, replicating existing concept). Thus, the use of such a process is time consuming, in addition to limiting in certain features such as design complexity, as only 2D interfaces can be made, manufacturing not being scalable, integration into products limited in its existing form and human-product interaction opportunities are narrow.

With the development of a new manufacturing process, multi-material 3D printing does stand out. This technology makes use of liquid printing materials in a liquid resin form, which is depositioned layer by layer through tiny droplets (polyjet), and hardened shortly after ejection due to the exposure to UV light. As a result, multi-colored and multi-material objects can be created, in which flexible and rigid elements can be designed with high detail into a single printed structure (chapter 4.2, Fluid system 3D printing research). These systems can be adapted to print non-curing liquids, in order to achieve parts with internal fluid structures (McCurdy, 2016). However this new adaptation is still in a novel development state, without any applications.

Figure 2: Polyjet 3D printing example

Therefore, with the concept of fluidic interfaces and the idea of printing 3D fluid geometries (fluidic systems) inside flexible-rigid solid structures, it opens the question whether these can be united, in order to combine the dynamic and interactive experience of a fluid interface and the design freedom of polyjet 3D printing. As a result, an innovative form of product interaction and design value could be achieved.

The intent of this project is to go beyond the initially constructed 2D interfaces, and create these directly in a 3D single printed structure. As a result more complex geometries could be achieved, therefore the term "fluidic system" will refer in this project to those 3D fluid structures that rely on fluid displacement for its use.

2.2 Research approach

The objective of this project is to translate the idea of fluidic interfaces into a new form of product interaction, with the use of experimental fluid 3D printing. Therefore in order to achieve this set goal a planned research strategy is considered with the aim of answering the following questions:

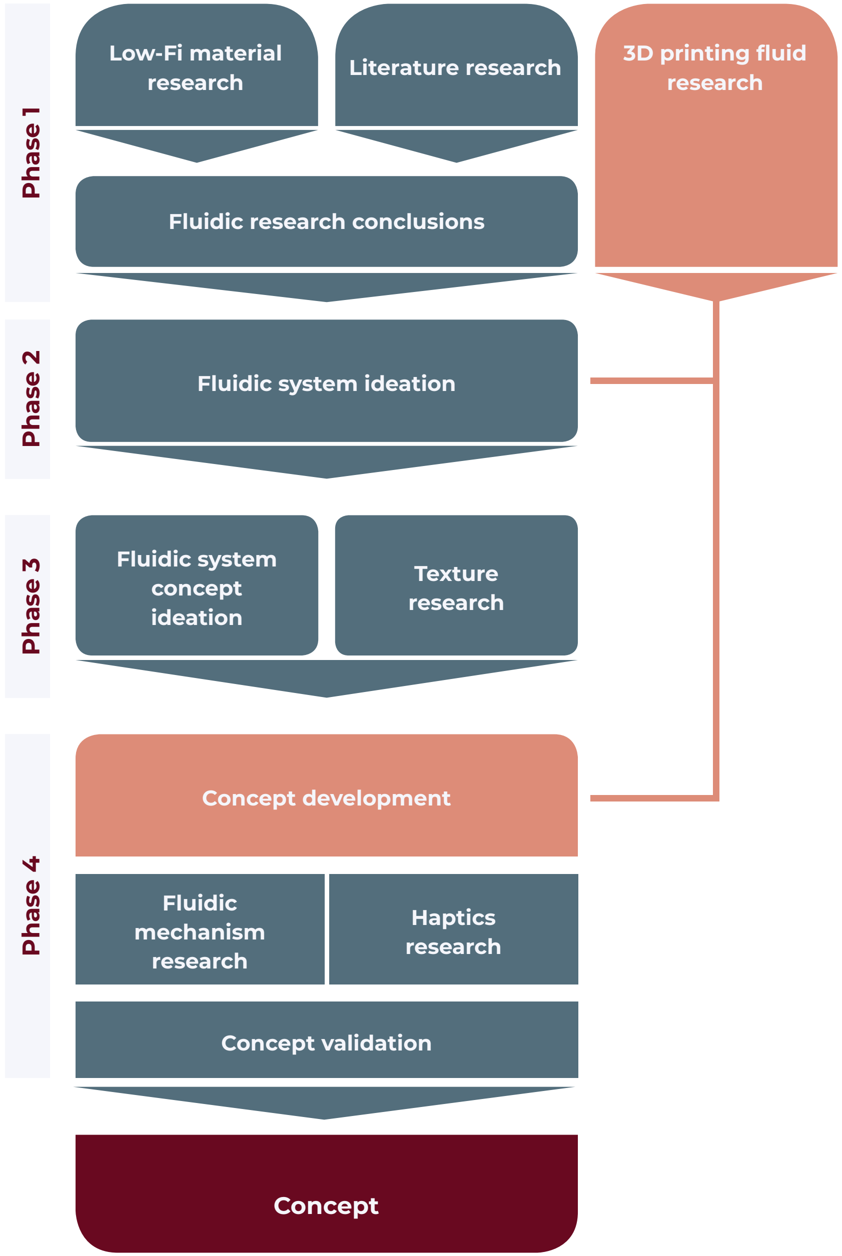
1. *What are the design opportunities when the concept of fluidic interfaces are transformed into 3D structures (fluidic systems)?*
2. *How does the use of polyjet 3D printing with fluid influence the manufacturing and designing of fluidic parts?*
3. *How can the concept of 3D printed fluidic structures inside objects, translate to new forms of human-product sensory interaction, beyond the existing visual interface concept?*

The approach of this project will not only be researching how to 3D print fluid structures and what could be achieved with this, but in addition one design opportunity will be developed into a concept in order to demonstrate the design value in this novel field. The project is therefore structured into three phases:

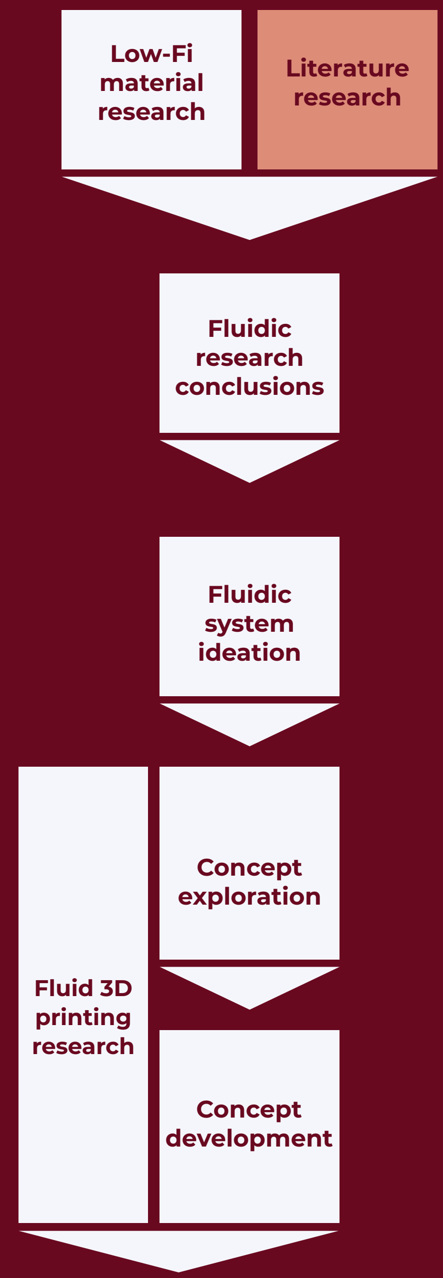
In the **first phase** (chapters 3, 4 and 5), the structure of what can be achieved with the idea of 3D fluid structures in an interactive environment is established, product innovations and developments are researched within feasible fields, and polyjet 3D printing fluid technology limitations and opportunities are explored.

In the **second phase** (chapters 6 and 7) design opportunities and feature ideas are created from the first phase research, resulting in concept opportunities. This is achieved through the use of a fluidic system product idea generating method.

In the **third** and last **phase** (chapters 7 and 8), the most viable idea, a haptic controller based on texture perception, is developed into a concept and demonstrated through a functional prototype, with the use of fluidic system mechanisms.



3. Literature research



Fluidic systems are structures that can achieve an intended purpose, through the displacement of internal fluids. This is by itself not a newly discovered concept, as hydraulics have been in existence for almost 3 centuries. However these systems are constructed from multitude of rigid parts (predominantly metals), and work through pressurising fluid, commonly oil or water, moving a piston through a cylinder. However the objective of this project is to make use of polyjet 3D printing technology, in order to create structures with both flexible and rigid material, without the need of complex plumbing parts. Therefore, the target is to find current developments and innovation which fluidic systems could replace in the near future.

In this chapter, a dive is executed into existing developmental research prototypes within the context of what a fluidic system could achieve on a first level (chapter 5, fluidic system research conclusions). Through observing similar outputs and interactions of what is observed with initial prototypes (chapter 4.1, fluidic system tinkering research), insights can discover potential fluidic systems applications, or how these could be presented as (output forms). The process of this literature study focuses on finding applications and research, relevant for potential future fluidic systems, and finding which uses could be substituted by a fluidic system by itself. The findings of this research have three purposes:

1. **Output form:** the concluding research will provide a final outer layer in the fluidic system structural model (chapter 5, fluidic system research conclusions) proposing how such systems could be presented as.
2. **Application concept ideation:** Output forms are used during the ideation process (chapter 6, fluidic systems opportunities), to produce feasible product ideas, which are created through the development of a specific idea generating tool.
3. **Concept selection:** in chapter 6 (fluidic systems opportunities, fluidic systems final idea selection), different feasible ideas are presented, of which one is chosen to be developed into a concept. The literature research insights benchmarks which idea is the most viable.

It is important to state that these findings are not timeless nor fixed. During this research, fields and developments have been explored departing from the fluidic structural design model. Yet, this is not a finished model, instead, it is designed such that future developments can expand further upon this content. Therefore, looking forward, more fields of research could add additional value to the ideation process. Alternatively, the found research and developments used during the ideation process could be outdated in future revisits.

3.1 Process

In order to efficiently gather, and analyse such vast a amplitude of a research field, the literature exploration process is divided into two steps:

Part 1: literature research
The material research (chapter 4.1, material research, fluidic system Lo-Fi material research), provides different output (outcome or resulting action) properties and interaction elements, in other words, what can be achieved with a fluidic system on a basic structural level. These are therefore the starting research fields in which exploration research will be performed:

- *Mechanisms creating physically dynamic responses*
- *Mechanisms creating visually dynamic responses*
- *Fluidic systems*

Through observing present studies, innovations and developments within these elements which are structurally achievable with a printed fluidic system (chapter 4.1, fluidic system tinkering research), similar forms in which a fluidic system could be presented can be deduced, along with possible value gaps and design opportunities. These sources are explored through digital platforms and scientific journals (Appendix 2, literature research method).

Part 2
The multitude of different findings within the research fields are grouped into an comprensible summary and overview which can be interpreted to understand fluidic systems design structure and opportunities (chapter 5, fluidic systems research conclusion), through:

a. ***Cluster and Group:* classification of findings:**
The value of each source, relevant for potential fluidic systems, can diverge between the different findings. Thus, similar sources are clustered together when their innovation value is cohesively similar. As a result, clustered insights can be analysed.

b. ***Key points***:
The sources clustered into similar innovation values, are analysed with the intent of discovering how fluidic systems could be presented as and, obtain potential innovation gaps and for new fluidic system concepts.

c. ***Benchmarking***:
With the insights of this study, different fluidic system ideas can be compared regarding their innovation value, and select which is the most viable and desirable opportunity.

Figure 3: Structuring and phases of the project

3.2 Classification of findings

The search for existing studies, innovations and developments related to dynamic mechanisms and fluidic systems, leads to a vast multitude of different sources. The majority of these are in an abstract concept phase, meaning that the initial technology and function demonstration is present , however, the use of these in a practical scenario (even less in a product) has not been designed or developed yet.

The found technology innovations have been predominantly found in video formats (Appendix 2, literature research method), which are made as early stage promotions. Therefore, through utilising innovations in its early development stages as form inspiration, with the purpose of this study being, 'how can fluidic systems present themself into product applications', fluidic systems could take a large innovation step in future opportunities.

Research clusters

The research departs from three fields, with as a result, when newly found technologies, innovations, applications or research are found within the value of such a field, these are placed within a similar information bubble. However, within these, new related elements and groups occur which can be relevant to potential fluidic system design opportunities (*figure 4*).

The classification of these groups depend on whether it is a dynamic physical output, provides dynamic visual properties, or a human-product interaction.

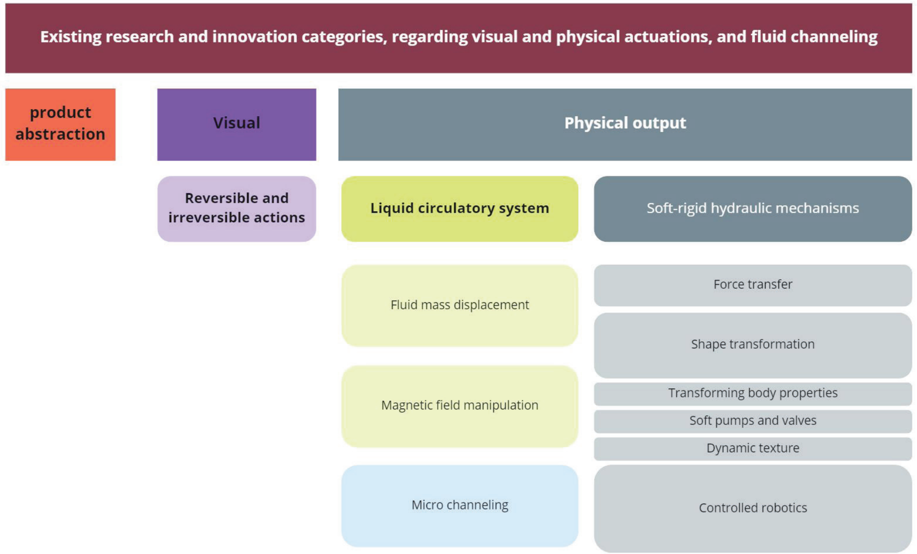


Figure 4: research findings fields categorised

Dynamic physical output

The first research category are those innovations in which a fluidic system could replace existing structures intended with providing a physical action. With this definition, it is meant with parts, materials or products intended with dynamic physical properties such as its shape, or material properties. Therefore, on a first distinction, the dynamic properties can be differentiated between external physical changes through altering the structure, shape or form (soft-rigid hydraulic mechanisms), or internal physical changes, through displacement of internal fluidics (liquid circulatory system).

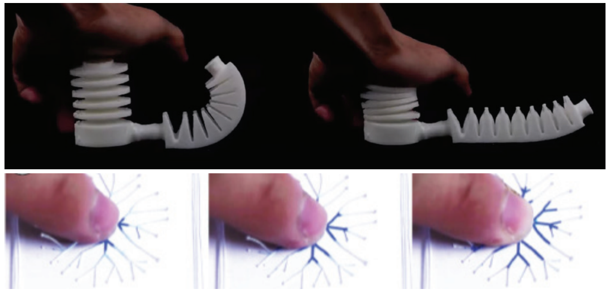


Figure 5: liquid circulatory (Mor et al., 2020) vs mechanism [39]

With research in the field of **soft-rigid hydraulic mechanisms**, the focus lies on structures that could utilise the full potential of multi-material 3D printing, therefore creating structures with both rigid and flexible parts and materials. The search for innovations and developments within this hydraulic mechanism category research, departures from three constructing output elements, established during the fluidic system material tinkering research (chapter 4.1.2, material tinkering);

1. Transformation of shape [6-16]
2. Transformation of mechanical properties [17-23]
3. Force transfer through fluid incompressibility [1-5]

With a search for sources departing from these three elements, new groups emerge sharing the constructing element. As a result, additional categories emerge within the opportunities of soft-rigid hydraulic mechanisms such as **controlled robotics** [33-50]**, soft pumps** [24-27]**,** and **dynamic textures** [28-32]. These, in addition to the three constructing elements, categorise what could be achieved (at the moment) when a fluidic system were to be designed with the purpose of constructing a soft-rigid hydraulic mechanism.

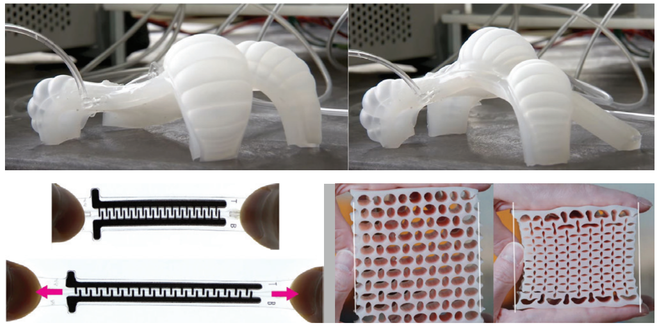


Figure 6: representation of soft-rigid hydraulic mechanisms [43], [25], [29]

When observing the latter, innovations within the output of a liquid circulatory system, the research element is the displacement of internal fluid. Through observing the material properties of a fluid (chapter 4.1.2, material tinkering) such as its weight, temperature or magnetism in case of a ferrofluid [53-54], new categories occur from these. In addition, through manufacturing on a micro scale with polyjet 3D printing, microfluidics [55-57] can be integrated into the design opportunities of fluidic systems based on fluid internal displacements.

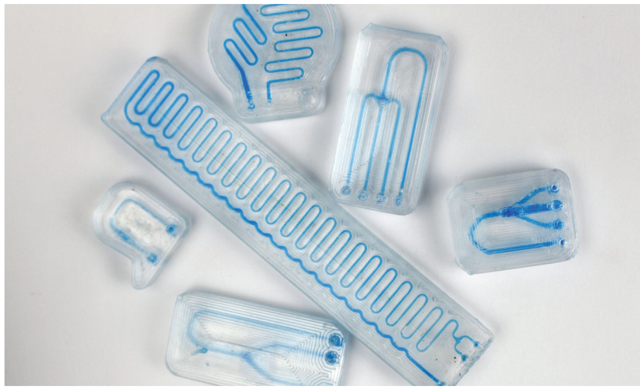


Figure 7: Micro channelling [57]

Dynamic visual properties

Fluidic interfaces are the starting point of this project, acknowledging that reversible changes in a product appearance can be achieved through the displacement of fluid. With this research being the discovery of new opportunities, the research innovations are focussed on the active behaviour of this change in appearance, either being a reversible or irreversible visual output.

Innovations found within these mentioned boundaries [58-64], are yet scarce, as the use of non-digital reversible visual outputs are mostly limited to chemical material reactions. However, the existing developments share in common the intended desire to enable a human to product visual interaction.

Figure 8: representation of visual dynamic properties [58]

Human-product interaction

The value of a future fluidic system could lie in the unexplored interaction between the user and the product, through generating innovative dynamic or sensory stimuli. Therefore, in this last research category, studies contributing to the understanding of the human product interaction are established [65-66], which could redefine how fluidic systems should or could be designed, to achieve a new form of interaction.

Having elaborated these different fields, they can now be individually evaluated in order to discover what its potential is for future fluidic systems. Each field can therefore be analysed regarding where the innovation is occurring, what are the benefits and potential downsides of including such in a fluidic system, and finally, the potential innovation gaps (Appendix 92, Literature classification of findings). However, it is important to remember that this is not a final research, instead, through this structure, future opportunities or new fields for fluidic systems can be added, researched and analysed for their innovation value regarding new fluidic systems.

These different fields that occur from classifying opportunities for fluidic systems provide new insight on what can be achieved and how fluidic systems can take form in functioning products. As a result, from these, a model can be created defining design opportunities of how fluidic systems could structurally be presented as (chapter 5, research conclusion).

3.3 Key summary

In the previous chapters, the structure of how the findings are categorised is elaborated. However the insights within these different categories regarding relevant innovation developments are addressed separately, to distinguish between what can be achieved (fluidic system structure model), and what should be made.

First of all, it is important to acknowledge a multitude of different fields have been researched, within a limited timeframe. As a result unknown valuable research might have been looked over, or new market progress can have occurred. Thus, the priority of this chapter is laying down a research foundation from which future research can depart from.

As the first and overall conclusion from researching innovations within the fluidic system design structure, there are a vast multitude of design directions possible, through replacing these output applications with fluidics. However the development of fluidic systems itself, within a flexible-rigid material environment is highly unexplored, and practically non-existent on the market. Thus, the remainder of this report focuses on finding and developing a viable design opportunity, which can be achieved with such a fluidic system structure. Through comparing how much developments are occurring within a specific field, the most viable design direction can be elected to continue with:

Dynamic physical outputs

Within this first category there is a large distinction in research developments between the different elements.

When observing progress regarding soft-rigid hydraulic mechanisms, the large majority of research is occurring in the fields of controllable robotics and transformation of shapes. The main focus on development within controlled robotics is about developing robotics which are able to be controlled freely in all directions [33-50]. However, in current existence these do correctly lack strength and overall precision, due to a lack of structural support (not yet adopting the flexible-rigid design structure), and relying on pneumatics.

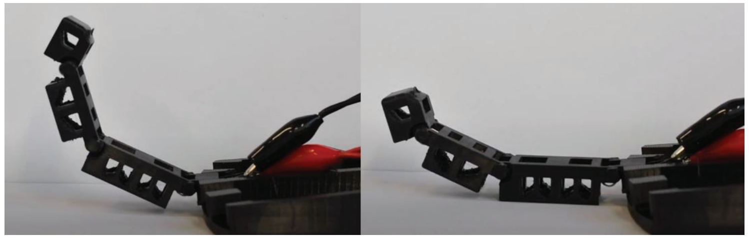


Figure 9: controlled robotics

Programmable materials are being developed to **transform** or recover a certain **shape.** However, these are yet in early development stages and can only remember one specific shape for now [6-14]. Moreover, early prototypes are in development consisting of strong contracting polymer fibres [16], however these need to be electronically powered, requiring large amounts of energy and heat dissipation . Nonetheless, concepts are in development combining multiple of these strands to mimic human musculature.

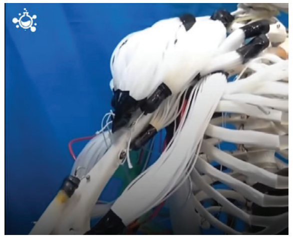


Figure 10: contracting polymer fibres

From these two elements smaller research fields present developments which could be replaced or implemented with a fluidic system:

Different prototypes present methods to **vary stiffness** within a body, either through an organic structural design [19-20], internal vacuum chambers (causing an increase in friction) [18] or raising the part temperature (increase in internal pressure) [17, 23]. However none of these are adjustable (either on or off) nor offer distinction in the direction of desired stiffness.

Figure 11: variable stiffness structure [20]

Force feedback is being implemented into remote controlled robotics, however, these are relying on electric actuators [2-5] (rather than fluid) as electric actuators ease the design and assembly of the interactive element (product).

Figure 12: force feedback [3]

There are designs of foldable geometries, to change **surface textures** [28-31], and overall shape [32], however these structures are mechanical assemblies, rigid and designed predominantly for saving space.

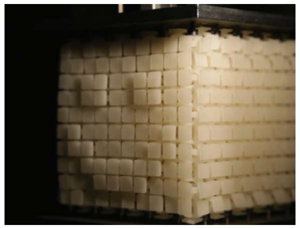


Figure 13: surface textures [29]

Electrically actuated flexible and **soft pumps** are in development [24-27], with the intent of providing hydraulic pressure for soft robotics. However none of these can provide high amounts of pressure.

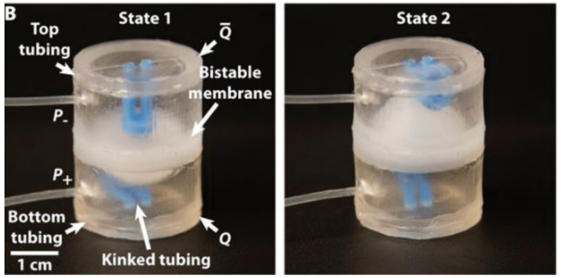


Figure 14: soft 3D printed pumps [24]

Regarding the development of concepts with fluid properties such as mass and magnetism, there are little research investments. However, an emerging market are **microfluidic** chips, with the intent of chemical and biological analysis in laboratoriums [55-57].

Dynamic visual outputs

Within this second category, dynamic visual appearances are in early stages of product design, relying mostly on electronic and computerised systems [58-64]. Yet, there is a gap for dynamic reversible appearances non-reliant on chemicals or electronics.

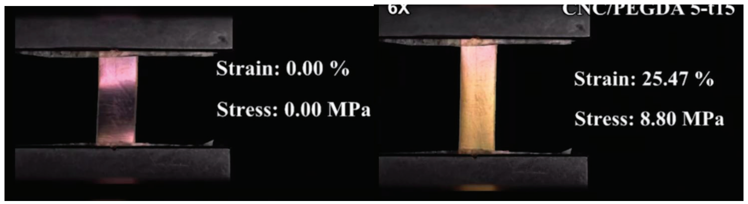
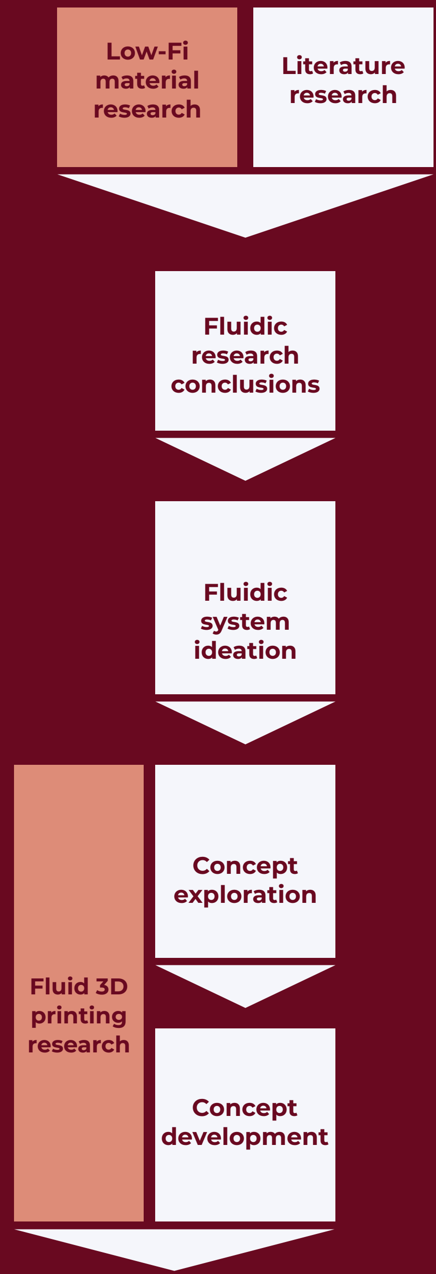


Figure 15: colour changing material when stretched [59]

4. Material research



In this research material research chapter, the following three fields of development are addressed:

1. **Low fidelity prototyping of fluidic systems (of mechanisms)**: in this first subchapter low fidelity (low-fi) fluidic system prototypes are explored, in order to discover how these 3D systems need to be structured for creating new human-product interaction forms. The findings from this research will provide knowledge on which fields these systems could be applied onto, establishing which different innovation fields should be researched (chapter 3, *literature research*).

2. **Fluidic system 3D printing research**: this subchapter focuses on analysing and discovering the design guidelines necessary for creating 3D printed fluidic systems. The findings from this research will eventually provide the knowledge on how dynamic texture concept can be manufactured (*chapter 7, morphing textures: idea to concept*)

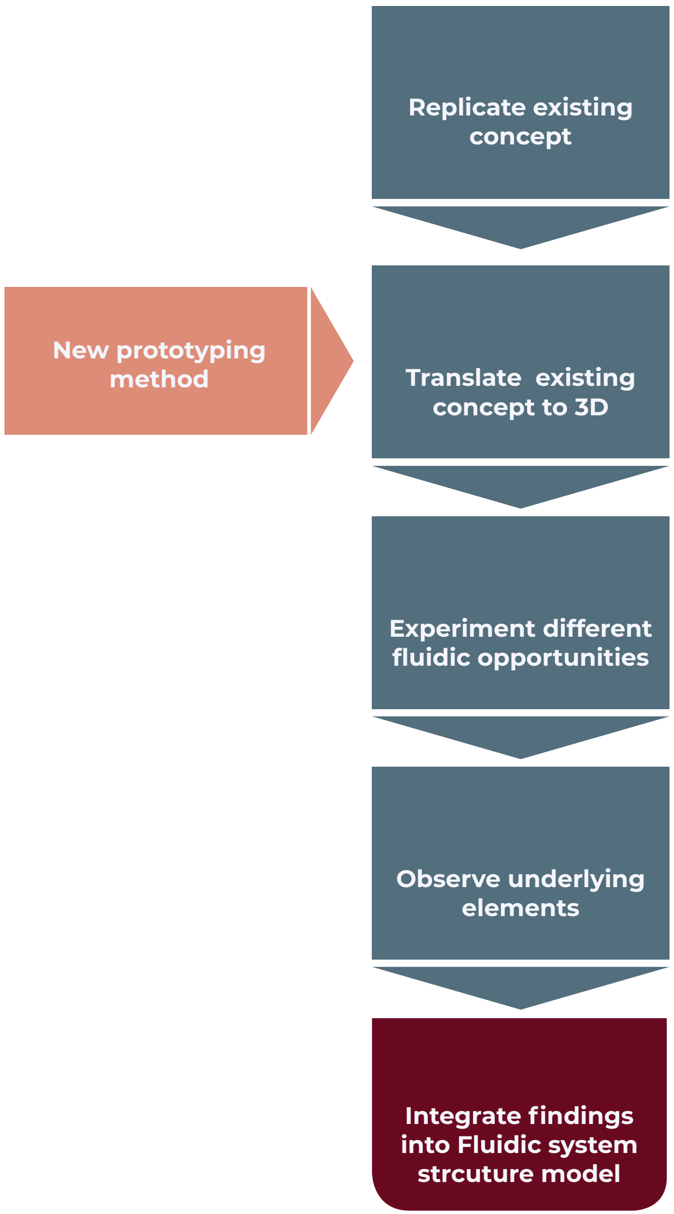
3. **3D printed fluid mechanisms analysis:** the final goal of this project is to demonstrate a new interaction form achieved through a 3D printed fluidic system. In this subchapter, the behaviour of such systems is explored, through establishing the hydraulic principles, and evaluating the effectiveness of finite element methods for predicting mechanisms deformation..

4.1 Fluidic system low fidelity material research

In this chapter, the design space of fluid mechanisms is discovered, in other words, through prototypes the design structure for flexible 3D fluidic systems is explored, along with a fist level impression of which interactions can be created. The findings from this material research, create a base on how a fluidic system which is intended for human to product interaction would need to be designed (chapter 5, fluidic system research conclusion).

The ultimate goal is to create entirely 3D printed fluidic systems. However, this low fidelity research process is carried out with silicone moulded structures, as an inexpensive and rapid solution to make different prototypes. Thus, to mimic the 3D printed result, a new manufacturing method is created to make sealed fluidic systems embedded into a flexible environment (chapter 4.1, manufacturing low fidelity fluidic systems).

Figure 16: Low Fidelity prototyping process



4.1.1 Manufacturing 3D Fluidic system Lo-Fi prototypes

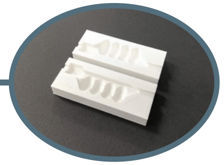
The existing concept relies on thin silicone sheets as the structure on which fluidic interfaces are assembled (appendix 1, replicating existing fluidic interface concept). These sheets are laser engraved in order to create channels in which the fluid can flow through. However, The objective of this material research chapter is to generate low fidelity 3D fluid system mechanisms and observe the underlying elements. Therefore, the manufacturing method of laser engraving can no longer be used as this highly limits designs to a single plane (x/y) fluidic design, nor 3D fluid printing as this is not yet available during the length of this material research phase. Thus, a new manufacturing method is created to resemble a 3D printed fluidic system, without the use of a multi-material polyjet 3D printer.

In order to replicate the multi material 3D printed flexible parts, silicone rubber is chosen as the material for the overall structure with the fluid embedded into this. The design and assembly of such a mechanism consists of 4 parts:

1. **Silicone**, consisting of 2 liquids (silicone base and catalysator), which, when mixed, harden after a specific waiting time (16h for the silicone used (Silicones and more B.V., 2021)). Thus, when poured into a mould while still in a liquid state, the silicone will harden into the designed mould shape itself, creating the flexible structure for the mechanism.
2. **PLA negative mould:** the negative mould in which silicone is poured is FDM (fused filament deposition) 3D printed with polylactic acid (PLA) filament. This material is selected for its low cost, ease and speed of manufacturing while maintaining a high level of detail.
3. **PVA removable insert**: polyvinyl alcohol 3D print filament is a water soluble material used to dissolve support structures of 3D printed parts. For this process, PVA is used to make 3D cavities within the silicones structure,
4. **Fluid**: changes in the placement and shape of the internal fluid structure determine the outcome of the fluidic mechanism.

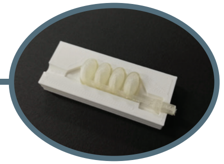
Manufacturing process

The manufacturing process starts off with a CAD design of the intended prototype. The assembly of such a low fidelity fluidic mechanism made with silicone and FDM 3D printers, follows the next steps:



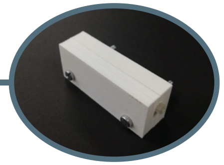
1. Negative mould is FDM 3D printed with PLA, taking into account that the silicone prototype must be removable when hardened.

2. PVA inserts are FDM 3D printed, taking into account during the design process that part of this must be accessible from the exterior once the silicone hardened, such that this can be dissolved.



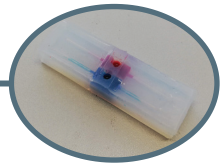
3. PVA insert is fixed into the negative mould, to create the necessary cavities where the fluid will be placed.

4. Silicone base and catalyst are prepared and placed inside a vacuum chamber to extract any air bubbles that might cause the prototype to be structurally defect.



5. Silicone liquid is carefully poured into the mould, with a focus on avoiding air cavities.

6. Silicone prototype is removed from the negative PLA mould, and placed in a water container for the PVA insert to be dissolved. Manual rubbing is required to extract the diluted PVA material. A silicone structure is created with internal cavities.



7. Fluidic prototypes are designed to have an open system (fluid is externally fed with a tube or syringe), or a closed system when the internal fluid structure is completely closed off. When closed, the fluid is injected into the prototype, and sealed with liquid silicone, which, when hardened, creates an airtight mechanism.

Evaluation of silicone for fluidic system low fidelity prototyping

The use of silicone moulded fluidic systems for fluidic prototypes comes with advantages and disadvantages. The central benefits of this manufacturing method lies in the ability of making rapid prototype iterations, at a significantly lower cost when compared to multi material fluid printing (chapter 4.2, Fluid system 3D printing research). However, with this process, some major disadvantages are present:

1. PVA is a highly difficult material to print with. Small features such as thin channels often fail during printing (fluidic design complexity limited by the 3D printing guidelines). In addition, PVA is brittle, and can break during the silicone pouring process when the structure is weak, or caution is not taken.
2. PVA dissolving is time and labour intensive, especially when including narrow fluidic channels, requiring rubbing and pumping of the sample for water flow. As a result, thin silicone prototypes can tear during this removal process.
3. Silicone is used to seal the opening to the fluidic channels once the fluid is inserted. However, in the short span of weeks, fluid will evaporate through this seal, internally drying out the fluidic system prototype.
4. The use of rigid materials is limited to inserts in the mould, thus not fully comparable to the polyjet multi material printing freedom.

Concluding, this prototyping method can be valuable when the advantages outweigh the disadvantages.

4.1.2 Tinkering research

The objective is to find common principles and opportunities in 3D fluidic structures, thus, a diverging exploration is carried out to observe what actually makes a fluidic system, and how changes in the design structure can result in different outcomes.

With an undefined research target, the tinkering approach taken to find defining characteristics of a 3D fluidic system, is through replicating firstly the existing fluidic interface concept. However, in this case, the planar fluid system (x/y) is transformed into a 3D fluid system(x/y/z), and the pressing interaction is repeated (figure 17).

Figure 17: first 3D printed fluidic system

From this first interaction two noticeable aspects occur: a visual change occurs due to the coloured fluid, and a deformation of the silicone structure itself. From this insight, the tinkering research proceeds with two paths:

1. *How could 3D fluidic systems be designed to achieve a change in appearance?*
2. *Can flexible 3D fluidic systems be designed such that deformations are controllable?*

Appearance

With the intent of observing how modifications in the fluid structure result in changes on the surface appearance, a first sample is made with large cavities just below the surface (figure 18). A second sample is constructed replicating the irreversibility feature of the existing concept, to understand how this could be applied to interactive appearances (figure 19). Last, a sample is constructed with the intent of changing appearance without being pressed onto (figure 20).

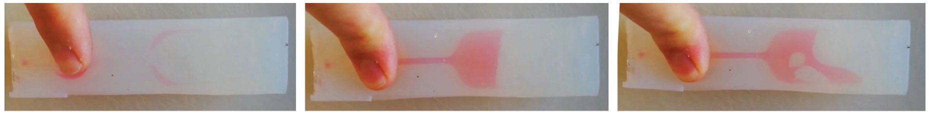


Figure 18: fluidic system with large dynamic appearance area. When fluid channels exceed a minimal size, fluid will flow loose through such channels as surface tension can no longer keep it united.

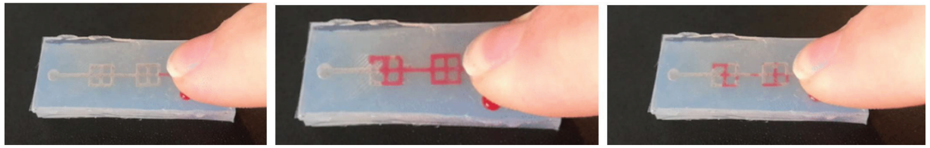


Figure 19: irreversible fluidic system

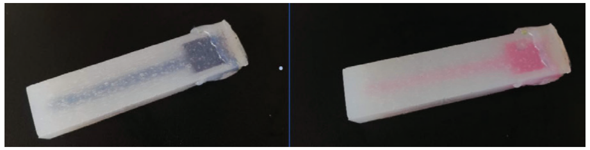


Figure 20: temperature reacting appearance, with the use of heat reactive colouring fluid

Deformation

Initial sample (figure 17) suggests that the displacement of fluid could be combined with a physical deformation to achieve a new form of interaction. A first thin walled sample is constructed, filled with fluid, to observe how these behave together (figure 21), a second sample is made to observe how fluidic pressure can cause a structure to deform (figure 22). At last, a sample is made to observe how changes in wall thickness affects the sample deformation under fluidic pressure (figure 23).

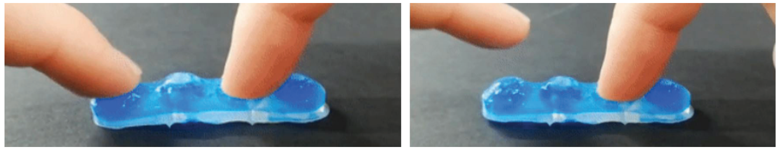


Figure 21: flexible fluidic structure

Figure 22: Fluid pressure in a silicone structure

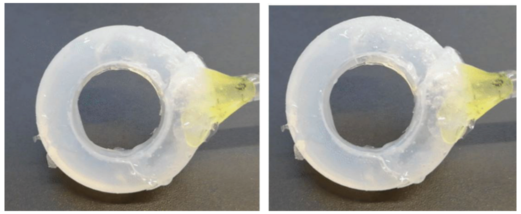


Figure 23: silicone arrangement affecting sample deformation. Minimal deformation was observed in thinner walled areas

Findings

The first and foremost is recognizing that all the fluidic systems are composed of an input, which "triggers' the displacement of fluid. Secondly, all systems eventually have a purpose resulting from this input, an output, result of the fluid displacement itself. The relationship between the input and output of such a system will therefore determine the interaction form designed.

This first low fidelity exploration with fluidic systems demonstrates that the displacement of fluid is the result of a force. However, inputs can be designed without this externally applied force.

A third insight is the intended value of the output which can be designed. A clear contrast in structure occurs between samples designed for altering its appearance against those that will physically transform its shape. This insight is therefore the first deciding factor for designing a fluidic system (chapter 5, fluidic system design structure model).

4.2 Fluid system 3D printing research

The objective established at the beginning of this project is to research how polyjet 3D printing could be used to create fluidic systems and add new product value (chapter 2.1, context). The concept of 3D printing with fluid is not a novel idea, however it is yet hardly explored beyond flexible hydraulic bellows (McCurdy, 2016). In this research paper, fluid is considered as eligible print material, with a set of design guidelines mentioned without further elaboration on implications of fluid printing itself.

With the intent of establishing a base on how fluidics can be considered in the design process, it is not only important to know a list of design rules, but in addition understand how fluid impacts the outcome of a printed object. In doing so, a deeper understanding is obtained of what solutions this new technology could offer. Thus, in this chapter, parts with internal fluid geometries will be 3D printed, analysing how different materials interact with each other. As a result, establishing design guidelines and recommendations which can be interpreted accordingly to the desired outcome.

4.2.1 Printer basics

In this chapter, the essentials of polyjet printing are explained.

a. Polyjet 3D printing

PolyJet is a powerful 3D printing technology that produces smooth, accurate parts, for research prototypes and tools. With a microscopic layer resolution and accuracy down to 0.014 mm, it can produce thin walls and complex geometries (Stratasys, 2021). During pre-processing, build preparation software (Grabcad) automatically calculates the placement of photopolymers and support material from a 3D CAD file. During production, a carriage with four or more print heads (8 in case of Stratasys J735, figure 24) and ultraviolet (UV) lamps traverses the work space, depositing tiny droplets of photopolymer materials that solidify when exposed to UV light. Fine layers accumulate on the build tray to create one or several, precise parts.

Where overhangs or complex shapes require support, the 3D printer jets a removable support material. This support material is easily removed by hand, with water or in a solution bath. Models and parts are ready to be handled and used right out of the 3D printer, without post-curing needed (*PolyJet Technology for 3D Printing*., n.d.)

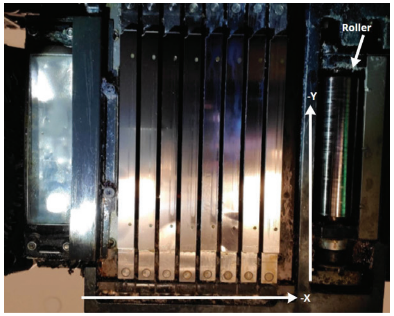


Figure 24: resin print jetters

b. Print roller and over extrusion

During polyjet printing, the printhead sweeps over the print bed depositioning tiny resin droplets, which are cured rapidly with ultraviolet lamps. However, in order to achieve a flawless print quality, the print heads extrude slightly more resin than necessary, which as a result, creates a taller layer height than what is supposed to. Therefore, in order to achieve the smooth intended layer height, a roller will pass over the just printed surface, sweeping away the excess material (see figure 25).

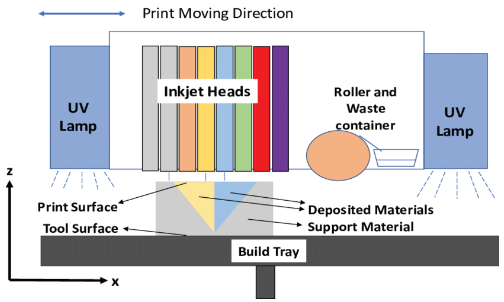


Figure 25: printhead configuration (PolyJet Printing Printhead and Roller, n.d.)

The precise operation in terms of pressing force, and roller RPM are confidential to Stratsys knowledge. However, we are certain that the roller spins at a constant clockwise speed, actuated by a motor. In any case, acknowledging the presence of the roller will allow identifying potential strategies regarding fluid printing.

c. Print axis

As has been mentioned in the previous section that the printhead sweeps over the print bed depositioning resin droplets. However the print jetter and the roller are placed 90 degrees along the printhead path direction. Therefore it is crucial to establish which are the axes of the printer itself (figure 26).

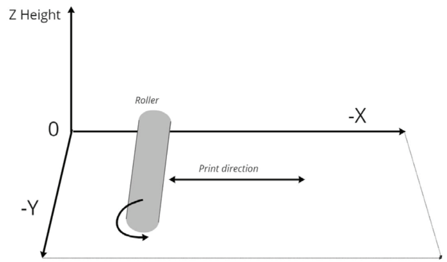


Figure 26: print bed axis

d. Polyjet printed surfaces

It is important to take into consideration how this printing technique works. When resin droplets are dropped on a surface, these will deform due to their fluid state, and when the UV light hardens such resin, these are no longer perfectly shaped droplets, but instead, a hardened splashed fluid. Therefore, on a microscopic level, surfaces are not perfectly smooth, nor different materials are perfectly separated, instead, droplets can mix with each other before the UV lamp cures these.

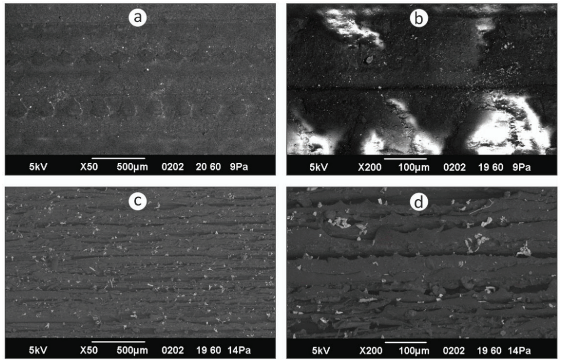


Figure 27: polyjet surface roughness, (a) top surface X50 zoom level; (b) top surface X200 zoom level; (c) side surface X50 zoom level; (d) side surface X200 zoom level. (Vidakis et al., 2020)

e. Polyjet materials

With the Stratasys J735, up to 8 different materials can be used (PolyJet Materials Stratasys, 2022) at the same time during printing, however during the extend of this research, four materials have predominantly been used, these are:

3. Agilus30: a flexible material with superior tear-resistance, capable of withstanding repeated flexing and bending. The ideal material for rapid prototyping and design validation, this rubber-like material simulates the look, feel and function of rubber products. It is important to acknowledge that Agilus30 will be weakened and produce less than desired performance if exposed to water for more than one hour (TriMech, n.d.). However, cleaning fluid (liquid used as the printed fluid) was not found to deteriorate Agilus30 even after weeks of exposure.

4. Veroclear: VeroClear is a transparent material that simulates PMMA (polymethyl methacrylate), commonly known as acrylic. Like PMMA, VeroClear is used as an alternative to glass and is ideal for concept modelling and design verification of clear parts such as eyewear, light covers and medical devices.

5. Cleaning fluid: this fluid is flushed through the printer piping, in order to rinse debris resin, and ensure proper printer maintenance. However, for this research project, this fluid is used as a printing material itself, which due to its nature, does not harden when the UV curing lights sweep over.

6. Sup706: Support material is a vital part of the 3D printing process; it helps support overhangs with larger angles and ensures that delicate elements don't collapse. Once the model has been printed, post-processing largely consists of removing support material. Supu710 is a gel-like support material that is not water or chemically soluble, but is easily removed by hand or with a water jet system.

As a final remark of polyjet 3D printing, with the information provided in this chapter, it shall be made clear here that no 2 prints are exactly the same, even if the CAD models are identical. The minor inconsistencies occur from the droplet depositioning and the roller sweeping over the printed surfaces.

a. Research package

Stratasys provides a research software for the Stratasys J735, enabling fluid as an eligible material. However, for the duration of this project this software is not put in use. Instead, the printer recognises a curable material from the casing digital chip, which is swapped with the liquid material (cleaning fluid).

4.2.2 Existing fluid 3D printing research

The idea of 3D printing with fluid as an eligible material is not a novel idea, however the research and development of this, is yet very scarce. The paper *"Printable hydraulics: A method for fabricating robots by 3D co-printing solids and liquids"* (McCurdy, 2016) is the first and yet only scientific demonstration of this technology (figure 28).

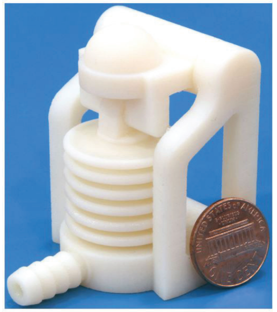


Figure 28: 3D-printed bellow produced via inkjet in a single print. Codeposition of liquids and solids allows fine internal channels to be fabricated and pre-filled. The part is ready to use when it is removed from the printer.

In this research paper, flexible hydraulic bellows are 3D printed, and a list of design rules to be followed is provided, in order to achieve successful 3D prints with internal fluids (figure 29). However the implications of 3D printing with fluid are not presented. Thus, it is unknown how fluid does impact the 3D polyjet printing process, the result, and why these provided design guidelines must be met. Therefore with this existing and new knowledge from this study, future fluidic parts can successfully be designed while taking into account the different effects and variables resulting from the non-curing liquid.

1	Separation (minimum along X/Y-axis):	0.4 mm
2	Separation (minimum along Z-axis):	0.2 mm
3	Feature thickness (minimum along X/Y-axis):	0.325 mm
4	Feature thickness (minimum along Z-axis):	0.2 mm
5	Feature growth (perpendicular to Y/Z-axis)	0.150 mm
6	Feature growth (perpendicular to X-axis)	0.2 mm
7	Solid-solid clearance at rotational joint	0.3 mm
8	Solid-over-liquid support thickness	0.2 mm
9	Solid-next-to-liquid support thickness	0.5 mm
10	Largest segment of liquid (dist in X or Y)	20 mm
11	Recommended width of support "pillars" inserted to connect model layers otherwise isolated by liquid; see Fig. 8 (X/Y-axis):	0.5 mm
12	Recommended solid feature thickness when adjacent to largest liquid segment (X/Y-axis):	2.11 mm

Figure 29: design rules provided by Robert McCurdy "Printable hydraulics"

4.2.3 3D printing fluid experimentation process

The objective is to discover how 3D printed objects with embedded fluids will impact the design process. In order to achieve this goal with limited time, fluidic parts are 3D printed in the interest of researching dynamic textures (chapter 7, morphing textures, idea to concept) while simultaneously these parts are analysed on the effect of printed fluid. Thus, this study focuses on observing where 3D printed objects fail, analysing this problem, and providing solutions to such problems. As a result, the quality of each printed batch is improved as defects are being identified and corrected.

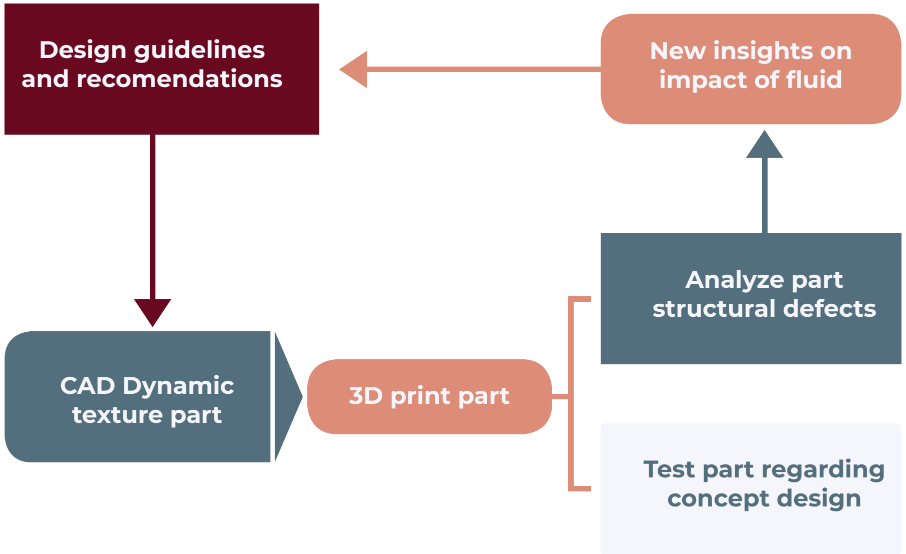


Figure 30: fluid printing research process cycle

4.2.4 3D fluid printing findings

With the established research method described in the previous chapter, prints with embedded fluid are analysed and improved with each printing round. As a result, defects and solutions are exposed, each relying on the previous for improved print quality. The findings are divided into the following segments:

1. *Resin curing imperfection*
2. *Curing*
3. *Sagging*
4. *Support printing*
5. *Print alignment*
6. *Print alignment for flexible parts*
7. *Layer adhesion*
8. *Slicing - From CAD model to voxel representation*
9. *Fluid micro channels*

Resin curing imperfection

When each layer is being printed, material microdroplets are positioned onto the part (polyjet 3D printing), and shortly after, cured with an UV-lamp. However, printing, the droplets of fluid and solid material might mix when these materials are next to each other (assumption). As a result, the solid could be diluted with the cleaning liquid, and not cure as normal. In figure 31, a colour visible decolouring is visible from this effect.

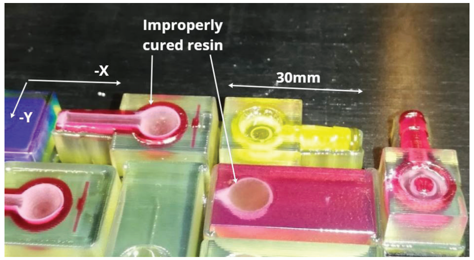


Figure 31: prints with visible improperly cured resin

When rigid materials are printed alongside fluid, a thin white layer will appear in between these two materials. However this will be even more noticeable when printing soft materials, as it creates a "sponge" structure (figure 32). The assumption is that rigid and flexible material resin mix with ease with the fluid when being ejected, and cure in a diluted state.

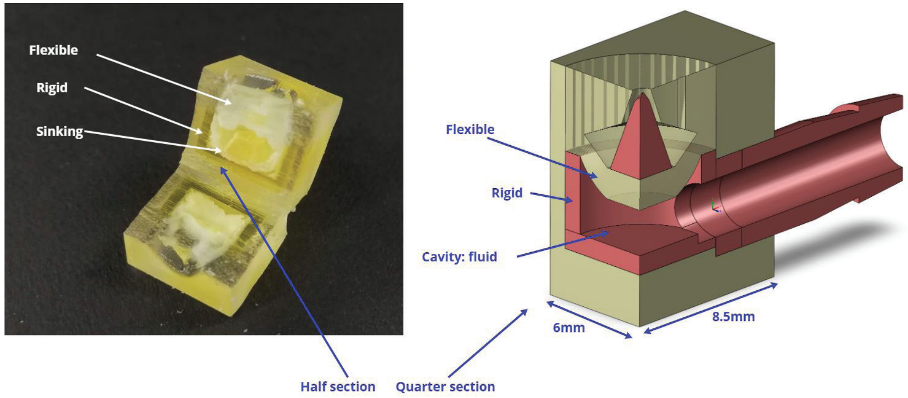


Figure 32: printed result vs cad model (yellow in CAD is assigned shore(A) 30)

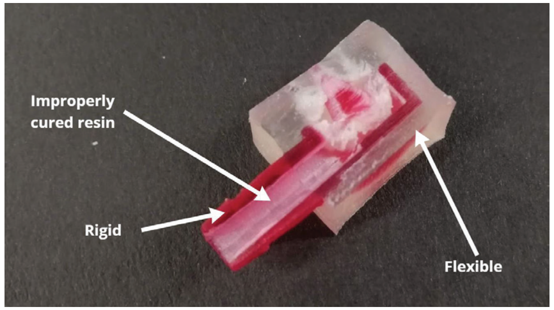


Figure 33: white powder layer on rigid material (pink)

Figure 34: white flakes scraped off rigid material (transparent), printed in contact with fluid

Sagging

During printing, solid layers printed on fluid can sag, due to a lack of support. The variables causing this are the fluid x/y area, the passing of and the printhead roller.

a. **Material hardness**

Sagging of structure overhanging fluid differs when comparing soft and rigid materials.

a. *Rigid*: when the area in contact with the fluid is rigid, the structure will remain in shape, with little visible deformation, including overhangs. This can be observed in the red sample of figure 35. In addition, printing completely on fluid appears to prove successful (figure 36).

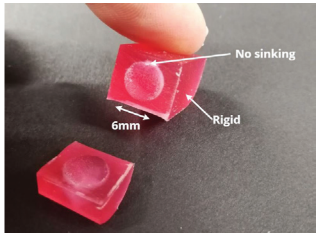


Figure 35: fluid sphere printed in a solid structure with no visible sagging

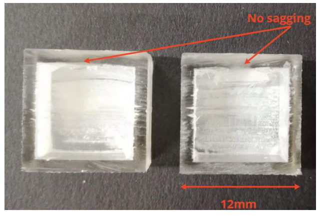


Figure 36: Hollow cube printed with fluid, cut open

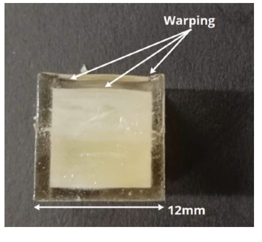


Figure 37: no sagging is visible on surfaces printed on fluid. However warping visible on the exterior edges of the part (not in contact with fluid)

b. *Soft*: when the area in contact with the fluid is soft, sagging of overhangs will occur (figure 38), result of curing imperfections, the roller pressing down, and droplets sinking in fluid (assumptions).

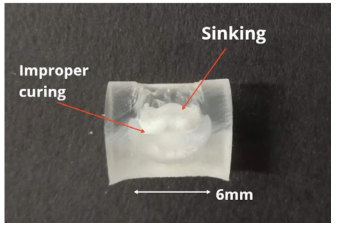


Figure 38: Fluid length along -x: the amount of improperly cured is more noticable

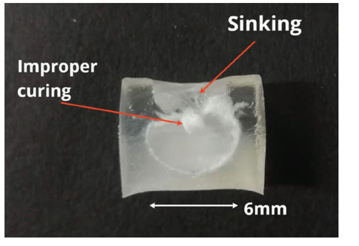


Figure 39: Fluid length along -y: the structure has relatively less sinking and less 'sponge like' volume

a. **Effect of roller**

When printing the roller will sweep over the part in order to scrape off excess material, and flatten the surface. However, as can be seen from the failed prints, the roller needs to be considered in the design process.
Two equal samples are printed, however, printed 90 degrees to each other. The magentared sample is printed along the -y axis, and the yellow along the -x axis (see figure 40). As a result, the red sample is printed successfully, while the yellow sample is not. There are two variables/effects that can play a role in this:

- Roller sweeping: The purpose of the roller is scraping excess material off. However when soft material is printed on fluid with no support, the roller might push the floating structure off its original position.
- Roller pressing: The 'floating' structures might be pushed downwards into the fluid itself, and therefore lowering the print surface (combined with curing imperfections).
- Surface adhesion: a printed material can stick to the roller (especially agilus and fluid) when this sweeps over.

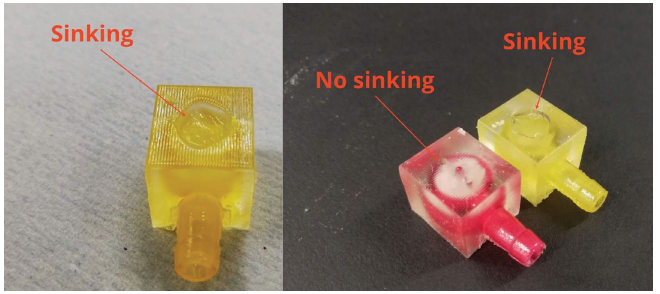


Figure 40: yellow print collapsed vs red print successful

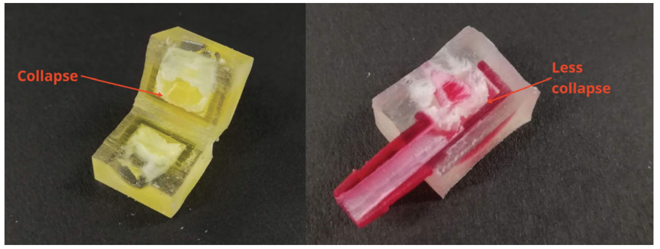


Figure 41: prints interior compared. Yellow print (cut along the width) fully collapsed to the bottom

Support printing

A cube is modelled, with rigid walls, filled with fluid and one floating sphere in the fluid made from support material. The purpose is to observe how support material will be printed on fluid.

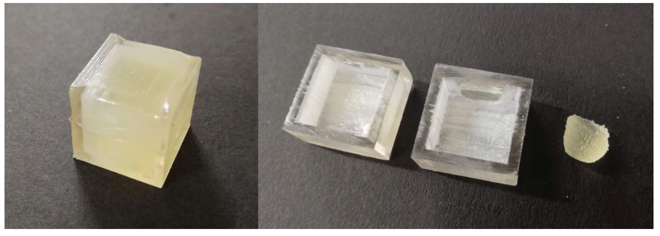


Figure 42: support structure printed inside the cube fluid environment

Support structures are yet effective down to very narrow columns, facilitating the printing of overhang angles.

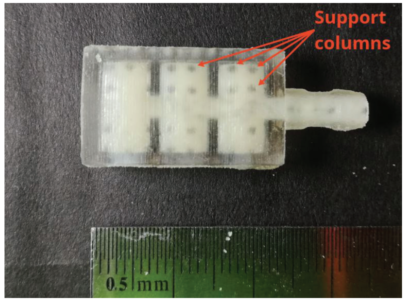


Figure 43: visible support columns printed in liquid volume

Print alignment

When each layer has been printed, a roller will sweep over the part in order to scrape off excess material, and flatten the surface. This means that fluid can be spreaded off its place onto other surfaces. As a result, less fluid can be present in the part itself (voids). The variables of this are the fluid area, and the material hardness:

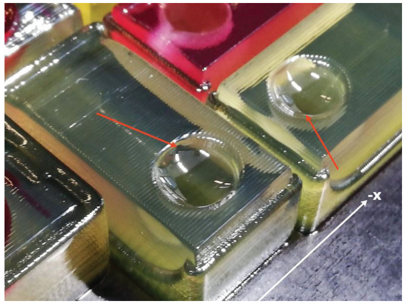


Figure 44: fluid volume significantly less than the supposed volume to be printed. surface

- A larger the length of fluid segment, will increase the chance of fluid scraping off. Therefore, this value should remain below 20mm to limit the risk of fluid overflow (McCurdy, 2016). Figure 45presents two identical parts, however one placed along the print direction (right), and 90 degrees to the print direction (left). The fluid channels inside these prints were both smaller than designed, however the print on the left has a more defined and less blurry channel.

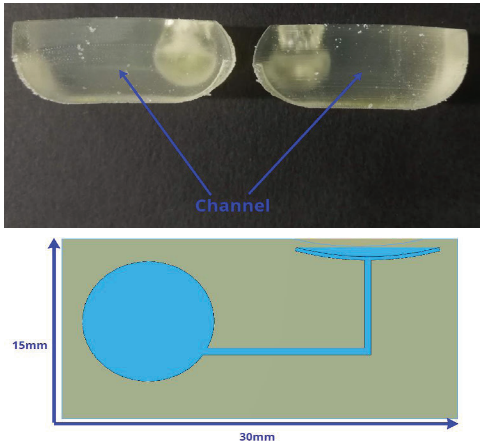


Figure 45: cad model and identical samples placed 90 degrees on the build plate

- Hardness of surrounding materials: A softer material will deform under the roller pressure, as a result, more fluid could be pushed out of its place (assumption). In contrast, rigid structures do retain more fluid.

Print alignment for flexible parts

Samples have been placed along different orientations to observe changes in print quality when prioritising the printing quality of flexible membranes:

a. Soft membrane on the bottom: In this orientation, the 1mm thick membrane is placed on the bottom, and the fluid is printed on top of this (figure 46), in the centre of the structure a support pillar is printed to avoid collapse of the rigid layers printed on the fluid.

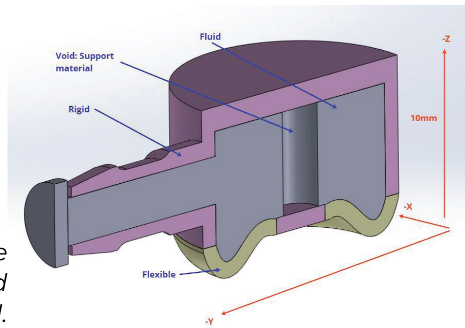


Figure 46: Placement of the sample on the print bed. Voids are printed as support material.

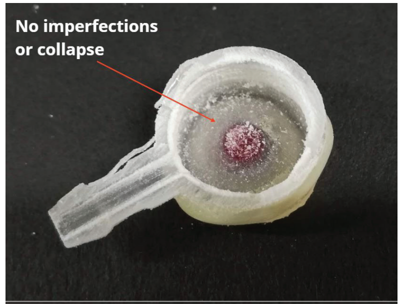


Figure 47: No imperfections or collapse can be observed on the soft membrane.

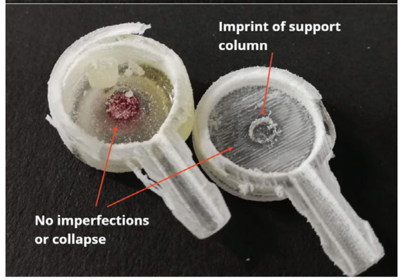


Figure 48: No collapse can be seen on the ceiling layer (right half). Imprint of the support column is still visible in the centre.

b. Soft membrane vertically: In this orientation, the 2.5mm membrane is placed along the -x axis to minimise spillover, and along the -z axis to avoid layer collapse.

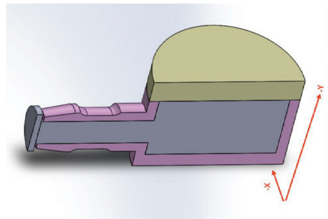


Figure 49: Placement of the sample on the print bed.

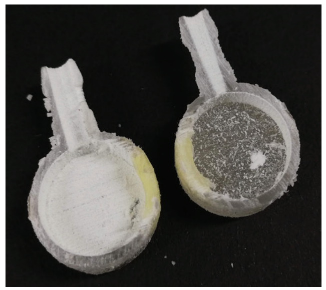


Figure 50: No imperfections or collapse can be observed on the soft membrane.

c. Soft membrane on the top: In this configuration the 1.5mm soft membrane is printed on top of the fluid. However it has been acknowledged already that Agilus30 will collapse when printed on fluid, two versions have been designed: with small support columns and with a single thick support column.

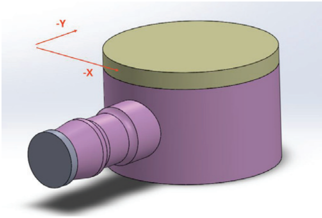


Figure 51: Placement of the sample on the print bed.

c.1 T*hick support colum*n: in this configuration a column of 2.5mm diameter is printed in the centre to avoid collapse of the soft membrane.

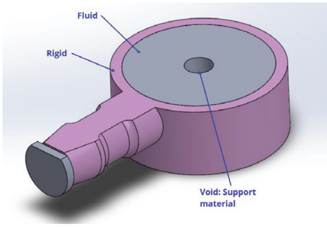


Figure 52: Placement of the sample on the print bed. Voids are printed as support material.

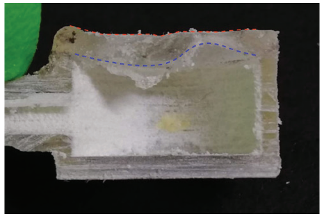


Figure 53: noticeable collapse of the membrane occurs. Even though the overhang is completely printed, layer thickness is inconsistent.

c.2 Thin support columns: in this configuration multiple columns of 0.5mm in diameter are printed to avoid collapse of the soft membrane.

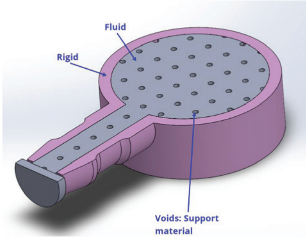


Figure 54: Placement of the sample on the print bed. Voids are printed as support material.

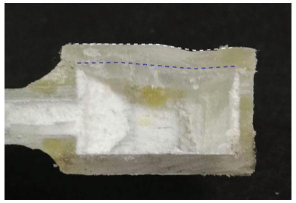


Figure 55: slight collapse of the membrane occurs, however much less than sample c.1. In addition, layer thickness is more consistent.

Layer adhesion

When 3D printing fluid volumes, these will be enclosed by solid structures, otherwise the fluid will drain out of it. However, the printing of these solid structures (plane parallel to the print bed) can be spilled over with fluid, and therefore decreasing the print quality (resin curing imperfections). This effect of improperly cured material is most noticeable along the -x axis, see figure 56.

Figure 56: improperly cured resin prominent along -y axis

a. Causes: The known variables that can cause this are the following:

- Roller: when passing over the printed surface, a wave can occur on the printed fluid surface, which can flow over non fluid areas, inhibiting the proper curing of these.
- Print-bed shake: When the print head reaches the end of its path, it will come to a stop and start back up again. This deceleration and acceleration causes a slight shake of the printer. Despite this, it is arguable whether it will affect the print quality, as no spilling was observed during these moments.
- Fans: Multiple fans are installed on the print-head, blowing air onto the print-bed.

b. Structural damage: The result of fluid spilling over the enclosing areas, will have a severe effect on the structural integrity of a print. The possible results are the following:

1. Wall holes: when rigid material is printed around fluid, there is a chance of this not properly curing. As a result, visible holes and sections can occur along walls (figure 57). As a result, it is recommended to not print walls smaller than 2mm next to fluid (McCurdy, 2016).

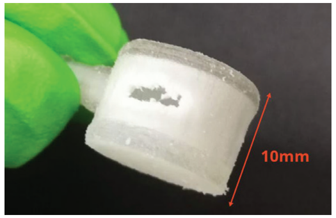


Figure 57: visible print failure

2. Layer adhesion: When fluid is spilled over rigid material, layer bonding will be affected. As a result, layers can separate under minimal loads.

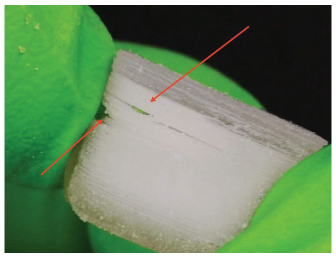


Figure 58: visible layer separation

3. Material transition bonding: As a result of fluid spillage between layers, the bondage between rigid and flexible material is especially weak, separating under minimal loads (if spillage occurred during printing).

4. Cracks: weak layer bonding will create surface cracks on soft material (agilus30) when being flexed, even well under its theoretical strain limit (figure 59).

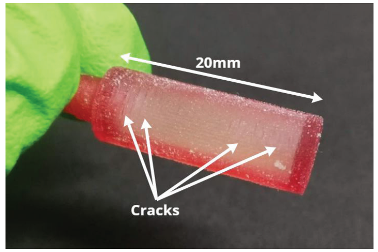


Figure 59: visible layer cracking

Slicing - From CAD model to voxel representation

During the design of these test samples, the polyjet printing matrix of 1200dpi was not considered. Therefore, with curves (especially small channels) in the printed samples, the layer slicing and material assignment might have played a role in the unsuccess of these. For future prints, this resolution needs to be taken into account when printing minimally sized features.

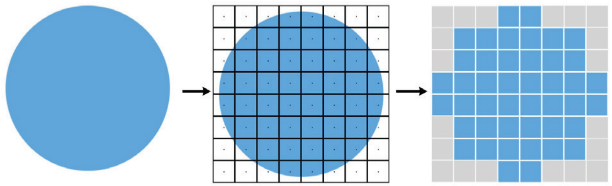


Figure 60: effect of resolution slicing on curves (Efficient Image Resizing With ImageMagick, n.d.)

Fluid micro channels

Existing research and concepts have been developed to print small channels to flow fluid through:

1. Biomedical purposes, semi-rigid vessels are printed (replicating blood vessels), however these are printed with support material, which is flushed out under pressure (*New Data Confirms Biomechanical Accuracy of J750 Digital Anatomy 3D Printed Vascular Models.*, 2021). In this case, a closed fluid circuit, or excessive details cannot be printed, as an opening in the loop needs to be present, and support needs to flush away.
2. 3D printed vascular simulation models, which print blood vessels in ABS. This printed structure is covered in a silicone layer, and once hardened, the ABS is dissolved and flushed out (*3D Printed Vascular Simulation Models Improve Training and Treatment*, 2020).

Previous printed samples with small fluid channels proved that the size and flow of fluid through these can differ from the expectations. (McCurdy, 2016), suggest that different solid features must be separated by at least 400 μm of liquid in X/Y or 200 μm in Z to remain distinct (figure 61).

Figure 61: Suggested separation between solid structures.

These sizes are effective when solid surfaces must be printed in proximity without merging together. However this does not emphasise the flow of fluid through these spaces. In addition, material hardness of the printed structure will affect the effective printability of fluid within. Therefore the research questions that need to be answered are the following:

1. *Size of channels along the -x, -y, and -z axis such that fluid can effectively flow through?*
2. *Effect of material hardness on channel size?*

For detailed features, the printer resolution 1200dpi might need to be taken into account. This resolution translates to:

- 1 printer dot=0.2117mm section.
- 1mm section = 4.72dots

a. Testing samples design

(McCurdy, 2016) suggests 0.4mm in order for solid features to be printed without merging, therefore this will be the starting point for the exploration. The channel sizes are multitudes of voxel resolutions, being:

- 0.42, 0.84, 1.26, 1.66, 2.08, 2.5 (size of section in mm)
- Separation between channels= 2.5mm
- Length of channel= 20mm

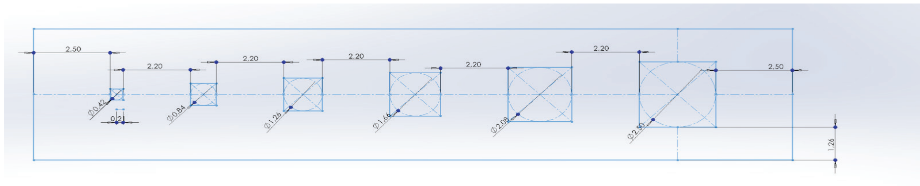


Figure 62: Sizing of channel section

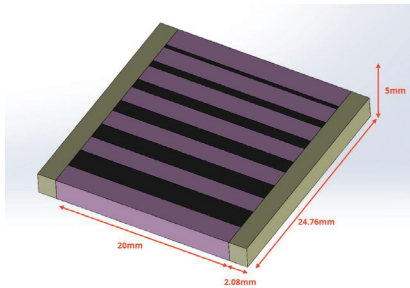


Figure 63: halve section of cad model

The sample core has the fluid channels along its length, and the caps, soft material is printed with the purpose of avoiding fluid leaking on the print bed, while still removable for testing.

With the different sizes mentioned above, the correct channel size for fluid flow can be extracted. However, as has been reported previously, the hardness of the printed material will affect the quality of the printed fluid section. Therefore, testing samples will not only observe the correct size, but also the changes necessary when printing with both rigid and flexible materials. Each channel test sample will be printed in 3 hardness:

- Shore (A) 30: super soft
- Shore (A) 60: medium-soft
- Shore (A) 90: hard, close to rigid

The last variable to take into account is the placement on the print bed. As has been found, the alignment will affect printability, therefore, prints will be placed along the x, y and z axis to observe differences. As a result, 9 samples are being printed (figure 64), of which 3 along each axis, with different hardness each.

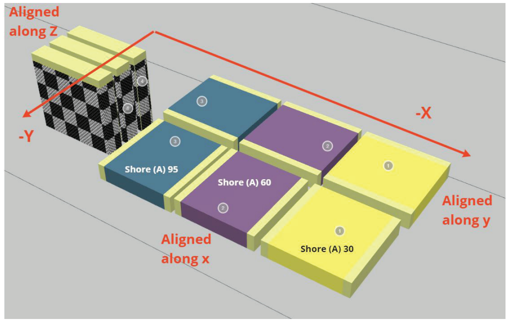


Figure 64: Placement of samples on the print bed

b. Sample tests analysis
The samples, are evaluated on:

- Printed quality: is the fluid channel sufficiently visible?
- Flow of fluid through the channel: can fluid flow through with little resistance?

In order to observe the printed channel in detail, the soft caps are cut off the sample (figure 65).

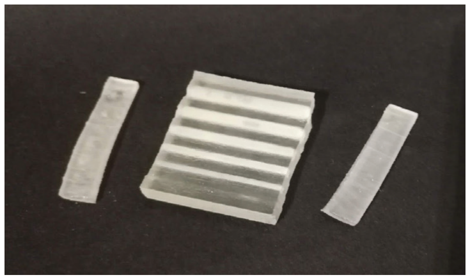


Figure 65: caps cut off

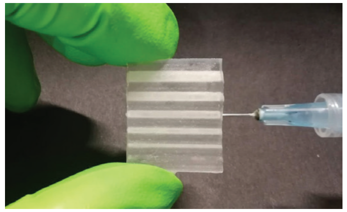


Figure 66: in order to observe the flow of fluid through the channel, water is injected through these.

		Channel size					
		0.42	0.82	1.26	1.66	2.08	2.5
Channel long -x	Shore 30	No	under high pressure	yes	yes	yes	yes
	Shore 60	No	yes	yes	yes	yes	yes
	Shore 95	No	yes	yes	yes	yes	yes
Channel long -y	Shore 30	No	yes	yes	yes	yes	yes
	Shore 60	No	yes	yes	yes	yes	yes
	Shore 95	No	yes	yes	yes	yes	yes
Channel long -z	Shore 30	under high pressure	yes	yes	yes	yes	yes
	Shore 60	under high pressure	yes	yes	yes	yes	yes
	Shore 95	No	yes	yes	yes	yes	yes

Figure 67: results of flowability through the printed channels. Each sample has been observed on the flow of fluid through the channels, and the quality of itself.

4.2.5 Design guidelines and recommendations

In order to achieve successfully printed parts it is first of all recommended to adhere to *“Printable hydraulics: A method for fabricating robots by 3D co-printing solids and liquids”* (McCurdy, 2016) given design guidelines as a rule of thumb. However, printing with fluid can still be problematic, therefore the most important recommendations and suggestions to achieve successful fluidic prints will be:

1. **Expect inconsistencies**

As a result of the different variables such as the printhead roller, fans, and the fluid itself, quality inconsistencies will occur. Therefore, during the designing of parts, large margins of structures next to the fluid are recommended if possible to improve the structural integrity (wall thickness next to fluid >2.5mm). In addition, this factor must be taken into account, as some parts can have defects, thus spares are recommended.

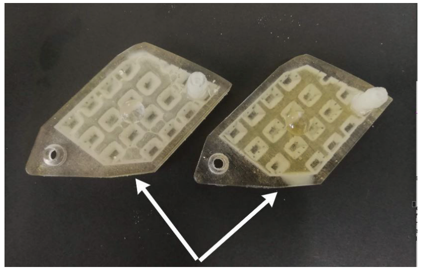


Figure 68: two identically printed parts (printed in the same batch), showing inconsistent irregularities.

2. Prioritise features

The print alignment of the fluid relative to the print bed will play a role in the structural integrity, as features next to, and on top of fluid will be of a lesser printed quality (resin curing imperfection, layer adhesion and sagging). Therefore it is recommended to print first flexible layers (more susceptible to resin curing imperfections and sagging), then fluid, and finally rigid layers (less susceptible to imperfections and sagging).

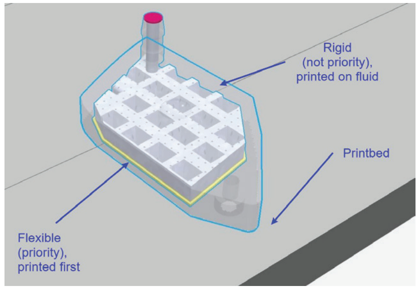


Figure 69: placement of fluidic mechanism on print bed

Parts with flexible and rigid layers must pay attention to the transition layer of these, as they are highly susceptible to lower adhesion (due to fluid spillover). It is recommended to design gradual material transitions.

3. Use of supports structures

The most valuable tool for printing with fluid is the use of support material, as this can save parts from printing defects without significant changes in the part design.

With support material membranes and columns can be included into the fluid volume [(McCurdy, 2016)]() (figure 70 and 71). Columns will avoid sagging (when printing flexible material a high number of columns is recommended), and membrane will highly reduce resin curing imperfections, and slightly layer adhesion due to spillovers when vertical.

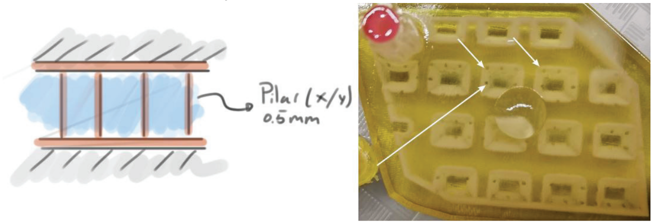


Figure 70: support columns

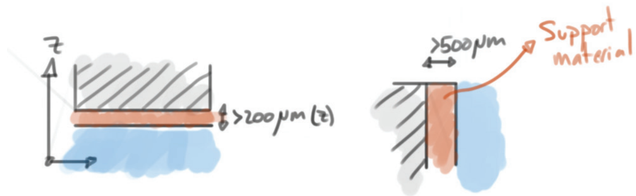


Figure 71: support membrane

In addition, support structure 'walls' can be placed inside large fluid volumes to reduce the -x length of fluid (figure 72), therefore lowering the fluid wave produced. Parts printed with this method demonstrated a significant improvement in terms of layer adhesion and structural integrity. In addition, through the increase in wall thickness at the end of long fluid areas (-y), large fluid areas can be printed.

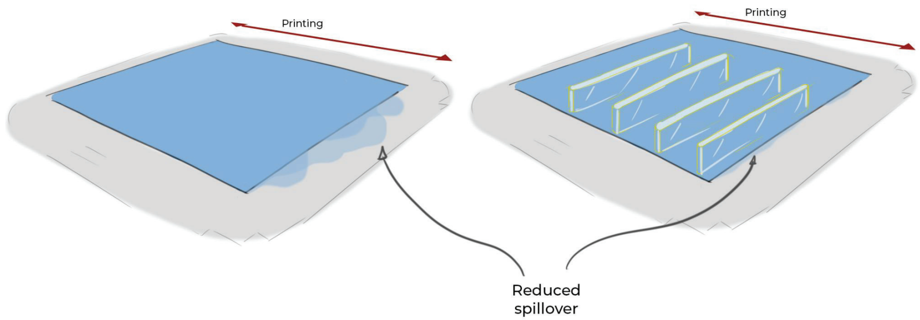


Figure 72: support walls

4. **Fluidic channels**

0.82mm in the channel section (square profile voxel integer) is the minimum a fluid channel can be printed for fluid to flow through. However, inconsistencies are present in the amount of fluid pressure needed for flowing. Therefore, from these results it is recommended to print cross sections of at least 1.26mm.

Figure 73: size of printed sample, with a needle inserted in 0.82mm channel for scale

Differences in print quality are observed according to the print alignment, visible imperfections observed in the samples aligned with the -z axis. Imperfections are more significant in those samples printed along the -y axis (figure 74). Thus it is recommended to print fluid channels along the -x and -z axis. If channels must be printed along -y, fluid spilling must be taken into account.

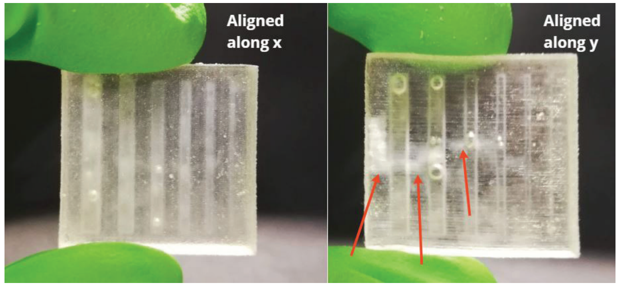


Figure 74: Channel imperfections

See appendix 7(Fluid print preparation), for the CAD preparation of a fluidic mechanism for a successful print result.

4.2.6 Future research

This research provides valuable insights on how fluid will affect 3D printed parts, however there is still room for exploration in order to successfully integrate this technology into large scaled fluid printed parts.

The first objective can be defining quantitative features such as fluid overhang angles (with different materials), wall thickness relative to fluid area, and lower the print inconsistencies between printed parts.

The next step in development can be the integration of this data into the printer preparation software (Grabcad e.g.), predicting not only where a print can fail due to its geometry, fluid geometry and support structures, but also taking into account elements from the printer such as the fans and roller. The research package could integrate gradual material transitions to improve layer adhesion where needed.

The last development step would be finding a way to scale up this technology, and become more accessible to the everyday prototyping processes.

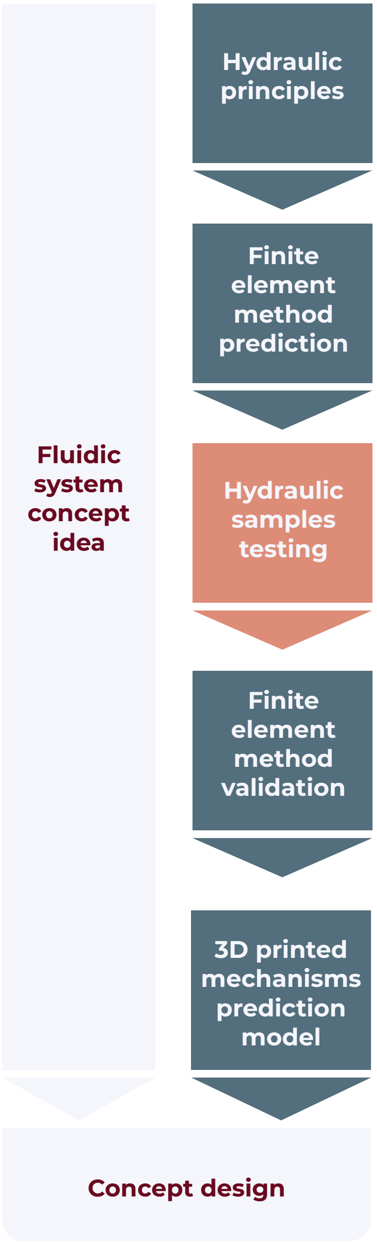
4.3 3D printed fluid mechanisms analysis

The final design objective is to create surface textures which can dynamically change with the use of 3D printed soft mechanisms (chapter 7, Morphing textures, idea to concept). Therefore, in order to achieve this goal it is important to acknowledge different hydraulic principles and how changes in the design will alter the intended outcome. In addition, a finite element model is set up for polyjet printed parts in order to predict approximate mechanism behaviour and avoid critical material stresses. The two main variables that play a role in how such mechanisms are constructed are:

- **Fluid properties;** hydraulic systems operate through transmitting force via an incompressible fluid. Therefore, in order to dynamically transform a surface texture, fluid pressure (negative or positive) will be applied to displace or transform the printed mechanism.
- **3D printing:** in this project the technology of polyjet printing is used, however, such technology does come with strengths and weaknesses. Different variables need to be taken into account in order to manufacture working texture mechanisms, such as printability, material selection (and their different mechanical properties), and the influence of fluid during the printing process.

In chapter 4.2, the printing design guidelines are researched in regards to adopting liquid as an printable material. However, during this process the hands-on experience demonstrated that the expected outcome of a printed mechanism can differ vastly from the actual tested result. With time being a limited resource in this research project, approximate predictions of the mechanism behaviour will allow for better working results, and avoid unnecessary iterations. In addition, experience regarding printed material properties will be gathered. The process followed in order to achieve this experience can be seen in figure 75. Complete process in appendix 8.
It is important to highlight that the objective of this process is not estimating with 100% accuracy the deformation of a mechanism. Instead, obtaining a close approximation will be sufficient as such insight can already present whether a mechanism will deform sufficiently and hold up to the applied stresses.

Figure 75: fluid mechanisms analysis process



4.3.1 Polyjet printing material mechanical properties

In this research study only 2 materials are used, one flexible (Agilus30), and one rigid (veroclear). The two materials work together in order to deform under hydraulic pressure in a desired direction. In this interaction, veroclear will be considered as a fully rigid material which will not deform under any load (this assumption is taken, as the applied loads are not sufficient to involve measurable deformation), meanwhile agilus30 will indeed deform. Therefore the objective is to discover the mechanical properties of this material, in order to design the right dimensions for such a mechanism.

In order to predict the mechanical behaviour of Agilus30, there are different elements which need to be known:

- *Tensile strength*: determines the maximum stress that a mechanism will be able to withhold.
- *Yield strength*: how much stress can be applied before the mechanism will deform permanently.
- *Elastic modulus*: how much the mechanism will deform (strain) under a specific load (stress).

Stratasys data sheet

The safety data sheet provided by Stratasys specifies the following regarding Agilus30 (Stratasys, n.d.):
- Tensile strength: 2.4-3.1MPa
- Shore hardness: 30-35 (scale A)
- Elongation at break: 220%-270%

With these three variables the required elastic modulus can be calculated as the failure stress and stress are known, through:

Young's modulus: $E = \varepsilon/\sigma$

However, the value resulting from this would assume that Agilus30 stress strain is linear up until failure, which will give an incorrect assumption. Therefore it is important to acknowledge the stress/strain of this material in the elastic region.

Tensile testing

"Material characterization of additively manufacturing elastomers at different strain rates and build orientations" (Abayazid & Ghajari, 2020), conduct a tensile testing study in which Agilus30 is printed along the different axis and tested until failure.

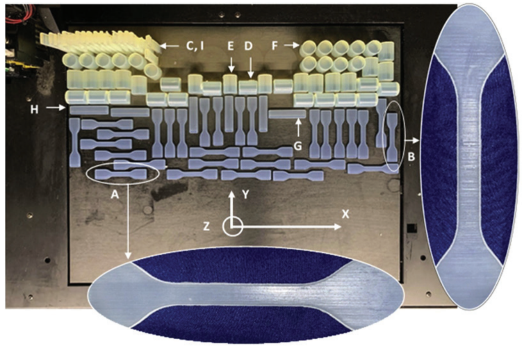


Figure 76: (Abayazid & Ghajari, 2020), test samples are printed along -X, -Y, and -Z. One batch printed at 0.003m/s, and a second batch printed at 0.300m/s.

All printed samples conduct a stress-strain study until failure. With this data gathered the following relevant mechanical properties are presented:

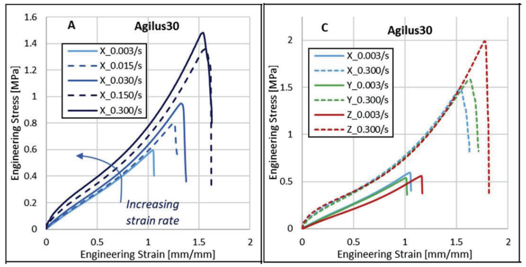


Figure 77: (Abayazid & Ghajari, 2020), tensile test bench results of Agilus30 along XYZ direction.

The results of this test are presented as engineering stress and strain (rather than true stress-strain), meaning that the changing area with time is not considered. However, considering that the objective is to obtain an approximate prediction of the deformation, this will not have significant effects in such prediction. The data from the fast printing speed is considered, as this speed is closest to that one used when printing the different samples.

The prediction of a mechanism will be performed with the Solidworks Finite Elements program, and the following values will be considered:

- Strain (-x,-y): 1.5
- Strain (-z): 1.785
- Stress (-x, -y): 1.5N/mm2
- Stress (-z): 2N/mm2
- Yield strength(-x, -y): 1.5N/mm2
- Yield strength (-z): 2N/mm2

From these variables the elastic modulus within the elastic region can be extracted.

Young's modulus: $E = \varepsilon/\sigma$

- Elastic modulus (-x, -y): 1N/mm2
- Elastic modulus (-z): 0.87N/mm2

With these different variables, Agilus30 can be recreated within the finite element simulation in order to have an approximate behaviour prediction. However, it is important to take into account the printability of such a mechanism, as different orientations will have different results in terms of quality (chapter 4.2.5, fluid printing design guidelines), and how this is simulated with regards to this print orientation.

4.3.2 Hydraulic principles

The concept design objective established is to create dynamic surface textures. However, before the design process of this objective is started, an initial exploration is done to observe the behaviour of a printed fluidic mechanism. Therefore, at this stage the exact mechanisms to be used in the final concept are yet unknown. However, it can be assumed that changes in the surface must occur.

A property of a 3D printed hydraulic single-part mechanism is the infeasibility of having sliding bodies (such as a hydraulic piston), as printing tolerances, and surface finish will not allow for such. As a result, the fluidic mechanism will have to deform its shape under internal pressure. In order to observe the behaviour three starting tests are designed which, in addition, can be utilised to calibrate the finite element simulation:

1. Radial expansion: the objective is to observe how fluid pressure will deform the flexible material Agilus30.

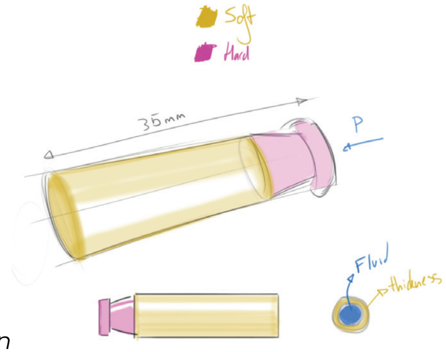


Figure 78: radial expansion

2. Dome inflation: the objective of this principle is to observe how rigid material can be placed strategically in a mechanism in order to specifically deform Agilus30 into a certain direction.

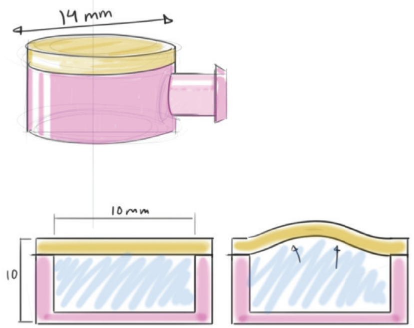


Figure 79: dome inflation

3. Displacement with minimal mechanical stress: in the previous two tests, the samples will deform through stretching the flexible material. As a result, a high surface tearing probability is present. Therefore, in this third principle, it is observed how changes in the flexible membrane can result in a more durable and larger displacing mechanism.

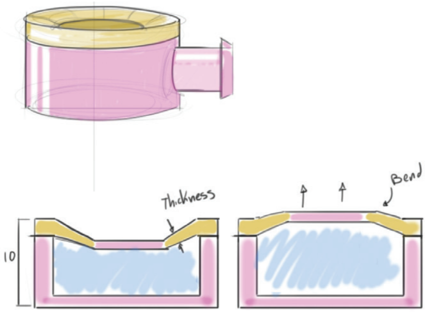


Figure 80: bending surfaces

In order to test these principles, a total of 9 different samples are printed (*Figure 81*).

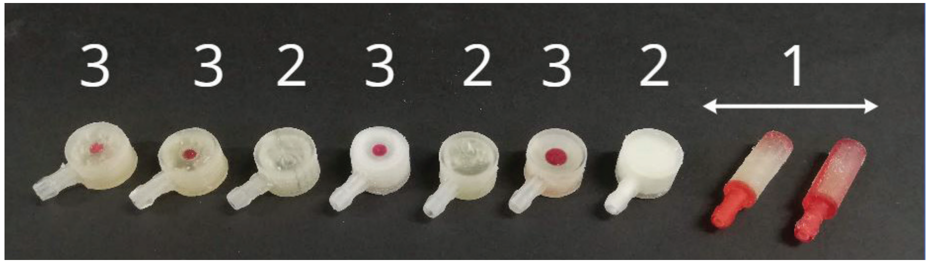


Figure 81: printed samples and their respective principles. All circular samples have a diameter of 15mm.

The objective of printing these samples is to gather data on how these do deform, and compare this to the finite element predictions. This model will be used in later and more complex mechanisms to achieve the desired deformations. In addition, these tests provide insights on how to 3D print fully functioning fluidic mechanisms and how these should be designed in order to handle hydraulic forces.

These three tests are relevant to development of the project concept (chapter 7, Morphing textures, idea to concept). However, when other inputs or outputs are selected, testing of more principles could be necessary.

Principles testing setup

In order to evaluate the behaviour of the 3D printed mechanisms, there are two variables which need to be recorded:

1. Record deformation: each sample is loaded under hydraulic pressure, by which it will deform. Therefore, an overhanging camera is placed such that this deformation can be recorded (figure 82). This method of data gathering can result in minor error due to inaccurate measuring (~0.25mm), however this is acknowledged, as the objective is to roughly predict the mechanism behaviour.

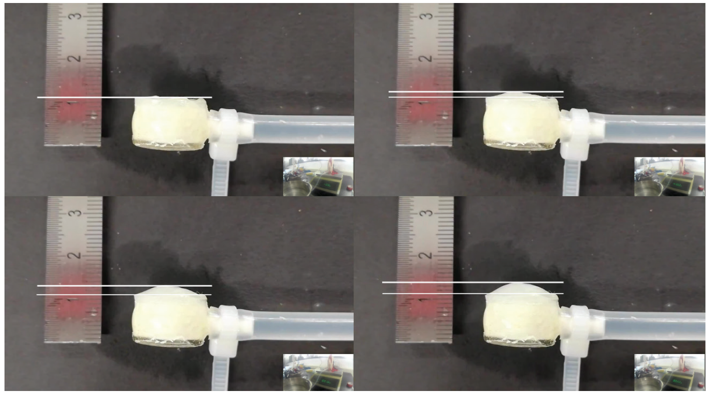


Figure 82: measuring sample displacement.

2. Measure input force: The load at which the deformation displacement occurs is measured (load due to friction from the syringe piston is subtracted from this value). To achieve this, a syringe (acting as a pump) is placed on a scale, and the loading force is recorded simultaneously along the sample deformation. Through measuring the syringe piston, the force applied onto the flexible membrane can be measured. For this, it is acknowledged that pressure is constant within the hydraulic system.

Figure 83: recording of hydraulic input pressure.

4.3.3 Finite element predicting mechanism behaviour

The deformation of each sample is recorded, along with the input force and respective hydraulic pressure, for different time stamps of the deformation process (figure 84).

Sample 1.1 color cap			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
410	250	0.01484848485	1.3
600	440	0.02613333333	2
900	740	0.04395151515	2.8

Figure 84: sample displacement and hydraulic pressure

With this data gathered, materials are assigned to the CAD model, with the mechanical properties defined previously while considering the print bed alignment (-x/y/z).

In this finite element simulation, large displacements are activated to minimise computing errors. As a result the predicted behaviour of the mechanism provides insights of how the mechanism will deform, with an experienced 10-15% deviation (deviation can be caused due to measuring inaccuracy, printing irregularities and simulation deviation).

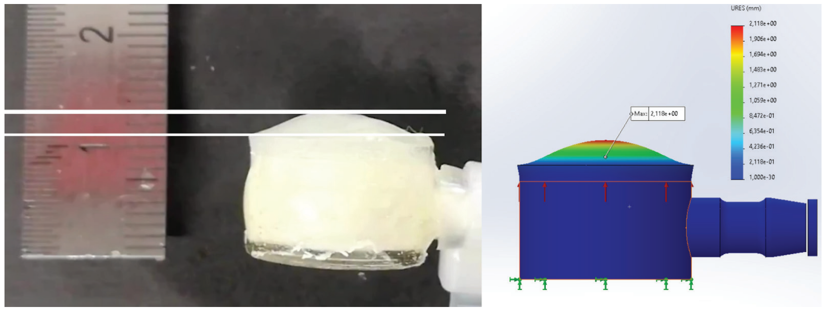


Figure 85: expected deformation=2.11mm. Measured deformation 2mm. Under a pressure of 0.026N/mm2.

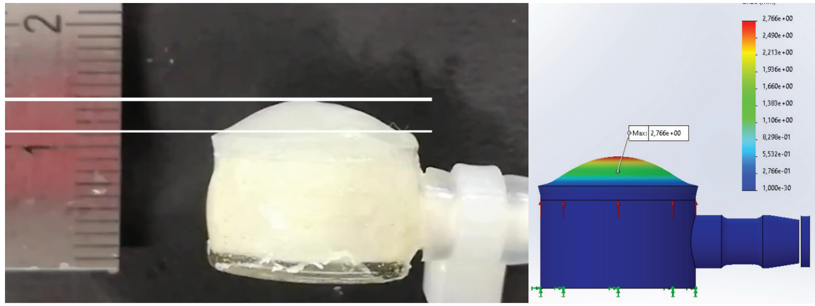


Figure 86: expected deformation=2.76mm. Measured deformation 2.8mm. Under a pressure of 0.043N/mm2.

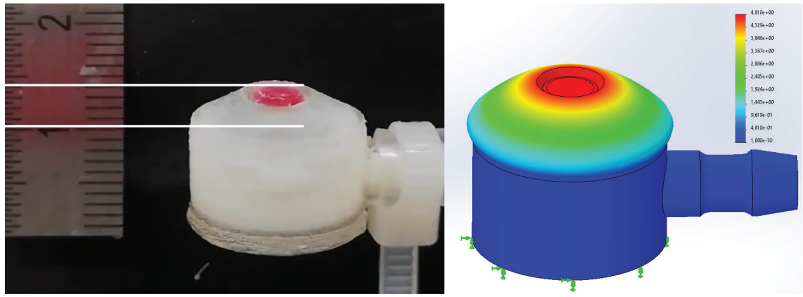


Figure 87: expected deformation=4.8mm. Measured deformation 4mm. Under a pressure of 0.028N/mm2.

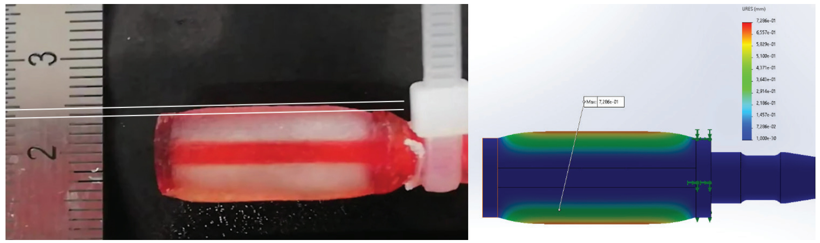


Figure 88: expected deformation=0.72mm. Measured deformation 0.8mm. Under a pressure of 0.079N/mm2.

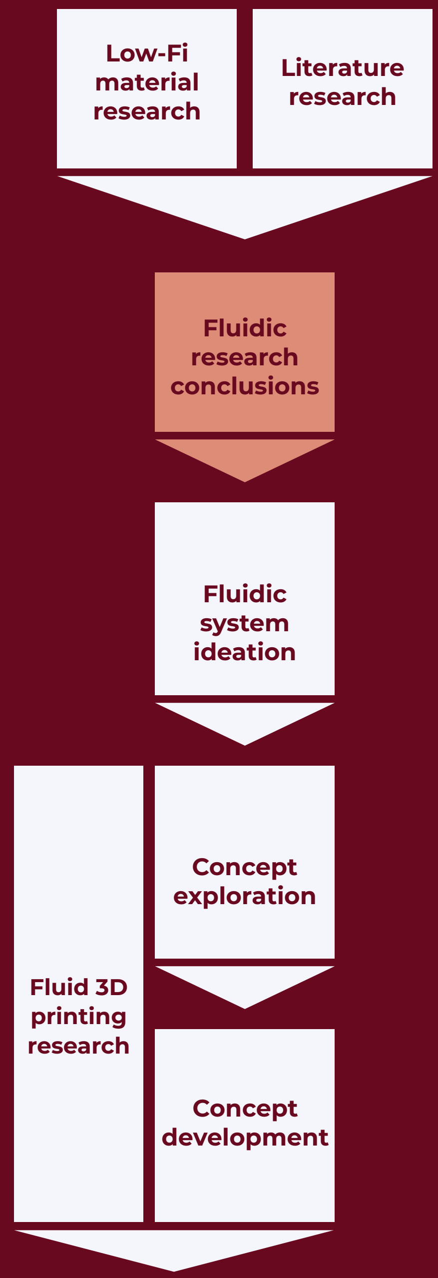
4.3.4 3D printed fluid mechanisms conclusions

From the process presented before, insight can be gathered regarding variables which will affect how well a 3D printed fluid mechanism will work. The different elements to be taken into account are directly attributed to the printability of the mechanism itself. As a result, the printing guidelines (chapter 4.2.5, fluid printing design guidelines) will affect the performance of the mechanism itself. The most important takeaways are:

1. **Size**: polyjet printing technology limits what can be achieved in terms of scale. As a result, flexible membranes are not recommended to be thinner than 1 mm to avoid mechanical weakness.
2. **Durability**: it is important to consider that the printed flexible material Agulis30, has poor cyclic fatigue resistance.
3. **Layer adhesion**: when 3D printing with fluid, this fluid will be washed in between layers. As a result, structural strength will be highly affected when approaching the minimum printable sized mechanisms. The use of support structures (chapter 4.2.5, design recommendations) is critical to avoid a reduction in mechanical performance.

With the use of finite element simulation approximate predictions can be performed to design the adequate mechanism deformation. However in this process, it is important to consider the variables mentioned above, as changes in one, will affect the others, therefore these must be taken into consideration as a whole.

5. Fluidic system research conclusion



The first objective of this project is to discover what are the design opportunities of 3D printing fluidic systems, with the ambition of creating new forms of product interaction. In chapter 4.1 (tinkering research), a low fidelity material exploration is performed with the aim of discovering what are the structural characteristics defining 3D fluidic systems. Furthermore, in chapter 3 (literature research), innovations and developments are researched sharing similar structural properties to those found in the tinkering research, to observe how fluidic systems could be designed and presented as.

From these findings, a fluidic system design structure model is created, with the intent of constructing a systematic design guide which provides insights on how a fluidic system can be constructed, in order to achieve a user-product interaction, through fluid displacement. In other words, this model establishes in steps, the design structure that an interactive fluid system will need to comply with to achieve a potential application form.

This system is constructed such that in future scenarios, designers can methodically decide which user-product interaction is most valuable for them, and the model will expose the different opportunities that can be achieved with a fluidic system for such intent. In this chapter, the different levels of this model (figure 89) are defined and how these emerge from the material and literature research. However, it is important to clarify that this is not a definitive model, instead, it is a base structure from which future potential opportunities can be added or updated when advances in fluidic systems occur.

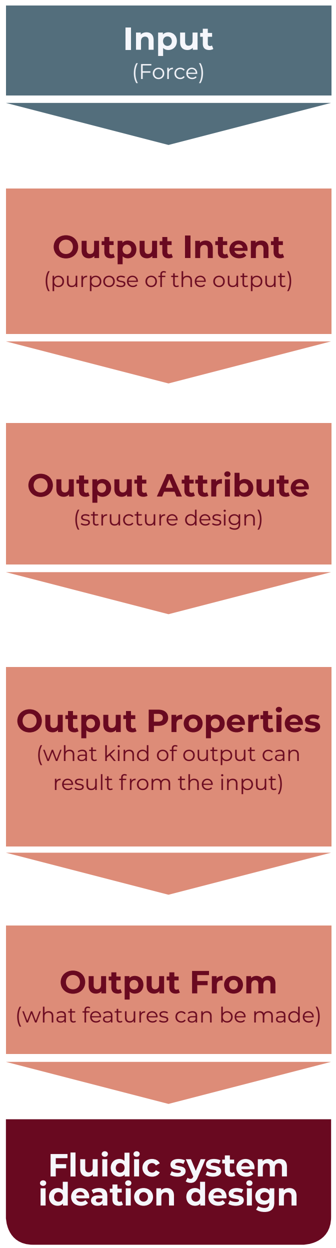


Figure 89: Fluidic system design structure

5.1 Defining interaction input

The essence of a fluidic system occurs when fluid is displaced through channels within a structure. However, under no action, this fluid is at rest and will need a starting trigger in order to displace the internal fluid within. Therefore, the first step in an interactive fluidic system is the input.

The input is the specific external action that provides a pressure to the hydraulic system. Therefore, with sufficient pressure, fluid can be displaced (when overcoming opposing air pressure or material resistance when deforming a shape). As a result, force is essential for this to occur, however, how this force is originated will define the first interaction with the fluid system. This input force can be achieved (for now) through two scientific principles, fluid incompressibility and fluid expandability:

1. In normal conditions, fluids cannot be significantly compressed. Therefore, when the shape surrounding the fluid is reformed, the fluid will be displaced towards the sections with the least opposing resistance. Thus, the external inputs based on force vectors that could be designed as the triggers are:

    a. **Applied surface pressure**: when an external force, either manual or mechanical is targeted at a specific surface area.
    b. **Structure deformation**: when a structure is bent, twisted or simply deformed, internal deformations will occur, which, when designed correctly can trigger fluid displacement.
    c. **Acceleration and gravity**: fluid has a mass, which is susceptible to acceleration and deceleration.
    d. **Magnetism**: with ferromagnetic fluid, a repelling or attracting force can be exerted onto the fluid, therefore causing a displacement in fluid.
    e. **Sound**: sound waves can create vibrations on the structure. If the fluidic system is sensitive enough, the vibrations could displace the fluid (*Sound Waves to Move and Filter Objects*, 2019).

2. Through fluid expandability:

    a. **Temperature**: when a fluid temperature is raised to a boiling point, it will expand, and as a result, creating an increase in hydraulic pressure. This increase in temperature could scientifically be achieved through radiation, convection or conduction. Furthermore, when fluid temperature is decreased, this can reach a solid state in which it will expand.

These mentioned force based elements could theoretically function as the fluidic system triggers, when the fluid is fully enclosed. However it is important to mention that when such a system is not fully enclosed (fluid can directly be accessed) a new category can be added regarding externally applied hydraulic pressure, which can digitally be motorised .

These elements define possible triggers, however, the design structure in which these will function can differ from element to element.

5.2 Defining fluidic system output

When an input occurs on the fluidic system, a resulting output will occur. This designed interaction between an input and output is what characterises a fluidic system. Therefore the following step in constructing a fluidic structure to determine the desired outcome. This process is split into layers, in which each new layer relies on the structure and adds specificity to the intended output.

Output intent

The first decisive step in constructing a fluidic output is the purpose of the output itself. From the material tinkering research (chapter 4.1), two feasible design paths have been discovered:

1. **Visual output:** when the purpose of the output is a change in external visual appearance.
2. **Physical output:** when the purpose of the output lies in actions resulting from the displacement of fluid, without specific intent of visual appearance changes.

Output attribute

The second layer or step in designing an interactive fluidic system is the output attribute, which defines how the fluidic system will need to be structurally designed. Departing from the intent, different purposes will require different fluid channelling structures. Attributes can be the following:

1. **Hydraulic mechanism:** the structure will be designed to transform the increase in fluid pressure into a structural deformation of the object.
2. **Liquid circulatory system:** the structure will need to be designed to circulate fluid in a specific path to achieve a desired displacement.
3. **Reversible and irreversible:** the structure will be designed such that fluid can revert its displacement or not.

The output attribute therefore defines the basic working principle of an output, This choice has a direct influence on how the system shall be structurally defined.

Output properties

With the output attribute chosen, a design direction is already established. Therefore, this level will define in more depth what output can result from that attribute. These properties have been drawn from the characteristics in the different working samples of the material tinkering research (chapter 4.1):

- **From a hydraulic mechanism**: through an increase in fluid pressure, a transformation in structure shape can be achieved, a transfer in force (result of fluid incompressibility), and an increase in structural stiffness.
- **From a circulatory system:** through the circulation of fluid, the internal (fluid) mass can be displaced, a change in temperature can be achieved through warm or cold fluid, and a change in magnetic field can be achieved when circulating ferromagnetic fluid.
- **From a visual intent**: a surface appearance can be altered, and the reversibility of this can be controlled.

These different output properties define what can be achieved with a fluidic system (up to this project). Therefore, through researching innovations, developments and studies within these fields (chapter 3, literature research), it can be discovered how a fluid system could be presented, both as output form, as well as interactions that can be designed from.

Output forms

The output properties dictate what kind of output can result from an input, and create an intended interaction. Consequently, acknowledging different design opportunities for 3D printed fluidics (chapter 3.2, literature research, classification of findings), an output form of these can be deducted, creating a final layer in the construction of a fluidic system. The output form will determine how the output of the fluidic system can be presented as the result of the chosen structure.

The choice of basing output forms from existing developments is due to the novelty of the concept itself, and therefore difficult to generate new opportunities from scratch. However, with this starting structure and expecting further expansion, new items can be added to this model (figure 90).

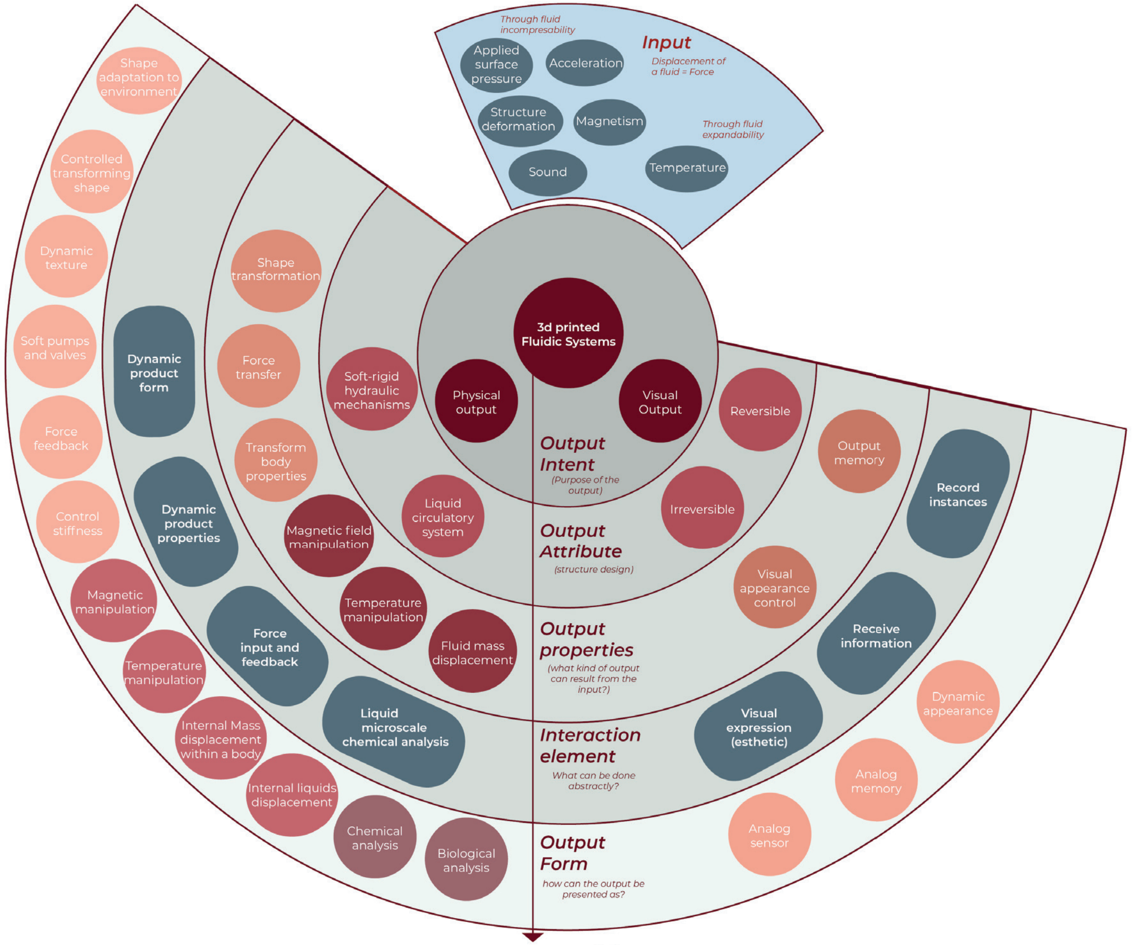
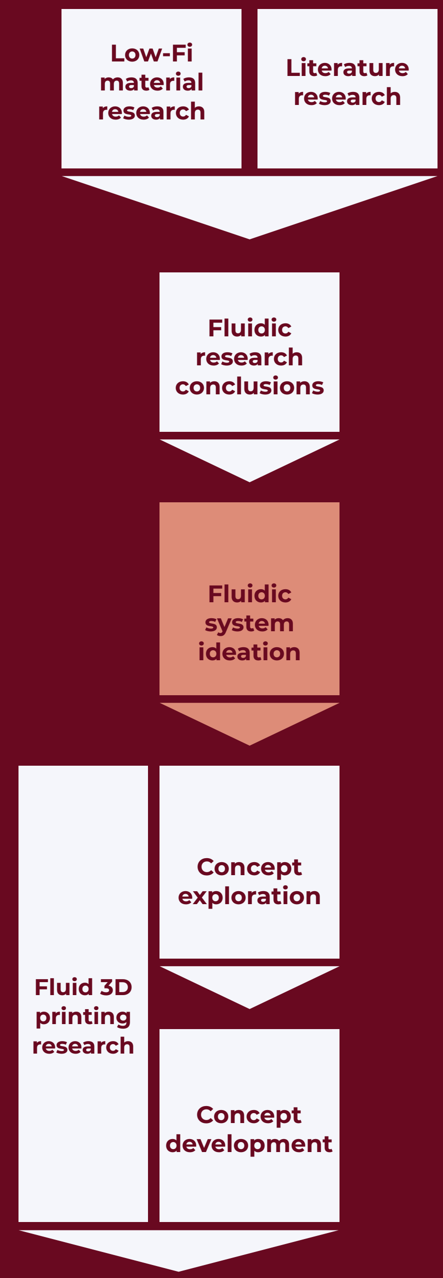


Figure 90: fluidic systems structure model

6. Fluidic systems opportunities



The intent of this chapter is to generate initial product use ideas with a fluidic system in an abstract form, which can later be translated into a concept design.

The structure for fluidic systems has been elaborated in the previous chapters, in which the different interaction layers which are achievable between a certain input and the desired output are constructed. Through different combinations of these, the results will be different, thus, fluidic systems can be shaped into different forms. However, this last layer of the fluidic system model (output form) (chapter 5, fluidic system research conclusion) defines how the output can be presented as for a use, without specifying further. Through closing the model on such an abstract level, it opens creative opportunities on what ideas, concepts and products these could be applied onto.

It is important to establish that in this chapter not all possible ideas with fluidic systems will be generated, instead, a specific ideation tool for these systems is created, which can be used and elaborated in further projects. Then, a number of ideas are generated, and the one with the highest relevance for showcasing the opportunities of fluidic 3D printing is selected. The chosen idea will be developed into a demonstrator and product concept in chapter 7 and 8.

6.1 Process

The goal of this chapter is to generate representative ideas showcasing the opportunities of 3D printing fluidic systems. Considering the novel concept of this, the ideation approach should emphasise the strengths and values of such systems into the ideation platform. Therefore, the process followed in order to achieve this, is the following

1. Develop a product **idea generating tool**: An idea generating method is created in order to achieve innovative uses with fluidics. This tool departs directly from the fluidic design structure model (chapter 5, fluidic system research conclusion).

2. **Ideation**: With the generating tool developed, a number of ideas are produced. Each idea is worked up to an equal level through providing a description, a visual and the innovation value that it creates. A total of 15 ideas are created, in order to meet the project time constraints.

3. Develop relevance **criteria**: The objective is to select the idea with most value to be developed further into a product concept. Therefore, a list of criteria is made, which establishes the value of each idea regarding their desirability, viability and feasibility within the project resources. This step is carried out after the ideation, with the intent of not hindering the creative ideation process.

4. **Idea selection**: With the ideas generated, and the relevance criteria set, the idea with most value is selected. From this process, three ideas tied in terms of result. Therefore, an argument choice is made comparing these three ideas and their innovation relevance.

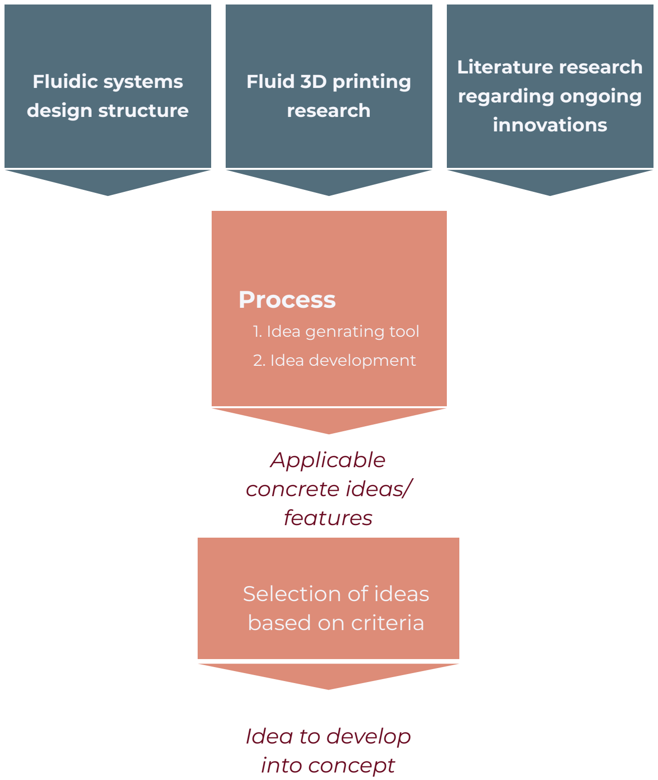


Figure 91: Fluidic systems design opportunities process

6.2 Approach idea generation

3D printed fluidic systems is a novel concept, and the objective of this project is demonstrating the potential of such technology. However, this approach is not market driven, meaning that there is no specific necessity for it. Instead, this is an innovation push approach, in which a new technology is developed which might offer the potential of gaining an entire new product or even creating a new product field. As a result, ideas cannot be traced from a problem, but instead need to be driven by technology capabilities.

The goal is to generate innovative ideas with the capabilities of fluidic 3D printing. In order to achieve this, a tool is created which can produce these ideas departing from the fluidic systems structure model. This tool departs from the structure model, and therefore is dependent on it, therefore, when new research and developments occur, these will reflect onto the ideation opportunities.

In the previous chapters, the function structure of a fluidic system has been established and broken down into different elements, categories, and layers, diverging into small and manageable bits. However, in such a condition it is difficult to facilitate the creative process to generate ideas with this concept. Therefore, the goal is to create clusters from this diversion, and converge the different elements into abstract ideas (Daalhuizen, 2014). Through such an approach, abstract ideas can be easily translated into more concrete ideas. In order to do this, a forced fit brainstorm is carried out (Heijne & Meer, 2019).

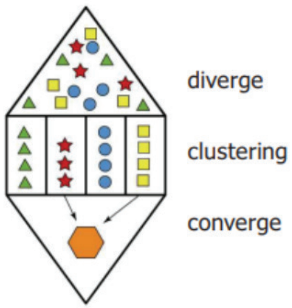


Figure 92: ideation process, "Delft design guide" (Daalhuizen, 2014)

The fluidic system idea generating tool adopts the technology elements of the design structure model as its building blocks. Each layer of this model represents how a fluidic system must be designed, and therefore dictate the boundaries of such a system. However, this does not mean that only one element can be used for each layer, instead, multiple of these can be combined to make and facilitate ideas.

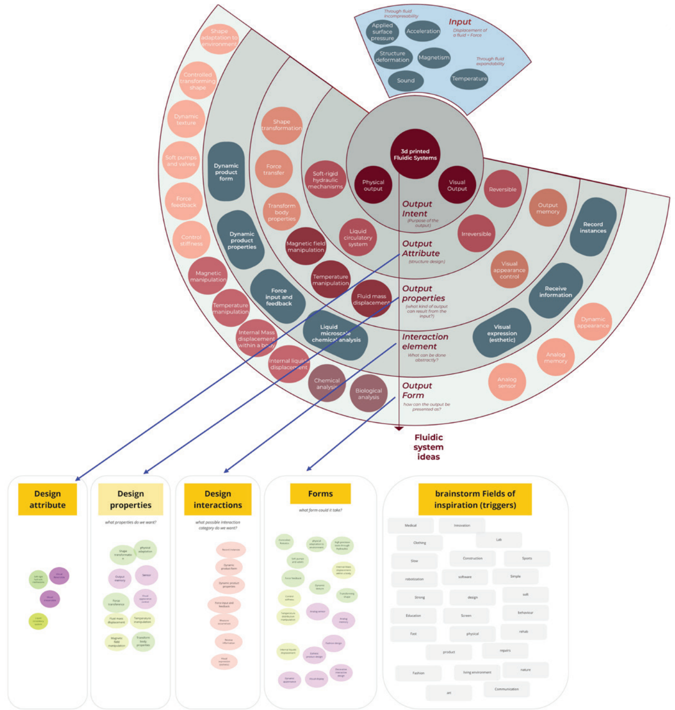


Figure 93: elements from fluidic system structure model to ideation tool

This tool is constructed through arranging the layers of the design structure model into groups, with their respective elements within (figure 93). Five groups make up the ideation tool, each determining the outcome of the resulting idea:

- Design attribute: determining the design structure and the purpose of the idea.
- Design properties: determining the desired properties for the resulting idea.
- Design interactions: determining the interaction category desired from the idea.
- Forms: determining the feature or shape the idea could take within a product.
- Triggers: facilitate the ideation process from clusters, into abstract ideas (appendix FIXE, Ideation triggers).

The method for generating abstract ideas is through placing different elements from the fluidic structure model into a cluster line (see figure 94).

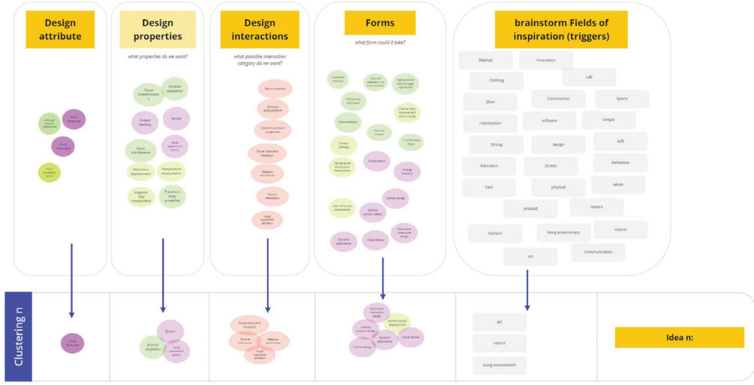


Figure 94: clustering of fluid system elements

Within each group, one or multiple of the elements are dragged onto the cluster line, and when this has elements from each constructing group, an abstract idea can result (Appendix 11, Fluid systems generated ideas).

It is important to mention that this tool will not create ideas by itself, instead, it facilitates the ideation process for an innovation push strategy. However, ideas can be generated with any cluster, therefore, recommending the use of external participants to fixation. *(For this project, three participants conducted the use of this method: one IPD student, one DFI student, and one AE student. All students of TUDelft).*

This method can be replicated in future projects. However, improvements for future versions are:

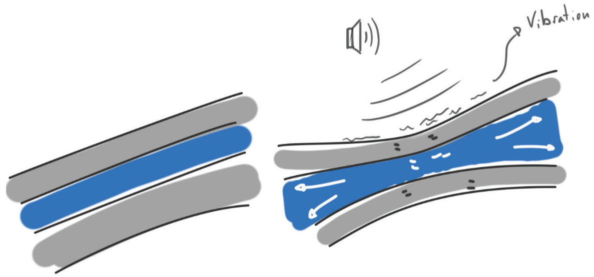
- Inclusion of an **input interaction** from the user. This could be merged with the interaction element for a richer product interaction result.
- **Market opportunities and needs** could be taken into account for desirable ideas.
- This tool focuses on 3D polyjet printing, therefore **new manufacturing methods** might add a new layer in opportunities.
- An opportunity could be adding extra **external instruments** such as electronics, to further enhance these elements.
- The listed **triggers** could be expanded further, and even be focussed on directing towards a certain design
- The tool is followed from left to right, however it could be interesting to alter this path, skipping or **rearranging groups**, which might result in different clusters.

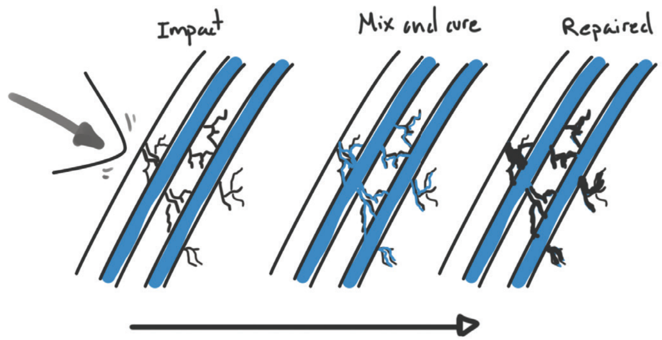
6.3 Ideas

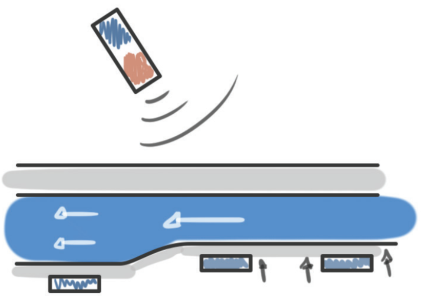
Through the use of the idea generating tool, different abstract ideas are created from clusters. One of these ideas will be developed into a concept which will showcase the value of 3D printing fluidic systems. Therefore the generated abstract ideas are expanded up to an equal level regarding its description, innovation value that this will bring in the specific field, and a visual representation (appendix 11, fluid system generated ideas).

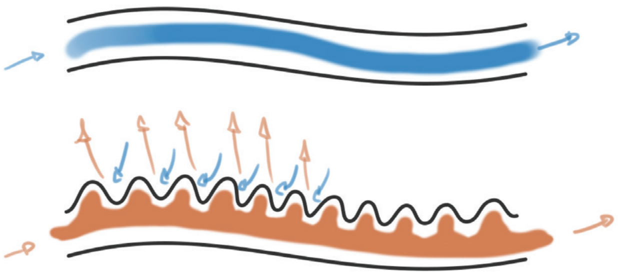
From this process, a total of 15 ideas are created,which are balanced between the different output attributes; soft rigid mechanisms, liquid circulatory system and visually reversible systems. These ideas are representative of what can be achieved through this method, however, they do not represent all the obtainable opportunities possible with fluidics. Thus, with future research, further ideas and concepts can be explored.

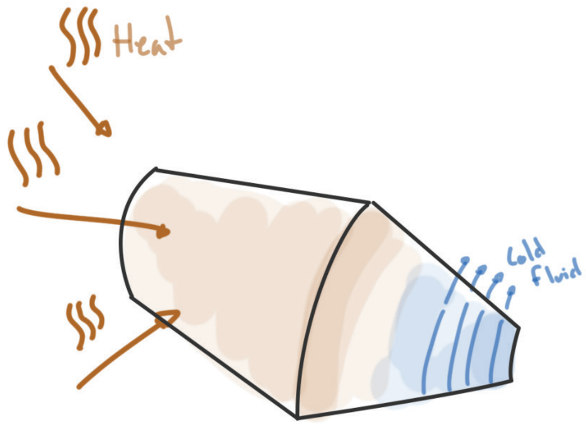
All the created ideas are in Appendix 11, “Fluid system generated ideas”











6.4 Criteria and idea selection

Through the use of the idea generating tool, ideas have been created, with all different purposes and respective innovation value. In order to fit within this project timeframe, one of the previously listed ideas is selected through a scoring in order to be developed further.

The scoring value can range from 0 (if the expected performance is very poor or nonexistent) up to 2 (if the idea has great promise within this criteria). In addition a valued weight is applied to each, in which important criteria are given a higher impact on the final score. The deciding scoring value of each idea is the initial score (from 0 to 2) multiplied by the weight of the criteria ranging from 1 to 3. (appendix 12, idea scoring sheet)

To validate the legitimacy of the idea scoring results, a sensitivity analysis is performed, in which ideas with a debatable score are given both a higher and a lower score, to observe whether a change occurs in the winning ideas. From this test, no change occurred in the decisive winning idea outcome. (appendix 13, ideas scoring sensitivity analysis)

The selection process is achieved through evaluating each idea on a listed criteria that reflects which option demonstrates the highest potential value. These criteria have been developed in order to minimise the subjective scoring, and is divided into three categories, with each containing three criteria on which the ideas will be evaluated on :

1. Desirability (24 points of total score): demonstrates that the result is desirable for a stakeholder applicable to the field of the idea, or it creates new value/meaning for society in general. The desirability will show why such an idea is better than other already existing things, based on:

- Weight 2: What innovation is being created?
- Weight 3: What design value is being created in terms of manufacturing, 3d printing, materials, product modelling, product interaction?
- Weight 3: How developed is this field already regarding innovation and knowledge? (competitors).

2. Viability (21 points of total score): demonstrates that the result can become viable, thus it can survive on a long term physically, or at least for as long as a specific use requires. Based on:

- Weight 4: Could this idea be replaced in the short term with a different/better technology/method (treaths)?
- Weight 1: Beyond the Stratasys, could this concept be manufactured without the use of multi-material 3D printing?
- Weight 2: Could there be room for future development and improvement?, Is it a dead end or can it be explored further in future projects?

3. Feasibility (15 points of total score): demonstrates that the results are achievable, or that a new method/demonstration is presented to achieve this, within the overall project time frame. Based on:

- Weight 2: Expected difficulty of showstopper to be overcome?
- Weight 1: Could this concept be developed, tested, and optimised within the given time frame? (subjective, yet indicative)
- Weight 2: Could this concept be developed with the available materials and resources?

Each idea is evaluated and scored individually on their desirability and viability. These scores are achieved through comparing the ideas to the existing knowledge, and market innovation in their fluidic system research category (chapter 3, Literature research).
Consequently, only those ideas showcasing a high innovation value (high score on desirability and viability), are scored on their feasibility (Appendix 12, idea scoring sheet).

6.5 Potential ideas

The criteria selection process resulted in three ideas with a comparable score. Therefore, rather than selecting the idea that won with a minimal score margin, it is more valuable to compare these and discuss which has a higher value in terms of innovation opportunities. Thus, these are presented on an abstract level, as they have not been developed yet, and a selection will be made in chapter 6.6.

Idea 1: Visual mechanical health

Micro-fractures in a functional part can be fatal, yet difficult to identify. Therefore through a laminar internal structure design, it can be possible to change the surface appearances of an object when these micro-fractures occur. In addition, parts can be modelled such that excessive overloads can be recognized.

Innovation: Visual feedback of a part mechanical health

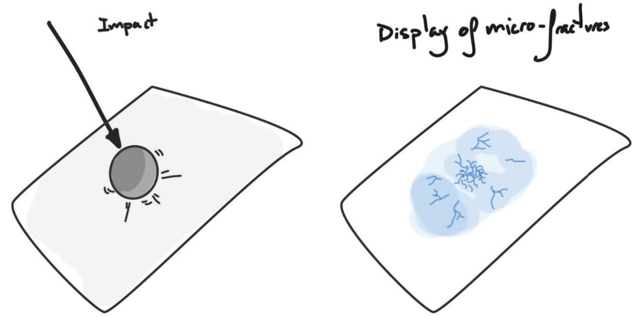


Figure 96: Visual mechanical health

Idea 2: Morphing textures

Products change their tactile texture, from a smooth surface, into a bumped, rougher or even sharper surface.

Innovation: flexible, dynamic and customizable surface textures

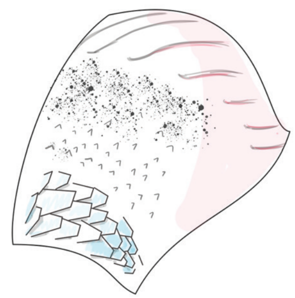


Figure 97: Morphing textures

Idea 3: Product-human usage feedback

A product can be designed such that it changes its mechanical stiffness and appearance when not used correctly. This can increase user self-awareness, which might be useful for rehab products or tools. To do the 'incorrect' usage is considered as the input and determines the intended product property change (output).

Innovation: Visual and sensory feedback of human-product behaviour

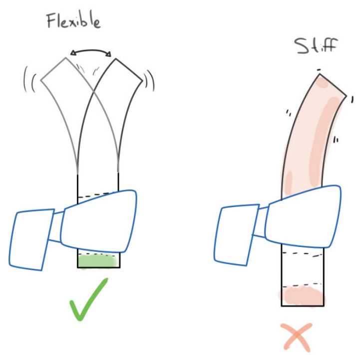


Figure 98: Product-human usage feedback

6.6 Fluidic system final idea selection

In the previous chapter, three ideas are briefly presented, of which one will be chosen to be developed into a concept. This selection is based on:

1. *Existing research:* how much existing research is already available, and are there already similar concepts/products?
2. *Interaction element*: can this product create a new value between a user and a product?
3. *Research opportunities:* how much space is there for future development, can a new product category be created?
4. *Application and manufacturing opportunities:* can this concept be made with a different manufacturing technique (other than polyjet 3d printing)?Are there already initial product ideas?

Visual mechanical health

- *Existing research*: in current existence, parts can rely on visual inspection, and external force sensors. However, self healing materials are in development [12].
- *Interaction element:* safety is the only driver of this idea.
- *Research opportunities:* through material and manufacturing research, structures could be made with embedded microfluidics.
- *Application and manufacturing opportunities:* this idea could be applied onto performance products, however this can also be achieved (maybe even more accurately) with the use of digital sensors, and structural integrity could be compromised due to the internal fluidic structure.

Morphing textures

- *Existing research:* deployable mechanisms which can fold with the purpose of reducing their size are in development [10, 29, 32], however, these are assemblies of different rigid parts. Meta-materials are in development, however these need to be large in size.
- *Interaction element:* products could be designed to be an emotional extension of the user. In addition, surfaces could be dynamic in terms of grip and light reflectivity according to the user needs.
- *Research opportunities:* Deployable control surfaces, and retractable structures could be researched which drastically rearrange the surface structure, or adjustable surface smoothness. In addition, the internal fluid displacement could be used to work as a fluidic interface to enable a change in appearance at the same time.
- *Application and manufacturing opportunities:* this idea could be feasible through complex mechanical mechanisms and electronics, therefore still unique. Some initial applications could be robotics, tools or clothes.

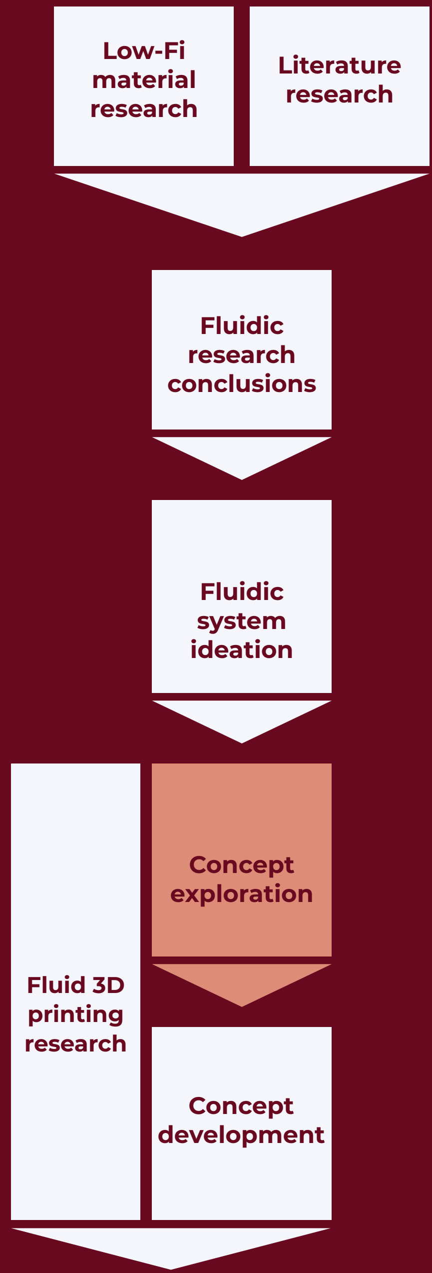
Product-human usage feedback

- *Existing research:* 3d printed concepts are in existence which can alter the stiffness of a product depending on how it is used [17, 23]. However these do not give visual feedback to the user.
- *Interaction element:* the value of this idea lies in correcting and improving physical behaviour.
- *Research opportunities:* the research fields of this idea lie in converting displaced fluid to structurally stiffen objects, and also alter the visual appearance of these. Although, very specific scenarios would need to be chosen beforehand.
- *Application and manufacturing opportunities:* this idea could be applied mainly in the fields of rehabilitation and sports, in which correct physical behaviour is essential. However, with the use of electronics, similar results could be achieved.

Conclusion

When considering the first idea (visual mechanical health), this might deviate the project research too much towards mechanical and material design, and not focus on the value of an interactive fluidic system. The third idea (Product-human usage feedback), might steer too much towards the fields of ergonomics and product interaction, and might not fully realise the capabilities of printed fluidic systems. At last, the third idea (morphing textures) can offer the right balance between 3d printing exploration, while also focussing on a product interaction and appearance. Therefore, morphing textures is the idea to be developed into a concept.

7. Morphing textures: idea to concept



Morphing textures is selected as the idea to represent the value of 3D printed fluidic systems. However, in order to achieve a concept from this idea it is necessary to acknowledge the following research question in order to design eligible concept ideas:

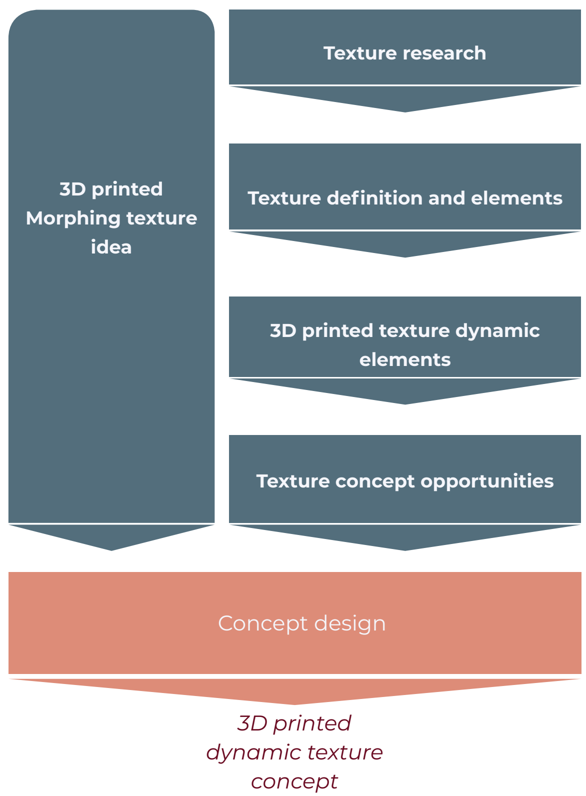
- *What defines textures?, and what can dynamically be changed in a design?*

In this chapter, the meaning of texture is explored, along with deconstructing the different elements which play a role. Continuously, texture elements and 3D printing capabilities are compared in order to establish what can and cannot be achieved within the project resources. Finally, two concepts are presented, of which one is selected to be developed further and be demonstrated.

Terminology

- Line: long, narrow mark
- Shape: geometric figure
- Form: visible shape or configuration of something
- Visual space: visual arrangement and repetition of shapes, lines or colours.
- Value: terms of hue, lightness, and saturation.
- Space: arrangement and repetition of shapes.
- Height: change in vertical displacement (normal to the surface)
- Curvature: degree to which a surface deviates from the plane
- Hardness: resistance to deformation when touched.
- *Reflectivity*: proportion of light reflected off a surface.
- *Opacity*: measure of impenetrability of visible light through a surface.

Figure 99: dynamic texture ideation process



7.1 Defining textures

The objective established in the design process is to dynamically change surface textures with the use of a fluidic system. However, before different ideas are presented regarding this objective, it is important to firstly analyse what are textures, what elements do compose this, and which can be dynamically changed with a printed fluidic mechanism.

Texture refers to surface characteristics and appearance of an object, given by the visual impression and the tangible feel of the surface itself (*What Is a Texture?*, 2006). With this definition is is important to recognize that texture is not just one piece, but rather visual and tactile elements interacting cohesively (figure 100):

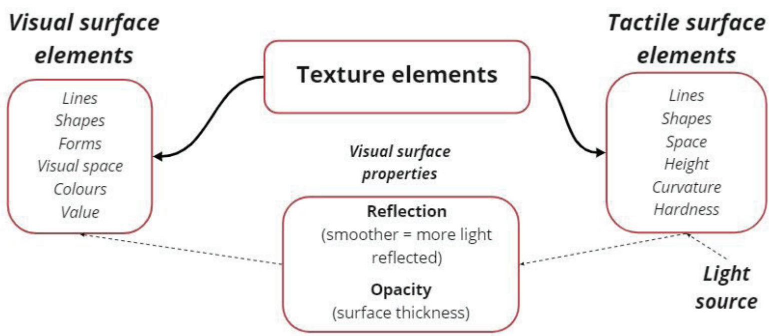


Figure 100: surface texture elements

a. Visual surface: this refers to the visual impression that is produced to the human observer, in different words, how a surface looks like it would feel to the touch ('Tactile Texture Archives', 2016). The different elements which build up a visual surface are visible in figure 101.

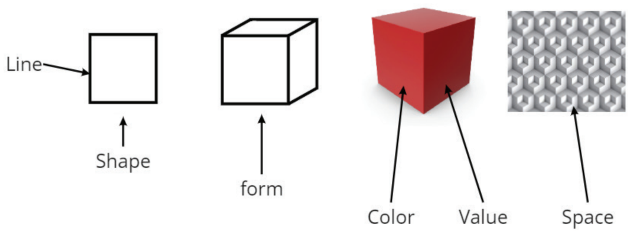


Figure 101: visual surface elements

b. Tactile surface: this refers to the actual tangible feel of a surface, which can categorically be classified either as smooth, or rough (Gadelmawla et al., 2002). The different elements which build up a tactile feel of a surface being: figure 102.

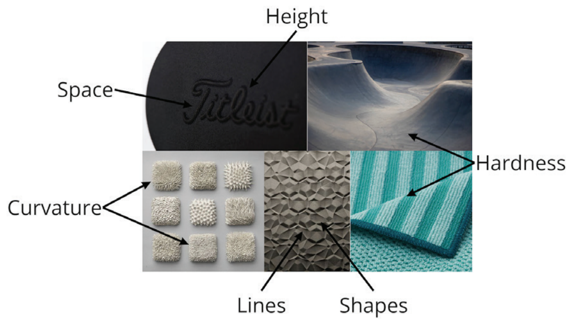


Figure 102: tactile surface elements

Changes in the balance of each single element can result in smoother or rougher surfaces. However, there are no set of rules dictating dimensions for each element in order to achieve the intended surface tactile perception. Instead, when one element is changed, the others might need to change too in order to maintain the surface experience. This creates a complex formula which does require testing to achieve the desired interaction (appendix 14, Interview with Karina Driller, expert in tactile surface perception).

c. Light interaction: as is explained before, a tactile surface can be experienced with just the human touch. However in order to observe a visual surface, light waves are necessary, which do reflect off this surface, and into the eyes of the observer. Thus, the visual impression is directly related to light reflecting off a surface. As a result, changes in a tactile surface can alter how light reflects and therefore reshape a visual impression of such a surface. Through this visual-tactile and light interaction, two visual elements occur (figure 103).

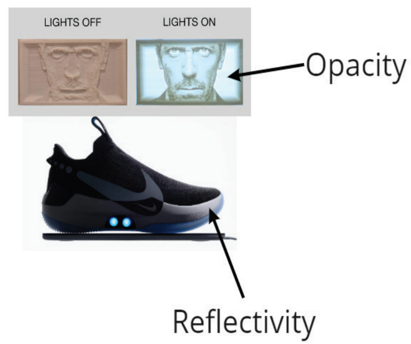


Figure 103: visual-tactile surface interaction elements

7.2 3D printed texture dynamic elements

The objective is to design dynamic surface textures with 3D printed fluid mechanisms. In chapter 4.3 (3D printed fluid mechanisms analysis), the basic hydraulic working principles of such a system are explored, and therefore providing insights on what could be applied onto creating changes in the previously mentioned texture elements.

The mechanisms in the mechanisms analysis shows that when hydraulic pressure is applied in a fluidic mechanism, the overall structure will remain constant (lines, shapes and space), however the surface can be deformed. From this deformation, two texture elements change, height (distance relative to the plane), and curvature (deviation in surface angle). In addition, the increase in hydraulic pressure can increase the structural stiffness, altering the surface hardness (relative to external forces).

Concepts designed with the intent of dynamically changing surface texture as a means to achieve a new product interaction, shall employ changes in surface colour, height, curvature and hardness as the available variables (figure 104) to achieve such intended interaction.

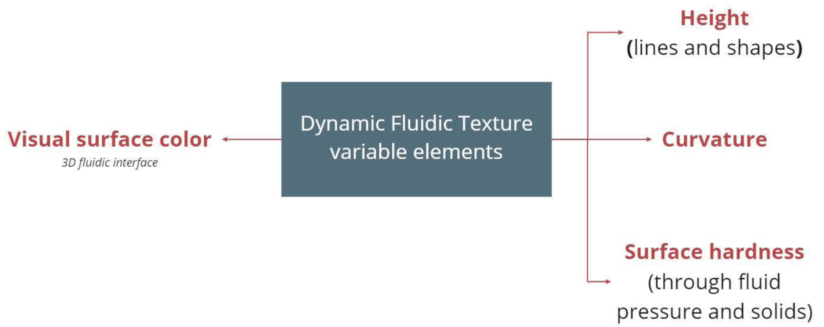


Figure 104: 3D printed fluidic morphing textures dynamic elements (that can be changed through 3D printed fluidic pressure)

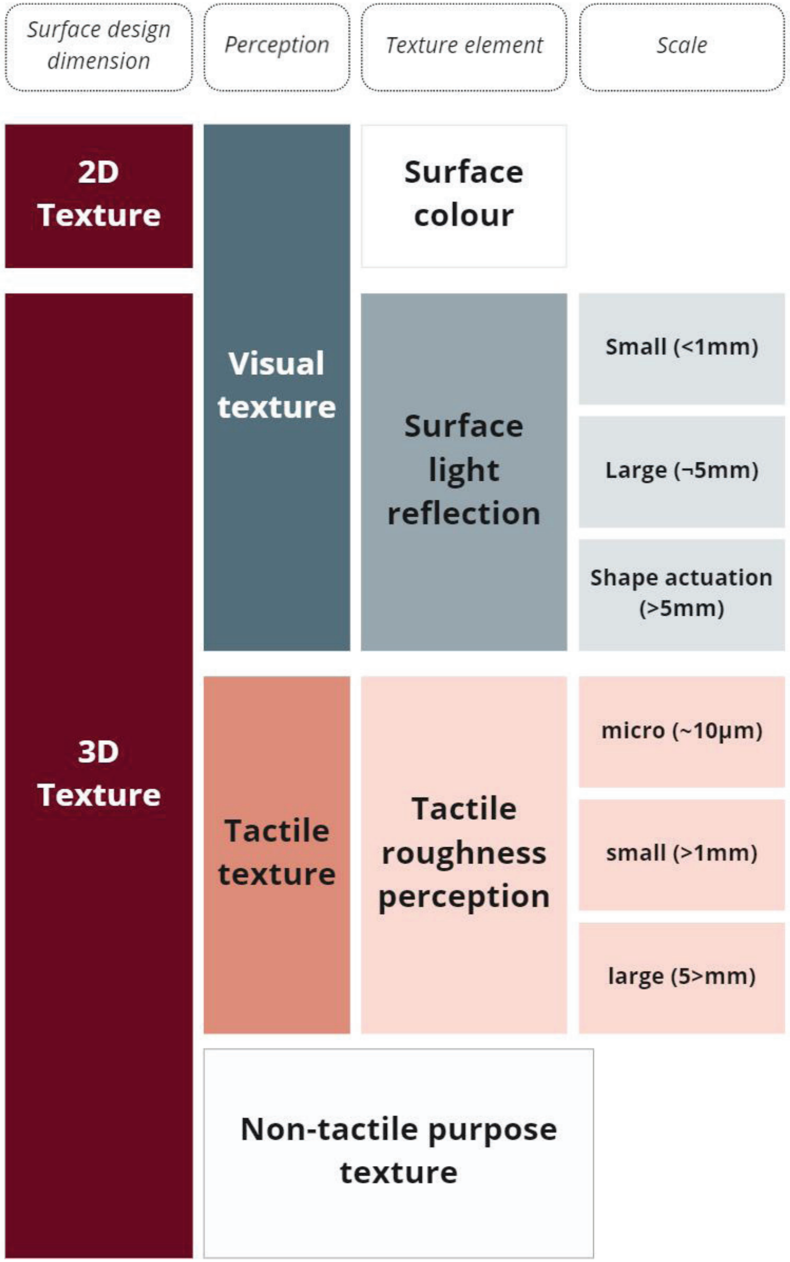
7.3 3D printed dynamic texture design routes

Textures are a cohesive working between visual and tactile surfaces, and light, however, the elements that can be changed are colour, height, curvature and hardness. Considering changes in this first element, colour, the perception of a surface impression can be changed without altering the tactile surface structure itself (fluidic interface). Therefore this design opportunity is classified as a 2D texture design opportunity. However, when modifications in surface height and curvature are made, physical changes in the 3D surface visual and tactile texture occur.

As a result, 3D printed dynamic textures can be designed to change a surface appearance (fluidic interface), but also through altering the surface 3D texture creating with three interaction elements:

1. 3D Surface visual impression
2. Tactile roughness perception
3. Non-tactile purposes

Figure 105: Dynamic texture design opportunities



1. 3D surface visual impression

Through changes in the surface structure, the light reflection off such surfaces can be altered, such that the visual impression to the observer will vary. This effect can be achieved on three different scales, each with a different design purposes:

a. Small scale (<1mm): on this scale the surface roughness perception could be altered. As a result, a surface could appear shiny or matte when height changes occur within 16 microns (figure 106) (He et al., 1991). Moreover, within a scale of 50-500 microns, a surface could appear smooth or rough (figure 107) (Leroux, 2014). Even with fine 3D polyjet printing resolution, the scale of such visual textures is currently beyond feasible grounds.

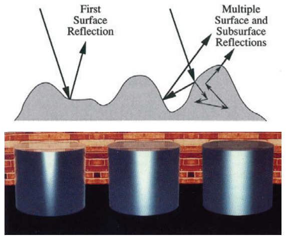


Figure 106: surface roughness influence on light reflection

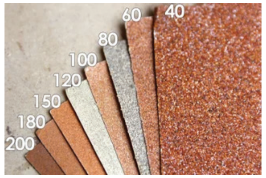


Figure 107: surface amplitude and increase roughness perception

b. Large scale (~5mm): on this scale, surface height and amplitude can be altered to create shadows on the surface itself (figure 108). Visual information, and surface perception can have an influence relative to the observer position

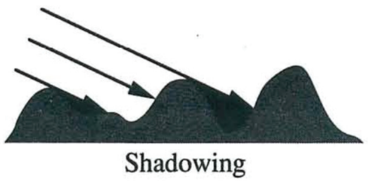


Figure 108: surface shadowing as a result of surface height changes.

c. Actuation of shapes (>5mm): On this scale, shiny surfaces could be actuated to change the reflection angle relative to the observer.

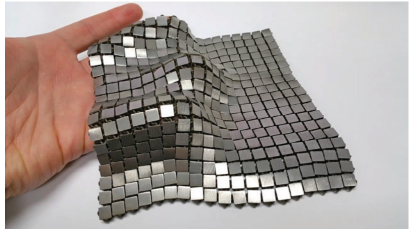


Figure 109: dynamic light reflection angle

2. Tactile roughness perception

Through changes in the surface height (relative to the plane), the tactile perception of such could be dynamically altered. This can be achieved on three different size scales:

a. *Micro scale (~10μm):* on this scale, the smoothness of tactile perception can be altered. Differences in height beyond 2μm are susceptible to the human touch (Skedung et al., 2011). However such a small scale is currently beyond the inkjet printing resolution (20-50μm).

b. *Small scale (~1mm):* on this scale, the roughness tactile perception of a surface can be changed. With the use of 3d printed flexible and rigid materials, dynamic actuators can be designed to create variations in height and curvature, to create shape and patterns (Winfield et al., 2007).

c. *Large scale (~5mm):* on this scale, the even feel of a surface could be changed through large height and curvature displacements. With solid structures, spatial rearranges could be achieved.

3. Non-tactile purposes

Through changes in the surface structure, elements such surface to surface friction or suction could be changed. However, the research focus of this project is aimed at the user-product interaction value that fluidic systems could provide. Therefore, no further research is conducted in this field, however future value can reside in 3D printed dynamic textures for non-human interactions.

7.4 Designing concepts

The definition of surface textures and the different design opportunities with fluid 3d printing are established in the previous chapters. With the objective of designing a concept demonstrating this manufacturing technology, different ideas are developed into possible concept ideas. Two ideas are presented best representing the intended objective:

Concept 1: sensory rehabilitation

Figure 110: Sensory rehabilitation concept

Concept rehabilitation product, in which patients have to feel and observe changes in roughness, and visual appearance. Once the rough spots are felt, one will be able to apply pressure to these spots reverting to a smooth surface again, then different sections become rough continuing the search and feel cycle.
This concept would be valuable in patients who have had nerve damages, as a result of an accident. During accidents, nerve connections can break which causes a lack of feeling in specific body parts. Nerves grow slowly back together (about 1 mm a month), and when the extremities of these connect together again, sensitivity can be regained through stimuli training (Marjan vd Groep, 2014). The stages at which this happens are:

1. Regain feeling of pain and temperature
2. Regain feeling of roughness
3. Regain tactile gnosis (identifying shapes through touch)

In addition, this could help with avoiding further degradation of neuropathy (numbness due to nerve dysfunction).

Concept 2: haptic feedback controller

Concept which utilises tactile perception to interact with a digital system such as a computer, modelling software, vehicles….
The handheld controller device is covered in texture mechanisms, which can change texture from smooth to rough. Therefore, when the user presses into a smooth surface, this will become gradually more rough, while at the same time working as a digital input for the software/vehicle being controlled. At the same time, through hydraulic pressure, the texture can change from itself, communicating back to the user.
Placing different of these dynamic texture actuators on a 'joystick' could extend the level of interaction and information between a user and a product. However such devices might need extensive training to get acquainted.

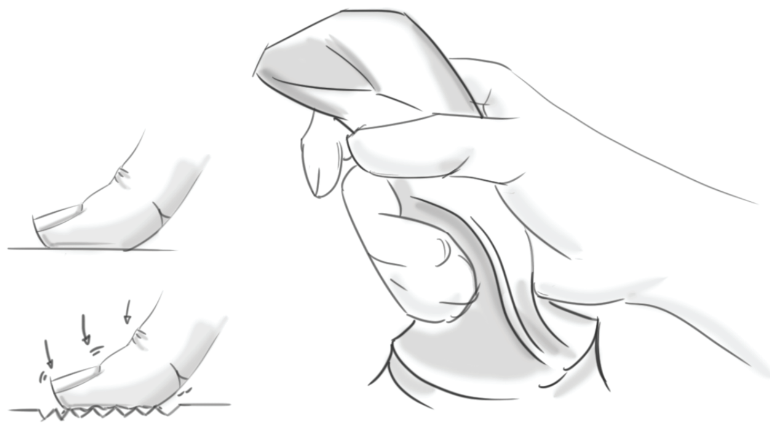


Figure 111: haptic feedback controller concept

7.5 Final concept

Two concept ideas are presented as candidates to be developed into an actual concept. Thus, the value of these two is compared regarding their innovation value:

Sensory rehabilitation

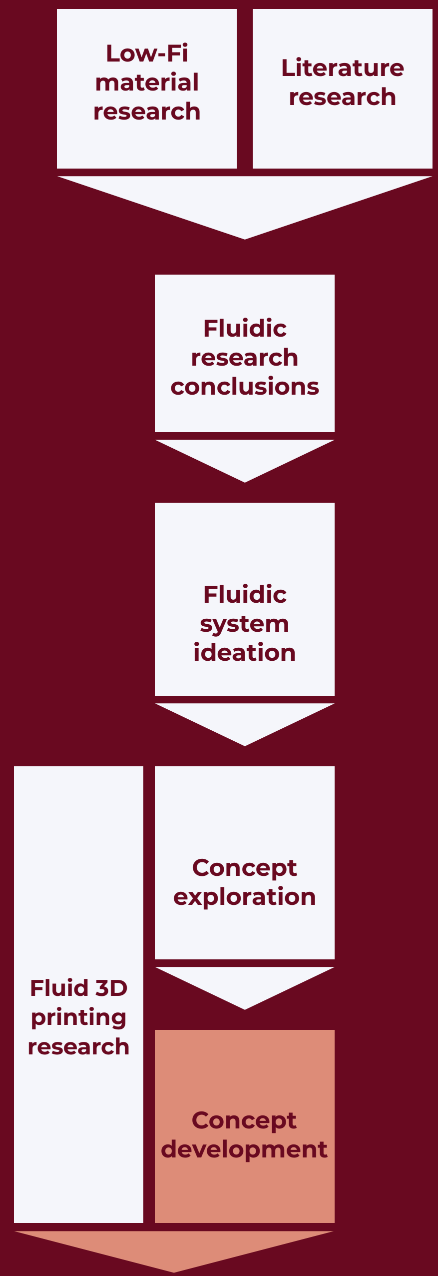
This concept is valuable for the field of rehabilitation, however this can also be achieved through the touch of non-dynamic rough/smooth surfaces. In addition, comparable products with the same intent exist in this field already [67]. At last, the market and room for future innovation of such concept is fairly limited

Haptic controller

This concept could be highly valuable for communication and control between a user and a computer, robot, vehicle... Existing controllers make use of a multitude of knobs and buttons, but lack the direct sensory input feedback from the controller. This concept could change the way we physically interact with software, additionally, with extensive room for improvement and innovation.

Comparing the further room for research and developments, possible market size, and innovation value, the haptic controller concept idea stands out compared to the sensory rehabilitation concept. Thus, the final concept to be developed along with a proof of concept will be the haptic controller.

8. Morphing textures concept

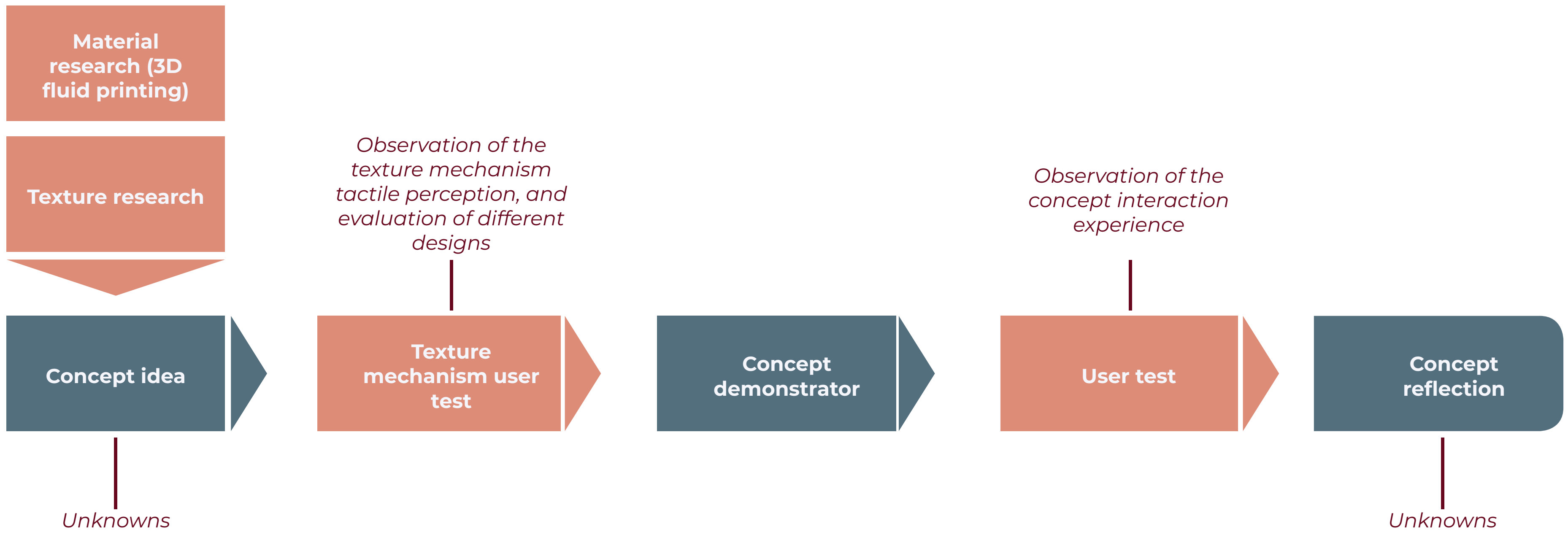


The idea of a 3D printed haptic controller, with fluidic systems enabling a dynamic change in surface texture, is developed into a concept in this chapter. This design process is structured into two sub-chapters:

In the first sub-chapter (**concept vision**), the concept is elaborated, detailing the envisioned use, the tactile variables playing a role, the mechanism working principles, and the interaction elements both tactile and digital.

In the second sub-chapter (**concept demonstration**), the concept is developed into a physical prototype, mimicking the user-product interaction with the intent of demonstrating the product vision.

Figure 112: concept design process

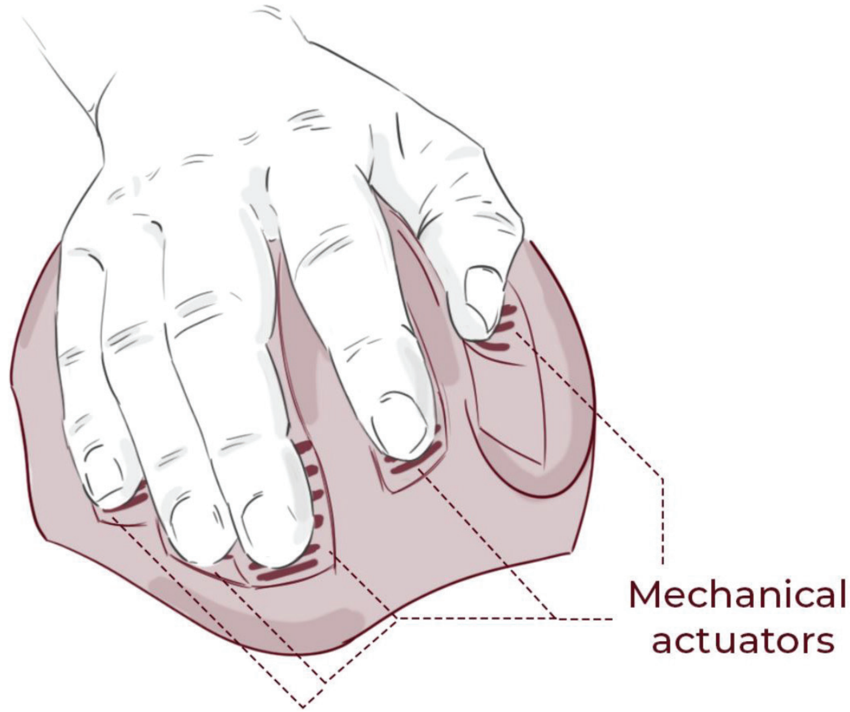


8.1 Concept vision

The concept vision is to use human tactile perception to create a new product interaction, between a user and a digital system (computer, software, vehicle...). The concept is a handheld device, which serves as the communication interface between these two. This device, is covered in variable texture mechanisms, which can change the surface perception with two intents:

1. **Surface texture transforms from smooth to rough** when the user presses into the surface which acts as the sensor. The more this sensing surface is pressed, a larger change in roughness perception will occur. This feature brings a haptic feel when the user interacts and sends signals to the digital interface.
2. **Surface texture transforms into relief shapes**, which dynamically appear from a smooth surface, into the contacted skin of the user. This texture actuation has the intent of communicating information to the user through different actuation patterns.

Through placing different of these dynamic texture mechanisms on a 'joystick' the human-digital interaction could be transformed, bringing a tactile feel to digital actions. As a result, this concept could be applied to programs in which obtaining a reference feel (such as CAD programs) can add realism, or to interactive actions (such as games) presenting an innovative immersive experience.



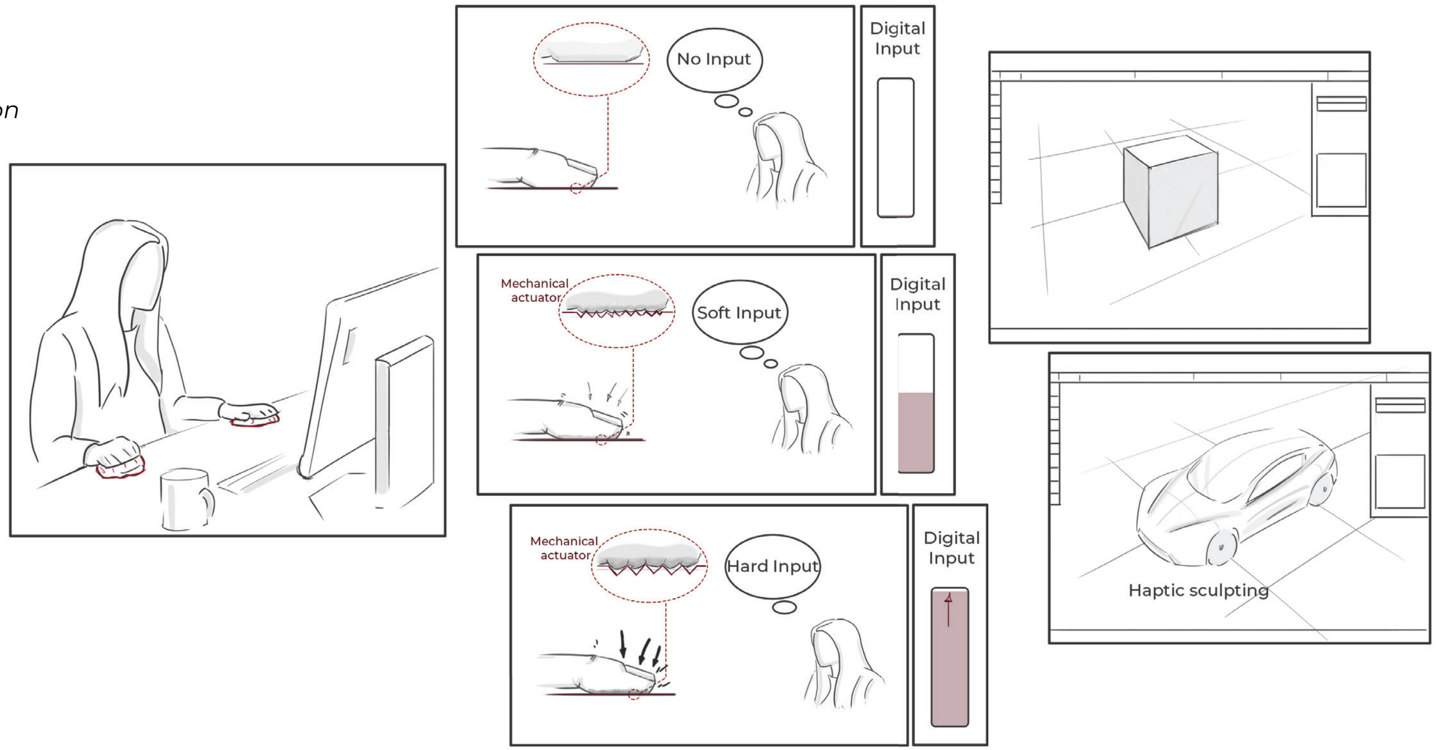
8.1.1 Concept interaction

This concept is the physical interface between a user and the digital software they are communicating with, which can be a CAD software, video game, controlling a vehicle, or any other unidentified uses. during this interaction, there are two communication paths:

1. User to product communication

In this interaction, the user will press with their fingers into specific surface areas of the controller which texture sensors are placed. When the user presses into one of these sensors, internal fluid is displaced, which can precisely be measured and serves as the user input towards the computer software. Meanwhile, the more is being pressed into such a surface, the rougher this will become. Thus, allowing an input range rather than a binary 'click' such as a traditional computer mouse. when pressure is no longer applied on the sensing surface, its texture will revert back to being completely smooth to the touch.

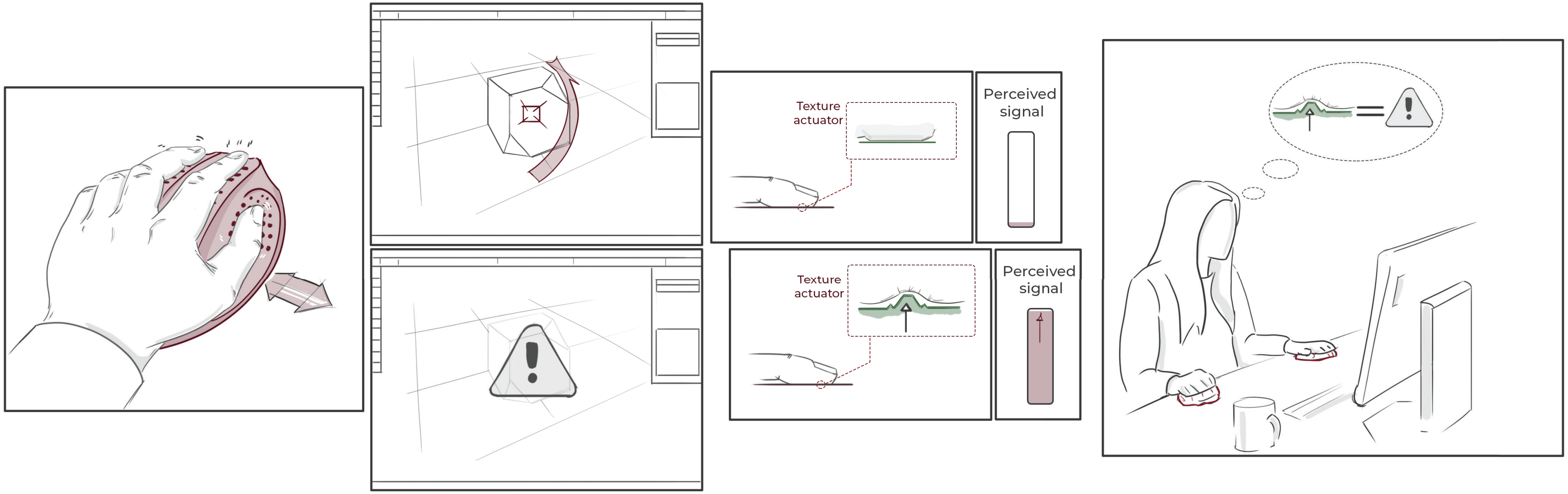
Figure 114: user to product communication



2. Product to user communication

in this interaction, the tactile interface is instructed from the software to change its surface texture. This change in this surface relief will be noticeable on the skin of the user, and will provide a certain signal. Through the placement of multiple texture actuators, numerous signals can be identified by the user. Which can transmit information through changes in the actuation pattern, or the location in the palm.

Figure 115: product to user communication



8.1.2 Concept tactile variables

The core of this concept lies in transmitting information through feeling changes in a surface texture. Therefore, it is important to acknowledge how the human tactile perception functions, and how this can be enabled into a physical product. Through understanding the different elements which play a role in the tactile perception, these elements can be targeted individually to achieve specific haptic signals.

The formation of tactile perception is related to skin receptors and the cerebral cortex. Different gratings induce different stress concentrations within skin that stimulate receptors, caused by skin deformation, contact area, friction force, and stress around cutaneous mechanoreceptors. In addition, there is a relationship between the activation in brain regions between contact conditions of skin during the tactile perception (Tang et al., 2020). The different mechanoreceptors are:

- **Meissner receptors:** Meissner's corpuscles are rapidly-adapting, encapsulated neurons that respond to low-frequency vibrations and fine touch, and located in the glabrous skin (skin devoid of hair) on fingertips and eyelids. Meissner corpuscles are most sensitive to low-frequency vibrations between 10 to 50 Hertz and can respond to skin indentations of less than 10 micrometres.

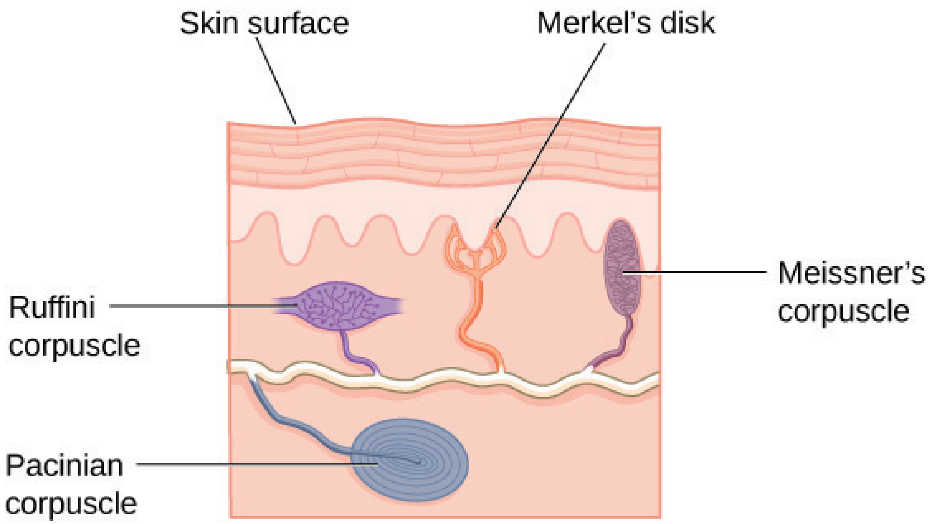
- **Merkel receptors:** Merkel's discs are slow-adapting, unencapsulated nerve endings that respond to light touch, and are present in the upper layers of skin.

- **Ruffini receptors:** Ruffini endings are slow adapting, encapsulated receptors that respond to skin stretch and are present in both the glabrous and hairy skin.

- **Pacinian receptors:** Pacinian corpuscles are rapidly-adapting, deep receptors that respond to deep, transient (not prolonged) pressure and high-frequency vibration. Pacinian receptors detect pressure and vibration by being compressed which stimulates their internal dendrites, with 100–300 Hz, being the most sensitive frequency range.

Through acknowledging these tactile elements, the concept texture mechanisms can make use of the different receptor conditions, enabling distinct haptic signals.

Figure 116: tactile receptors



8.1.3 Texture fluidic sensors and actuators

The interaction element of this concept is the variable surface texture mechanisms, which deform the surface in different ways in order to send and receive information through signals from and towards the user. These mechanisms work through combining three constructing elements:

- **Rigid structures:** mechanisms are constructed in a rigid shell maintain the actuator shape required, even when pressed forcefully. In addition, fluidic sensors make use of this rigid structure to enable a change in perceived tactile roughness.
- **Flexible membranes:** the mechanism surfaces are flexible thin membranes, designed to deform vertically under a load.
- **Fluid:** which applies internal hydraulic pressure to deform the flexible membrane, or, be displaced when the membrane is deformed from an external load. When this occurs, hydraulic pressure sensors can measure this change in pressure.

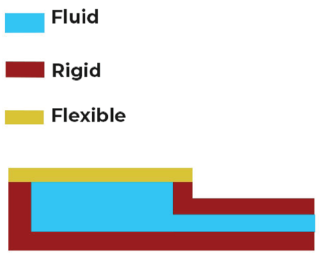


Figure 117: fluidic texture mechanism elements cut view

working principle

With the three constructing elements (fluid, rigid structures and flexible membrane), and the tactile variables which influence texture perception (chapter 8.1.2, tactile variables), the fluidic mechanisms can be designed to achieve the designed two-way communication.

With the concept being a joystick or controller, It is important to take into consideration when designing these mechanisms being the lack of hand movement from the user over a surface. Thus, a lack of skin vibrations which are best identified by Mesisner receptors (Bergmann Tiest, 2010).

The working principle of such an actuator is in essence straightforward, either moving an membrane up or down. However different arrangements in the structure and execution will offer a large number of design opportunities for an innovative interaction. As a result two mechanisms are designed, a sensor and a actuator:

a. Roughness sensor: when the user presses with their fingertips into the surface of this mechanism, the flexible membrane will deform, and as a result, internal fluid volume will be displaced, which is measured and is translated into a digital input. However, in order to achieve the variable perception in surface roughness the flexible membrane will deform around an intricate rigid system. This causes the rigid structure to be embedded into the fingertip skin, signalling the Merkel and Ruffini receptors, with a stronger signal the harder it is being pressed against.
The construction of this mechanism has different design elements (figure 120) which will determine the perceived roughness (chapter 8.2.1, Texture mechanism user testing).

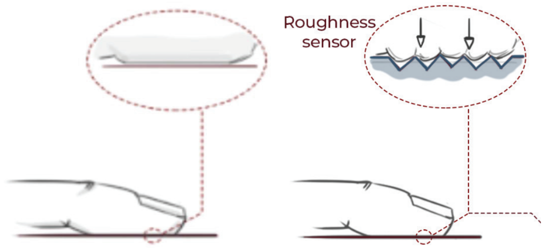


Figure 118: texture deformation contact feeling

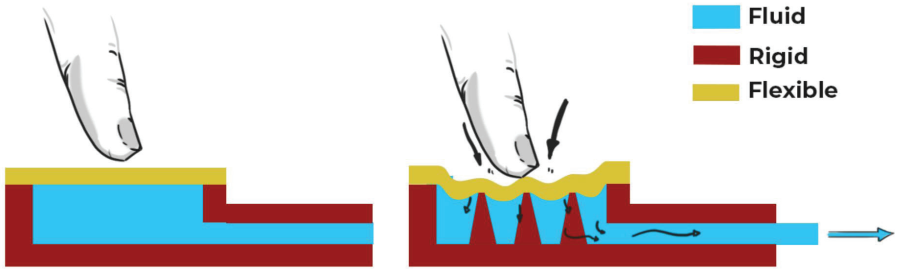


Figure 119: fluidic system texture sensor working principle

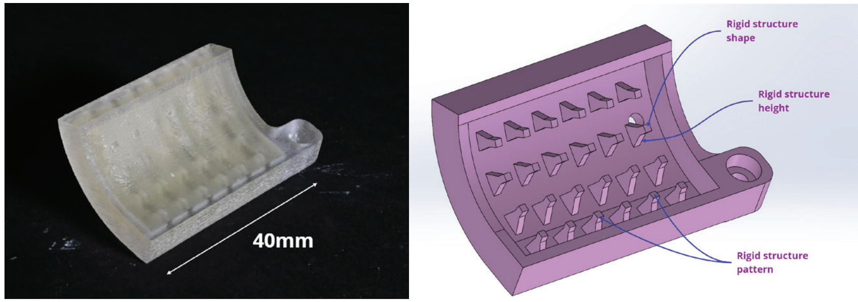


Figure 120: fluidic texture roughness sensor design elements (chapter 7.1, defining texture elements).

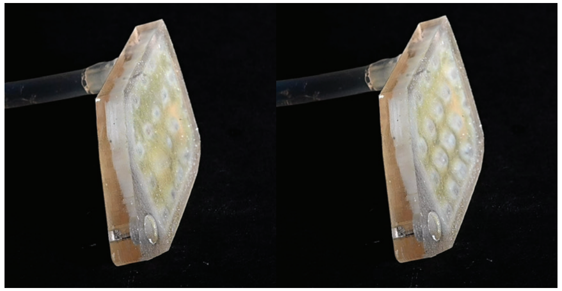


Figure 121: roughness sensor deformation (a vacuum in hydraulically applied, mimicking the deformation that would occur when the surface is pressed)

b. Texture actuator: through an increase in hydraulic pressure within the controller, commanded by the digital software the user is interacting with, the flexible structure will deform vertically. This deformation results in a change in surface relief which will be noticed by the user (when working the different receptor boundaries). The different elements that can be altered in the mechanism will be the height displaced of the membrane, the area of the membrane and the deformation speed itself (Figure 124)

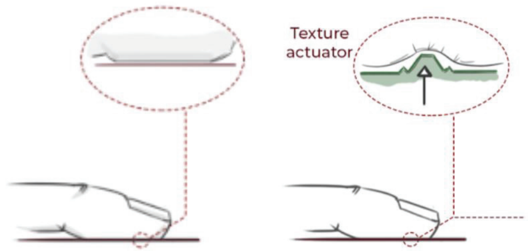


Figure 122: fluidic texture actuator working principle

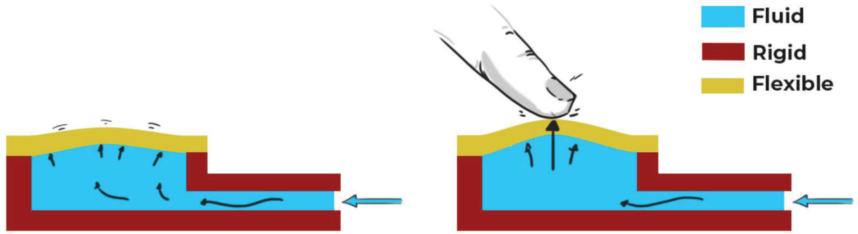


Figure 123: fluidic texture actuator working principle illustration

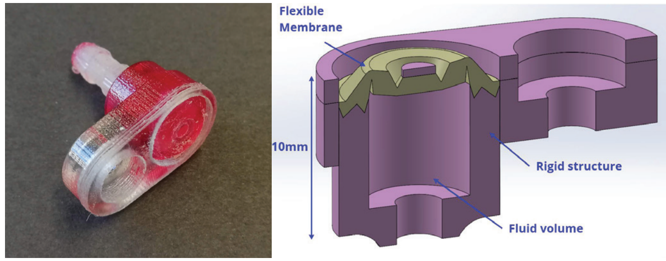


Figure 124: fluidic texture sensor construction

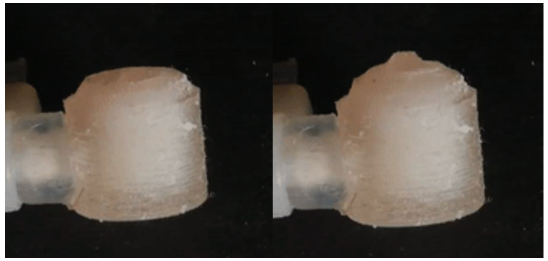


Figure 125: texture actuator actuation

With these sensing and actuating principles, a communication interface is created with a broad range of design opportunities in terms of materials, mechanism design and different deformations. In this project, only one sensor mechanism and one actuator mechanism has been selected from various ideated designs (appendix 17, texture sensor and actuator design testing) to represent this concept, as a result of a limited time frame.

8.1.4 Texture actuator language

The actuating mechanism principle has been elaborated in the previous chapter, however, through minor changes in how this flexible membrane is shaped and deformed, different communication interactions and signals to the user could be produced. Thus, through varying the actuation of this mechanism, a new communication language is achievable, consisting of the following forms:

1. Tactile gnosis

Tactile gnosis is the ability to identify the shape and form of a three-dimensional texture on a surface. In other words, the ability to recognize changes in surface relief, and identify the shape or pattern being present. Individuals experienced in this practice, such as the visually impaired who read braille, are able to identify and instantly understand surface patterns (from smaller than 1mm features, up to hand sized surface patterns) through Merkel and Ruffini receptors, and transform these signals into a readable language . This translation from tactile signal to a cognitive responsive requires exercising, becoming faster and more natular the more is practised (appendix 15, interview with visually impaired individual about tactile perception). Thus, through the placement of multiple texture actuators on the hand surface, this concept can be adopted for tactile reading, with sufficient training from the user.

2. Actuator vibrations

Through rapid vertical displacements (up and down repeatedly) of the flexible membrane, Meissner (10-50Hz) and Pacinian (100-300Hz) receptors can be strongly signalled. Thus, through this distinctive form, information can be transmitted to the user independently from the tactile gnosis form.

3. Deformation elements

When a texture actuator is actuated, there are three dynamic elements, the direction of deformation (upwards or downwards), the height displaced, and the speed at which this occurs. Through changes in these elements, the user could perceive (chapter 7.3, Tactile roughness perception) and understand the meaning of such a signals,

With these three communication forms a new and extensive haptic language form could be created. The use of tactile gnosis and the use of deformation elements is briefly tested in chapter 8.2.1 (texture mechanism user testing) demonstrating on a superficial level its operation. However, the full concept idea of applying this to an innovative haptic language is at the presentent time theoretical, as it has not been tested yet.

8.1.5 Placement of actuators

Texture sensing or actuating mechanisms can be placed strategically on the interface to achieve an optimal interaction experience.

Firstly, **variable roughness sensors** require active and controlled pressing from the user into the surface. Thus, fingertips are exclusively the positioning of such a mechanism, furthermore resembling present controller interaction (mouse, joystick...) lowering the adoption threshold.

Secondly, **texture actuators** do not require active pressing from the user. Therefore these must be placed against skin areas where they will be recognised best from the user:

Skin areas with a lower pain-pressure threshold (PPT) are more sensitive to externally applied surface pressure (EASP), therefore smaller changes in texture will be perceived more accurately (Fransson-Hall & Kilbom, 1993).

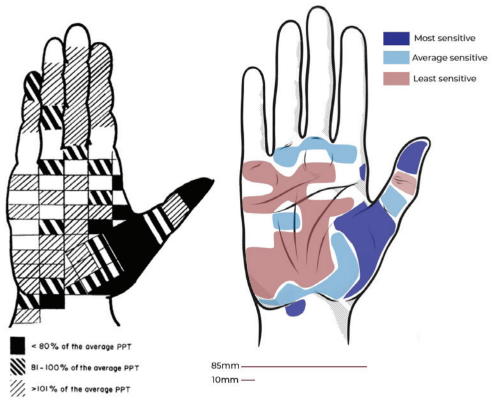


Figure 126: relative PPT on the right hand (mean of eight females and eight males). Map is translated to a visually identifiable coloured map on the right

Texture actuator will press into the user skin, therefore, when placing a multitude of these, it is important to identify how precise individuals can identify such signals. Figure 127 presents the error in localising a constant-touch stimulus (Nakada, 1993).

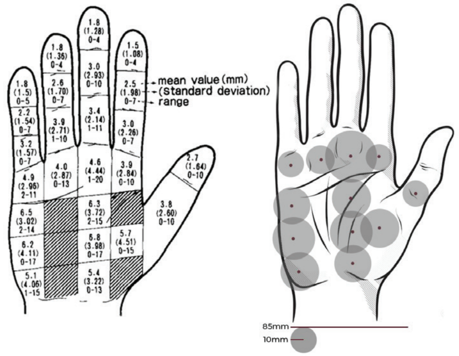


Figure 127: image on the right presents the error in localising touch stimulus, with values presenting the mean (mm), standard deviation and range of test results. Image on the right pinpoints the localised touch stimulus and visualises the range within subjects identified such stimulus.

With the PPT and localised error identified, both maps can be overlaid to identify areas in which the user will not mix up signals while ensuring this signal can be recognised with ease. 8.2Proof of concept

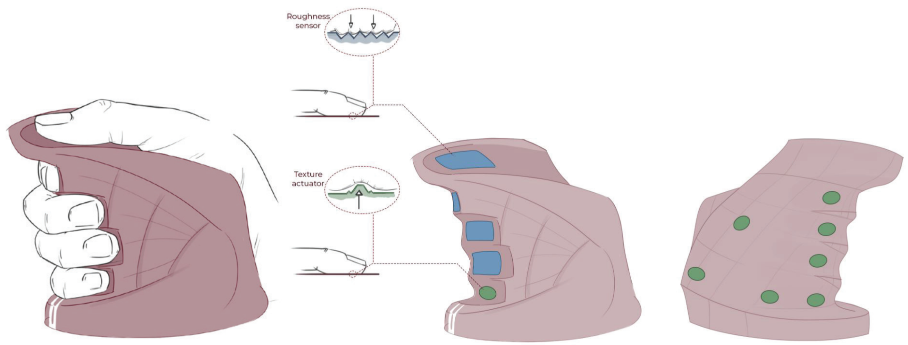


Figure 128: demonstration of texture mechanisms placement on the controller concept, with roughness sensors located on finger tips, and texture actuators on the palm of the hand.

8.2 Proof of concept

The haptic concept which enables a new form of product interaction with the use of a 3D printed fluidic system, is developed in the previous chapter (8.1). However, this haptic controller is yet at a concept level, therefore the aim of the proof of concept or demonstrator, is the validation of concept idea (feasibility), by showing this through a qualitative concept experience. Thus, the objective is to observe how participants experience the use of variable texture mechanisms, mimicking the user-product interaction.

The interaction value on which this concept is based on communication and feedback between a user and the product. Therefore the two demonstration targets are:

1. User to product communication: participants are not only able to send a signal, but in addition feel and recognize changes in surface roughness.
2. Product to user communication: participants are able to feel and recognize different texture signals while simultaneously sending signals through the roughness sensors.

Demonstrator limitations

Due to time and resource constraints, the entirety of the concert cannot be demonstrated. Therefore, the following conditions are chosen:

1. Selection of texture elements: There are different dynamic texture actuator opportunities (chapter 8.1.3, texture actuator language), which are based on **extensive training from the user**. However, considering this demonstrator is tested on participants with no prior experience, the texture elements are chosen based on the demonstration value and the expected learning curve. These being tactile gnosis (circular shape) for the texture actuator, as vibrations could also be achieved with a non-3D printed mechanism, and deformation elements might not be identified by the user yet (low tactile experience).
2. Selection of texture mechanisms: **mechanism design** can offer different texture perception opportunities (appendix 17, texture sensor and actuator design process), however these do need to be individually designed and tested for sufficient durability (long enough to withstand the test), and simultaneously achieve the correct tactile perception. Therefore, only one texture mechanism is chosen for a roughness sensor (chapter 8.1.3), and one mechanism is chosen for texture actuators.
3. Hydraulic system limitation: The prototyped hydraulic system can only apply positive or negative hydraulic pressure in case of the texture actuators. However, measuring the hydraulic pressure in the roughness sensors is not possible yet (with available resources). Therefore, digital sensors replace this hydraulic element.
4. Selection of texture **actuator placement**: The intent of this product is to place different actuators along the surface area of the hand. However identifying these would require extensive training from the user itself (assumption). Therefore, only 4 actuators are implemented into the demonstrator, proved to be identifiable (chapter 8.2.1, texture mechanism user test)

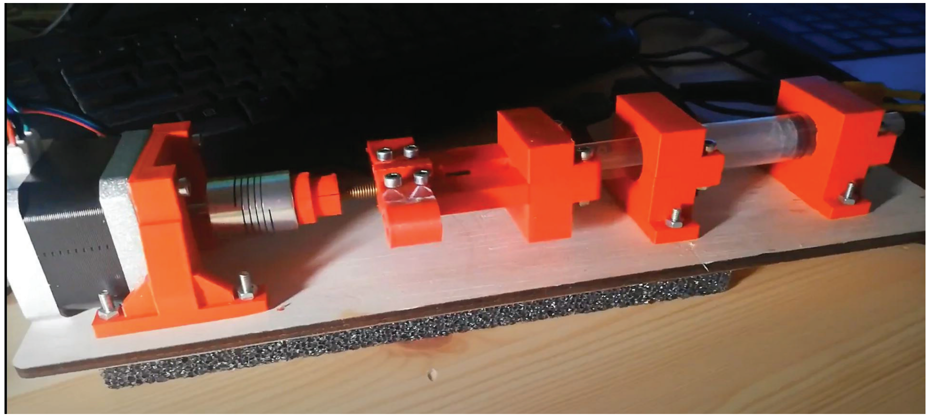
3D printed Hydraulic system

The demonstration of the texture actuators shows how these can be actuated in different patterns, therefore a low fidelity programmable hydraulic system is designed to achieve this goal, with the following advantages:

1. **Replicable**: the main structure of this system can be 3D printed, therefore, extra pumps can be rapidly added to the overall hydraulic system if required. In addition each requires one stepper motor, screws (M3 and M5), one syringe and a stepper motor driver.
2. **Programmable**: motors are connected to an arduino platform, as a result, different actuation speeds, ranges and interactions can be pre-programed.
3. **Precise**: the motor axis is attached to a screw, which when turned, compresses the syringe. With motor rotations being divided into 200 steps, the displaced volume can be controlled with high accuracy.
4. **Modular**: Different sized syringes can be placed in the system, as a result different pressures and fluid displacement rates can be achieved.

See appendix 9 for complete assembly overview

Figure 130: 3d printed hydraulic system



8.2.1 Texture mechanism user testing

The fluidic system mechanisms used in the concept have been elaborated in chapter 8.1.3. However the different design elements enabling the envisioned interaction is yet unknown. The purpose of conducting this qualitative sample testing is to observe how participants interact with dynamic texture mechanisms. With this research, a first-hand practical experience is conducted, through which participants can feel the varying tactile textures and reflect upon this impression. Meanwhile, the observer will gather information on the interaction behaviour between the participant and the tested material.

With this first material impression, the interaction experience that these mechanisms deliver can be observed, along with, which design elements are successful, and where changes are needed. The elements to be studied differ between the roughness sensor and texture actuator mechanisms are:

1. Roughness sensors observation points

- *How do participants experience the change in surface texture?*
- *How do participants experience changes in the design elements (rigid shape form, size, spacing, and surface curvature)?*
- *How do participants press into the surfaces?*
- *How do participants experience skin contact with the variable texture? Skin Numbness, discomfort?*

2. Texture actuators observation points

- *How do participants experience the change in surface texture?*
- *How do participants experience the simultaneous activation of multiple actuators?*
- *How do participants experience changes in the design elements (membrane height displaced, membrane area, and deformation duration)?*
- *How do participants experience skin contact with the texture? Skin Numbness, discomfort?*
-

Test setup

To observe participant interaction with 3D printed dynamic surface textures and answer the research questions, two handheld devices are constructed allow interactive freedom, with the following design features:

1. Roughness sensor mechanisms
Five sided Block with 11 samples in total (figure 131), with on each side changes between the different design elements:

- Side 1: Rigid shape form (squares, crosses, and lines)
- Side 2: Rigid shape size (small, medium, and large)
- Side 3: Spacing between rigid shapes (small, large)
- Side 4 and 5: curved surfaces (convex, and concave)

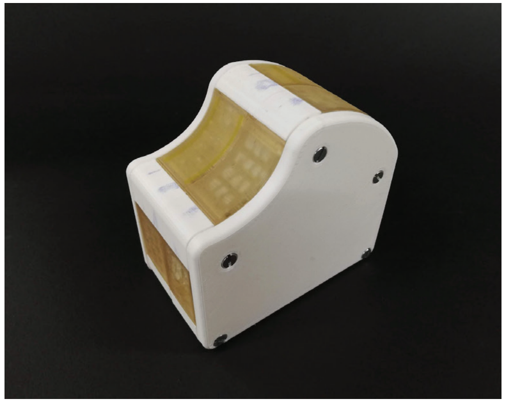


Figure 131: roughness sensor mechanisms testing tool

2. Texture actuators
Two sided Block with 8 actuators (figure 132), to observe the variable texture experience through changes in:

- Size of actuator (small, large)
- Height displaced (controlled with 3D printed hydraulic system)
- Duration of deformation (slow and fast)

Figure 131: roughness sensor mechanisms testing tool

Test

The research is conducted with three participants with no prior experience in tactile environments, nor acknowledged about the project research. The test is structured in three parts:

Part 1 and 2: feeling variable textures

Participants are given the roughness sensor and texture actuation testing tools separately, and the first impressions are observed, along with how differences in the design elements affect this impression, and how participants interact with the surfaces (pressing angle in the case of the roughness sensor).

Figure 133: part 1, interaction with roughness sensor tool

Figure 134: part , interaction with texture actuation tool

Part 3: feeling roughness and texture actuator simultaneously

Participants are instructed on feeling the roughness sensor and texture actuation mechanisms simultaneously, recording the impression, and the effect on participants' cognition.

This test is video recorded for observational analysis, and questions are asked to the participants regarding the different experience elements. Complete results and questions in appendix 19 (User testing of concept mechanisms).

Figure 135: Part 3, interaction with roughness sensor and texture actuation tool

Test results

1. Variable Roughness texture mechanisms

- *Participants express that they can feel a change in surface texture according to how much pressure they are applying on the surface*
- *Participants express that the dynamic surface texture felt odd, yet intriguing and relaxing.*
- *Participants are able to feel changes in patterns and shapes,but couldn't really understand why these feel different (without observing).*
- *Changes in the structure shape, pattern and curvature resulted in a more/less pleasant pressing experience. Concluding in a better experience with a larger pressing range (more depth).*

2. Texture actuators

- *Participants are overwhelmed initially, but able to identify the signal of individual actuators (after accustoming to it).*
- *Participants mention the feeling of the actuators as organic, relaxing and natural, almost like a "living"" in the palm.*
- *Actuation feels like a pinpoint signal, but spreads and fades rapidly.*

3. Simultaneous use

- *On a first impression an overwhelming number of stimuli, however after multiple cycles, participants mention being able to focus on the different actuators and while feeling the surface roughnesses.*
- *Harder to concentrate, however, focus improves rapidly.*

In addition to these qualitative results, preferences for the design elements of the texture mechanisms are obtained (appendix 19, User testing of concept mechanisms), which are integrated into the demonstrator.

8.2.2 Demonstrator shape and assembly design

Up to this chapter, the concept mechanisms have been developed and tested, along with the overall elements of the concept. Therefore, this has to be shaped into a physical construction to perform the concept user test.

It is important to mention that this is not how the final product would look like, instead this shape is the first prototype demonstrating the concept value as a whole.

Requirements

The shape of the demonstrator must be able to fulfil the following requirements:

1. Variable **roughness sensors will be placed on the top of three fingers** (thumb, index and middle finger). During the user tests, participants experienced a more ease and familiar pressing experience when pressing with the thumb and index finger. However a third mechanism is added to showcase the concept and observe the user interaction.

2. **Pressing angle onto the roughness sensors** shall occur at a slight tilt (~20 degrees), as participants mention this to be the most pleasant pressing angle while being able to identify the variable roughness (chapter 19, user testing of concept mechanisms).

3. Roughness sensor mechanisms shall have at least **one mechanism with a concave surface** for demonstration (chapter 19, user testing of concept mechanisms).

4. During the user test, participants demonstrated difficulty identifying 3 actuators, however this improved drastically with time. **Three actuators on the palm, and one actuator on the little finger** will be implemented.

5. During the user test of texture actuators, skin contact with these actuators varied regarding the hand placement (resulting in inconsistent results). Therefore, the demonstrator shall have a shape in which **skin contact with the actuators is constant.**

6. The shape must be **sturdy** enough to withstand the holding and pressing onto the surface mechanisms. In addition, the hydraulic **plumbing and wiring shall not be visible** on the demonstrator surface.

7. **Texture mechanisms must be removable,** to account for mechanism failures and allow for repairs without the need for an entirely new demonstrator.

Placement of texture actuators

In chapter 8.1.4, the feasible locations on which texture actuators can be placed is elaborated. Therefore, acknowledging that 3 actuators will be placed on the palm, the location of these can be determined (figure 136).

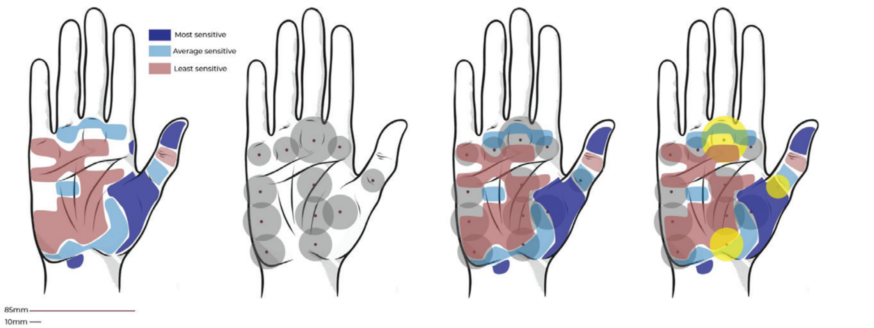


Figure 136: first image locates skin areas with a lower (PPT) (Fransson-Hall & Kilbom, 1993), second image presents the error in localised touch (Nakada, 1993), the third image overlays the localised error with the respective PPT. The fourth image showcases three selected pressure points (yellow) with a low PPT and sufficiently distanced apart.

Demonstrator shape prototyping

The shape housing the texture mechanisms is FDM (filament deposition modelling) 3D printed with PLA (Polylactic Acid) as this allows for extensive design freedom at a low cost and rapid manufacturing.

The design requirements are established, therefore rapid prototyping is carried out to successfully meet these demands (figure 138), with a focus on surface pressing angle, number of mechanisms and permanent skin contact (figure 137).

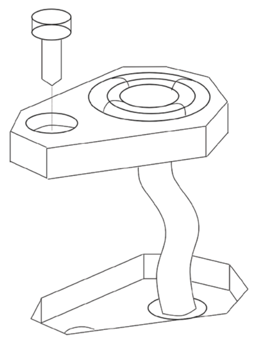


Figure 137: attachment of mechanisms to the demonstrator for rapid removal during repairs

Figure 138: shape inspiration from ergonomic handheld controllers with direct skin contact along the entirety of the palm.

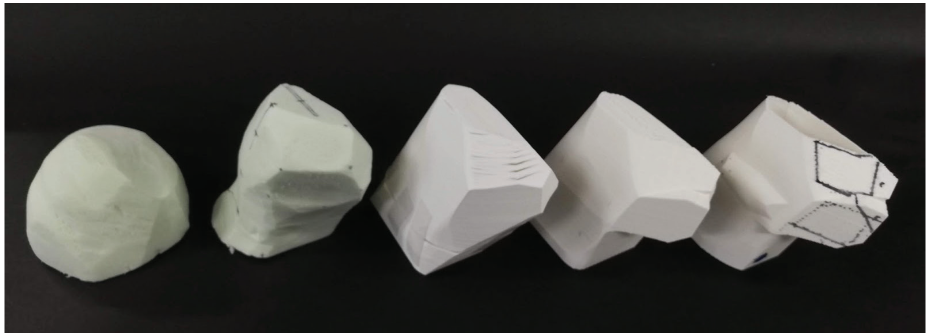
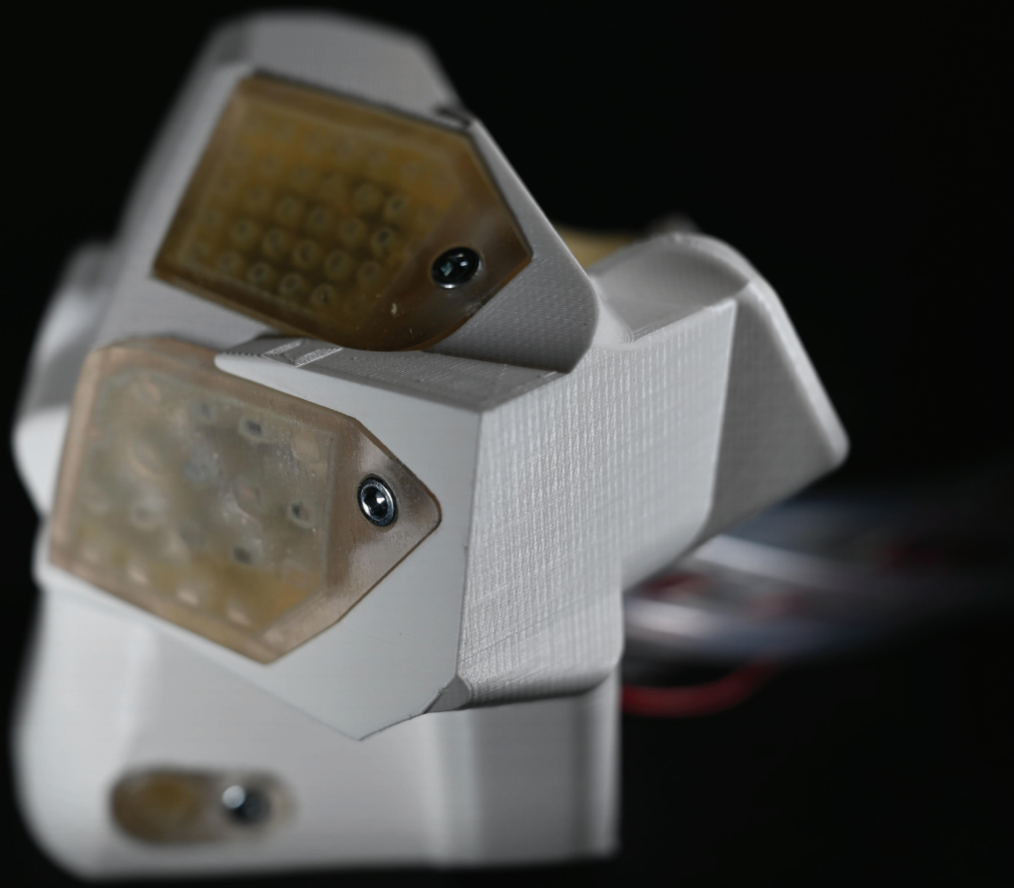
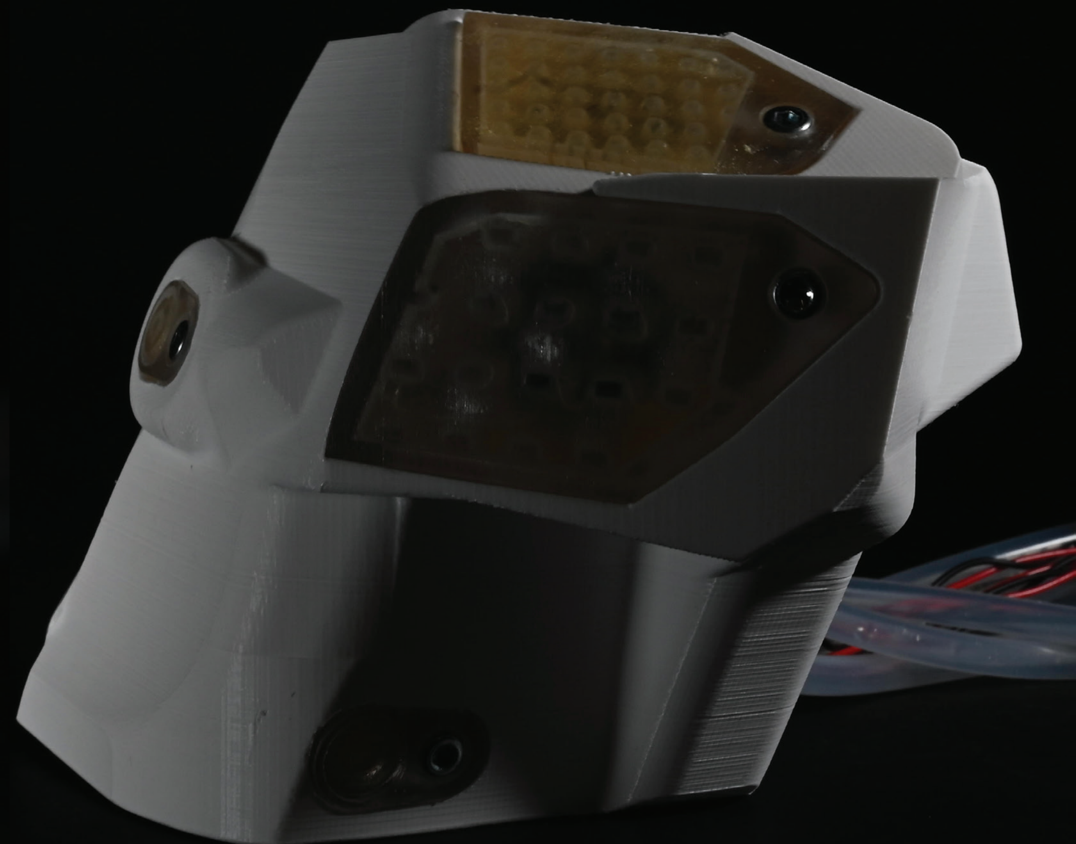


Figure 139: prototyping iterations for demonstrator shape

8.2.3 3D printed fluidic system, haptic controller demonstrator





Demonstrator design features

Figure 141: Analog force sensor underneath roughness sensors to measure input signal from the user

Figure 142: attachment of texture mechanisms

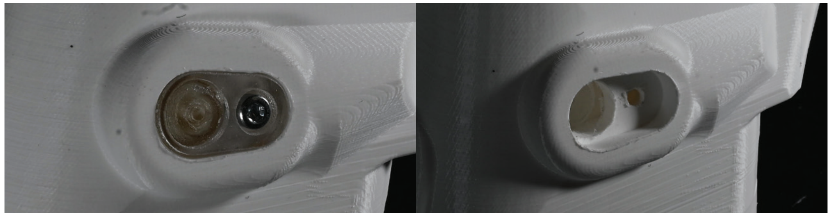


Figure 143: roughness sensor flat and concave surface curvature

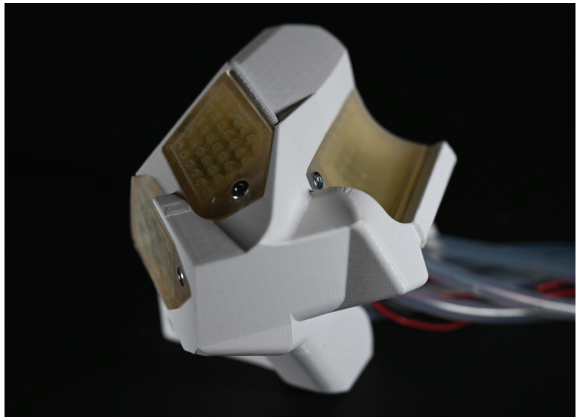


Figure 144: demonstrator interaction ergonomics

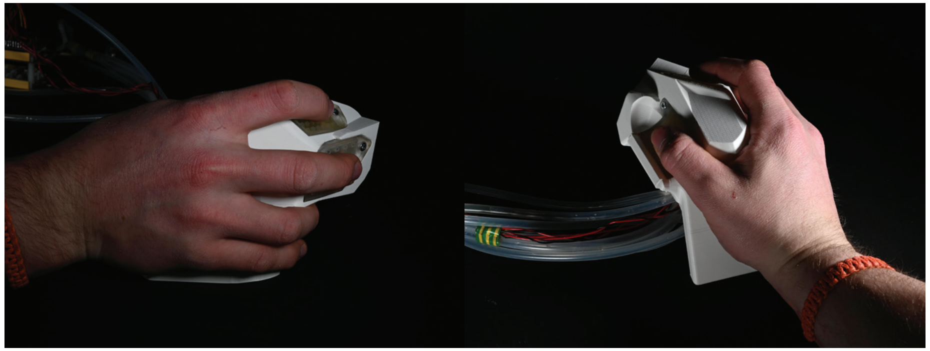
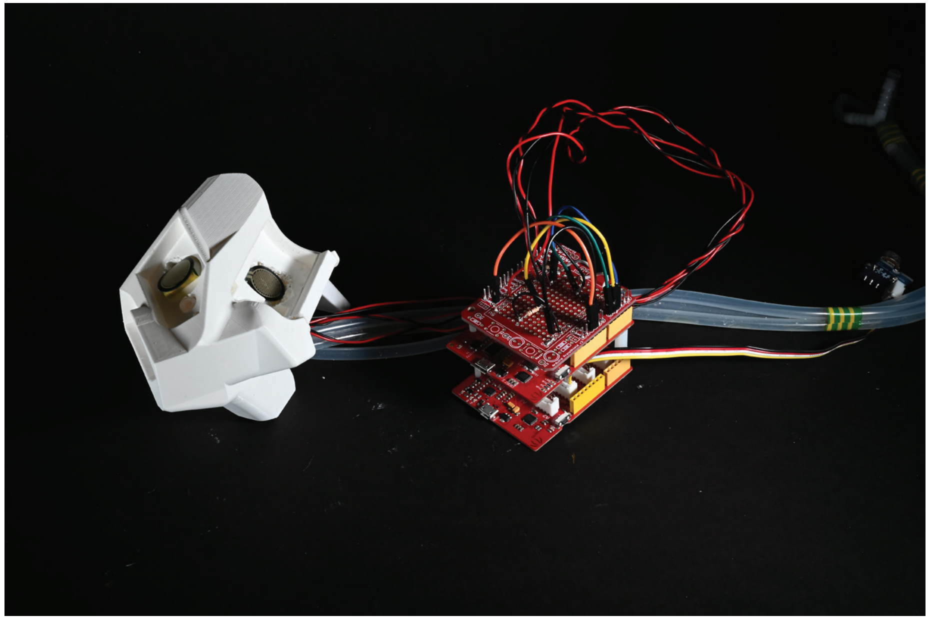


Figure 145: hydraulic plumbing and arduino controller externally located



8.2.4 Demonstrator user test

The objective of this qualitative study is to discover how participants experience the use of dynamic surface textures for an interactive product-user tactile communication. The research questions are the following:

1. *How do participants experience these textures cohesively, when actively sending an intended signal to the "computer" (arduino visual), while simultaneously receiving ones too (texture actuators)?*
2. *How is participants' cognition affected when actively engaging with the signals from the surface sensors and actuators?*
3. *Can participants' feelings be influenced through different texture actuation patterns and speeds?*

With these research questions, it is important to establish how participants can be engaged in the product interaction in order to obtain qualitatively valuable results:

Test setup

Each texture roughness sensor is connected to an analog force sensor, which measures the force being applied onto roughness sensors in real time. This data can be converted into an onscreen visualisation with Arduino Processing (figure 146) (appendix 20, demonstrator design and testing, for Arduino and Processing codes), from which participants can engage, as a result, mimicking the concept digital interaction on a basic level.

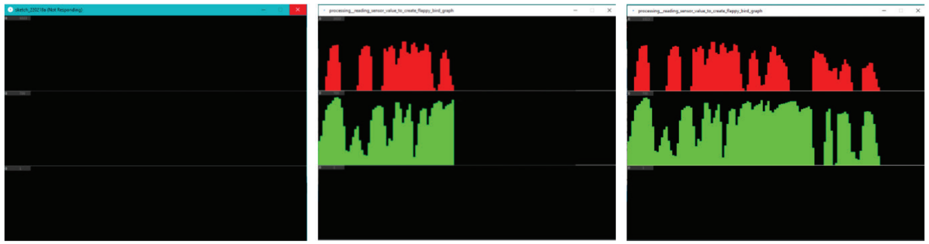


Figure 146: arduino processing visual

For the chosen visualisation (with the time available and previous programming experience) three continuous drawing screens are placed on top of each other (one screen for each roughness sensor). When the test activity is started (after accustoming to the variable texture mechanisms), the "drawing line" will move from left to right, with vertical movement when force is applied on the roughness sensor. As a result, a drawing is screened from each sensor.

With the visual interaction established, the user test is conducted through instructing participants what they have to "draw" (figure 148). These drawings are variations of lines (figure 147), which appear on paper. With these instructions in mind, participants will actively engage with the roughness sensors, meanwhile different texture patterns are occurring cyclically simultaneously. Participants will be video and audio recorded, and the visual graphics will be saved to be used during the results analysis.

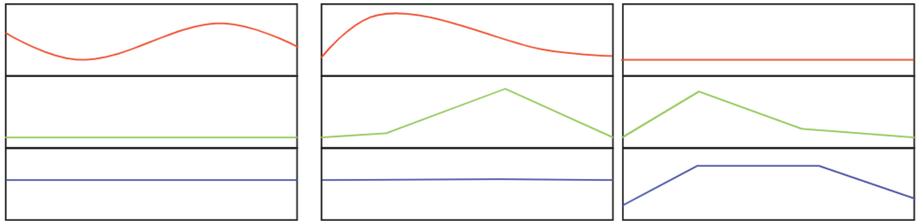


Figure 147: drawing instruction for participants.

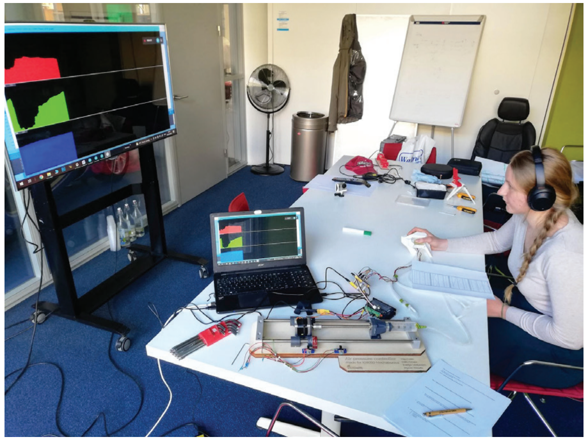


Figure 148: testing setup. Participants face the digital visual, wearing noise cancelling headphones to avoid distractions caused by the hydraulic pump

Test results

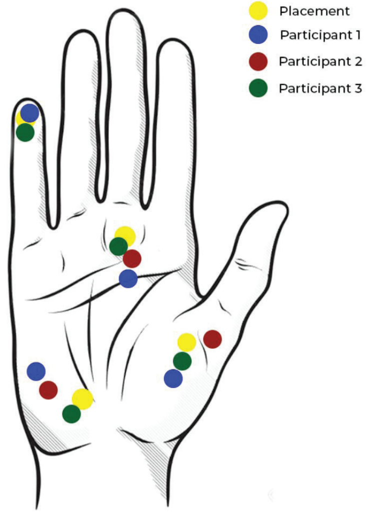
During the testing, participants (total of 3) are firstly introduced to the variable roughness sensors, successfully validating the design guidelines for effective variable roughness perception mechanisms (appendix 19, user testing of concept mechanisms).

When introduced to the roughness sensor's visual interface, participants recognize a more immersive digital experience (compared to a standard computer mouse), as their tactile roughness perception is significantly greater when they want to communicate a certain signal to the digital interface. However the use of 3 roughness sensors is mentioned to be too many, due difficulty with completing the activity instructions, result of exercise inexperience (not due to a sensory overload).

When participants are introduced to all 4 texture actuators, this is a noticeably strong signal, however, when participants exercise simultaneously with the visual activities (interacting with the roughness sensors, while the actuators are cyclically being activated in the palm), this signal perception is significantly weakened. As a result, participants mention no cognitive distraction result of the actuators signals, while performing the activities

When the texture actuation pattern is increased in cycle speed (2.5 times faster) during the instructed exercises, participants are not directly receptive to this change. However, when asked the placement of the texture signals, individual signal points are being recognised (figure 149).

FIgure 149: allocation of texture actuators according to test participants, (From left to right: placement, participant 1, participant 2, participant 3). A cause for slight placment deviation can be result of changes in hand sizing



8.2.5 Conclusions and further research

The content of the concept is fully elaborated in the previous chapters (8.1 and 8.2), however, this is a first version of such an idea and therefore improvements can be made during further developments, and unknowns can be answered through additional research (unknowns extracted from the concept elaboration and user test).

On a first observation, participants showed that the actuators' signal and pattern speed had no impact on their **cognition**. However, it is unknown whether it is the result of the cyclic pattern of these. Therefore, it is recommended to perform a quantitative study comparing different actuation patterns (repetitive and non-repetitive) to the input visual result quality.

The use of 4 different **actuators** has been successfully demonstrated to be recognisable by the participants. However, with this result, it is unknown **how many** of these can actually be used, while still being identifiable. In addition, it is unknown when sensory overload will occur, and whether different actuation patterns will affect this. In addition, the influence of tactile experience is another factor to consider in this equation.

The observed value of this concept lies in two **potential applications**, either for an digital immersion or for creating a new haptic communication language.
This first application, the use of this concept for a deeper **digital immersion** would require the texture actuators to be designed such that the deformation elements could noticeably be perceived, and the most effective patterns each intended emotional impact to be found for (demonstrating this first).
The second possible product application could be the integration of the texture actuators l**anguage communication** when individually controlling each texture actuator, either for obtaining information from a system, or to create an entirely new haptic language (replacing braille), with the main benefit of this being the direct haptic translation of information, without the need of visual contact. However it is unknown how long it would take to adapt to such a new language.

Durability of the 3D printed texture mechanisms is poor, therefore, this technique is recommended for the research, and product development of the concept. However, if this concept is to be produced into a product, alternative manufacturing methods might be necessary to improve fatigue resistance.

Finalising this concept research, the demonstrator has proven successfully that this concept idea can be used to improve the existing digital interactions. However, when comparing the use of variable roughness sensors, to the use of texture actuators, this last shows larger promise when implemented into haptic devices, with the intent of creating a new communication interface, or improving immersiveness experience.

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10. Appendix

Appendix 0: 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 !

family name: Speijer Diez 5375
initials: P given name: Pablo
student number:
street & no.:
zipcode & city:
country:
phone:
email:

Your master programme (only select the options that apply to you):
IDE master(s): (★) IPD ( ) Dfl ( ) SPD
2nd non-IDE master:
individual programme: - - (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: Zjenja Doubrovski dept. / section: SDE-MF
** mentor: Willemijn Elkhuizen dept. / section: SDE-MF
2nd mentor:
organisation:
city: country:
comments (optional)

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.

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

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30 Page 1 of 7

Procedural Checks - IDE Master Graduation

TU Delft

APPROVAL PROJECT BRIEF

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

chair: Zjenja Doubrovski date: 05 - 11 - 2021 signature: Digitally signed by Zjenja Date: 2021.11.05 17:14:15 +01'00'

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
Of which, taking the conditional requirements into account, can be part of the exam programme: 27 EC
List of electives obtained before the third semester without approval of the BoE

(★) YES all 1st year master courses passed
( ) NO missing 1st year master courses are:

name: J. J. de Bruin date: 17 - 11 - 2021 signature: J. J. de Bruin, SPA Digitally signed by J. J. de Bruin, SPA Date: 2021.11.17 11:05:21 +01'00'

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

comments

name: Monique von Morgen date: 23 - 11 - 2021 signature:

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30 Page 2 of 7
Initials & Name: P Speijer Diez 5375 Student number: 4534727
Title of Project: 3D Printed Dynamic Fluidic systems

3D Printed Dynamic Fluidic systems — 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 10 - 09 - 2021 — 18 - 02 - 2022 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, ...).

Fluidic interfaces is a novel concept and approach of an interactive material utilizing fluid channels. In these dynamic fluidic interfaces, fluid is considered as the medium to drive tangible information triggered by deformation, and at the same time, to function as a responsive display of that information. This concept has been explored on a small scale, in which a set of simplistic venous structures were designed that respond to mechanical inputs from the user, and act as embedded analog fluidic sensors, dynamically displaying flow and color change (See image XX).

This existing concept mentioned above is constituted of three thin silicon sheets, which need to be individually laser engraved, manually deposition internal fluids and adhesived together. This design reveals a complex, yet simple programmable dynamic interface. However, the use of such processes is highly time consuming, in addition to highly limiting in terms of complexity, manufacturing scalability, product integration and new human-product interaction opportunities.

Dynamic interfaces can allow products to change and adapt their appearance dynamically as a result of external influence. This, with the technology of multi-material 3D printing, can create new value for product interactions, as complex three dimensional shapes can be created, and new triggers can be designed into products or parts. However, the use of 3D printing for this concept is yet to be accomplished. Therefore, during this project new opportunities are explored regarding the use, interaction, manufacturing and product integration of this concept. Considering the novelty of this concept and design process, fluidic interfaces might just be the beginning of a new series of products and applications that make use of 3D printed fluidic systems.

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introduction (continued): space for images

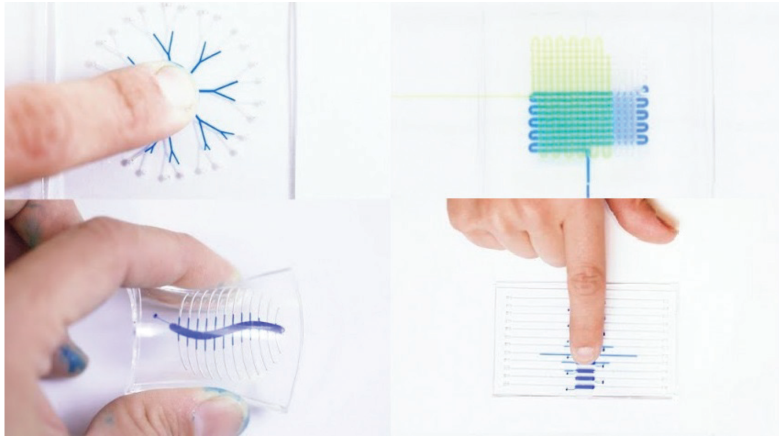


image / figure 1: Existing concept, consisting of 2-dimensional simplistic dynamic fluid interfaces test samples

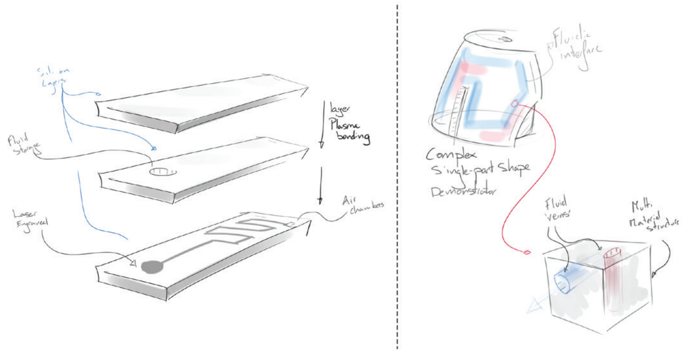


image / figure 2: Current developed fluidic interface structure (left), and assignment proposal (right)

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 existing fluidic interface concept is severely limited when it comes to possible product integration opportunities. This is due to their laminated silicone structure, which is laser engraved and assembled by hand. As a result, only two-dimensional dynamic shapes are possible to design, and therefore lacking in freedom of complexity and market desirability.
The scope of the project will be achieving three dimensional soft and fluid structures, making use of multi-material 3d printing, with the goal of discovering and creating new product interaction value. Thus, the challenge will be to discover which are the principles for 3d printing soft and liquid materials collectively into a functional fluidic system.

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.

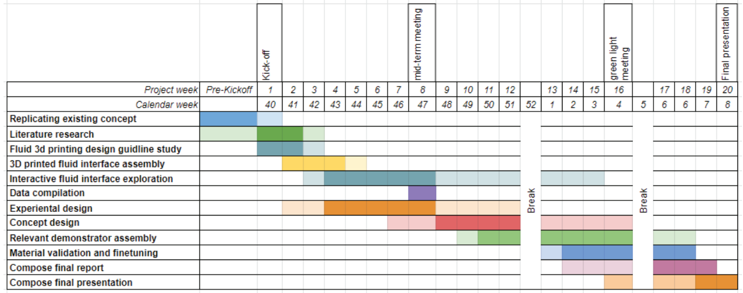
In this assignment, we will be researching how to generate, design, and create 3D printed venous fluidic systems, which are able to react and respond to different physical inputs, with the ultimate goal of creating value for new product interactions.

This project will be divided into two main phases. During the first phase, extensive research will be done regarding how to 3d prints parts with fluids in them, and then how to integrate these into more and more complex structures. The goal is to create parts that can displace these internal fluids (output), when a certain input occurs, which can be a human interaction, but also non-human. This output can be a change in appearance, or yet something to discover. Therefore, in order to discover these working principles, guidelines, mechanisms and find new product opportunities, extensive material tinkering will be performed, through samples, prototypes and iterations, generating valuable concept directions.
During the second phase of this project, the concept direction with most value (viability, desirability. feasibility) will be chosen and elaborated further into a demonstrator. However this concept application is not yet set, as relevant uses are perhaps yet to be discovered. Having such specific application goals as objective in this phase, it will allow finetuning and ensure mechanical, material, experiential, and repetitive validation of the fluidic systems.

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 10 - 9 - 2021 18 - 2 - 2022 end date



The main purpose of this project will be providing research and knowledge regarding the capabilities of 3d printing fluids in printed parts in order to achieve changes in appearance during an interaction. During the first half of this time, extensive research and prototyping will be carried out in order to discover and map different capabilities of this new concept along with the necessary design guidelines. Having compiled the data gathered during this timeframe, different suitable new future applications will be elaborated during a concept design phase, which one will be chosen and further developed into a product demonstrator. When designing this final concept, material testing and finetuning will be carried out in depth.

During the first Xmany weeks 4 weekly hours will be dedicated to TA work, however, full time hours can be assumed for the graduation project as the TA hours will be compensated along the week. Two breaks will be taken during the project, calendar week 52 (2021) and calendar week 5 (2022).

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.

This project has been chosen for my graduation project, as a result of the experiences build upon the bachelor and master courses:
During the bachelor Industrial design engineering, my affinity during projects went towards the technical side of design, with a deep emphasis on manufacturing, material design, computational design and rapid prototyping. However, considering this, I personally believed that more complete and scientific projects were missing during this education. Therefore, I chose the master Integrated product Design
During the master courses AED and ACD i truthly discovered that my motivation as a product designer lies in the capability of designing for manufacturing, in other words, designing and assembling products for ease of fabrication and optimal performance while taking into account costs and resources. This foundation and motivation was strengthened with electives such as 'digital materials', 'material driven design' and 'design with composites'.
Meanwhile besides the master courses, at home I worked on different projects. Firstly acquired a 3D printer which is being used on a daily basis for small projects, which broadened my knowledge and motivation regarding rapid manufacturing and CAD software. However, my main project is the construction of a high speed aerial photography drone, in which the use of rapid prototyping, electronics, software, and mechanical design are a consistent cycle.
These projects, courses and activities have driven me to pursue a graduation project that emphasizes the previously mentioned topics, as subsequently I envision myself working in the design engineering department.

FINAL COMMENTS

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

Appendix 1: Replicating existing fluidic interfaces concept

Silicone sheet moulding

Silicone sheet moulding

The goal is replicating 1.5mm thick PDMS sheets used in the existing concept. The requirements are the following:

1. Smooth and level surface: without this, inconsistencies will appear during laser engraving.
2. Free of bubbles: these can affect the laser engavring and possibly the working of the interface

Why this should be replicated?

-**Costs**: many 2d test can be done for little costs

-**Valuable knowledge** regarding:
a. Fluid channeling sizing
b. ratio of air and fluid chambers for sensitivity

-Possible use of laser engraving in future prototypes

Available silicone material

Silicone A40 fast

Making use of shore A40 silicone. Demoulding time 15min

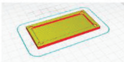
www.siliconesandmore.com

Silicone Addition Transparent 40 (Hard) - Fast hardening

The Silicone A Transparent are a very versatile 2-component (Platinum) Poly-addition pourable silicone which cures at room temperature.

A. 3D printed mould small

3d printed mould with dimensions: 30x70x1.5mm



Limitation: the small scale of the mould did not require much silicone mix. Therefore making it difficult to pour and mix the right quantities. In addition, mixing small quatities of silicone introduces lots of air bubbles.

A.1.1 Silicone vacuum and pouring

First vacum mix, then pour into mould
-Result: very smooth surface, but with a few bubbles which occured during mixing and pouring

A.1.2 Silicone double vacuum

First vacuum, then pour into mould, then vacuum again
-Result: very rough surface, unclear the cause.

B. Large silicone mould

Silicone mould with dimensions: 3.5x6.5cm. The larger scale should make mixing silicon easier.

Limitations:
- The large scale of the mould makes it difficult to precisily create a 1.5 mm thick sheet
-The resulting surface is uneven.

Next improvement
-Add spatula in order to level surface at 1.5mm

B.1 Silicone vacuum and pouring

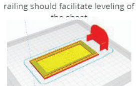
First mix, then pour into mould.
-Result: smooth but uneven surface, with lots of large bubbles.

B.2 Silicone single vacuum

First pour into mould, then vacuum.
-Result: very rough surface, unclear the cause.

C. 3D printed mould large with spatula

3d printed mould with dimensions: 40x100x1.5mm. A spatula and railing should facilitate leveling of the sheet



C.1 Silicone single vacuum

First pour into mould, then vacuum.
-Result: very rough surface,

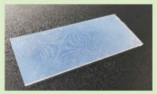
-Cause of rough surface: the silicone mix cures within 15 minutes. Due to this, the liquid silicone starts hardening when boiling under vacuum, thus unable to smooth out.

D. Silicone A40 slow

Making use of shore A40 silicone. Demoulding time 6 hours. this longer curing process should allow time for vacuum and smooth leveling

D.1 Silicone double vacuum

First vacuum, then pour into mould and smooth with spatula, then vacuum again
-Result: very smooth surface, thickness 1.5mm+-0.2mm



D.2 Silicone double vacuum

First vacuum, then pour into mould and smooth with spatula, then vacuum again

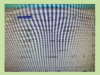
Thick layer created for the base. This will provide a stronger support and

Silicone laser engraving

Silicone Laser engraving

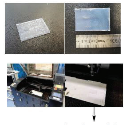
The goal is to engrave 1mm deep into the silicone. The two most important machine variables are:

1. Laser head speed: a faster laser with burn-off less material, and a slower head, will burn-off more material.
2. Laser power: to more power, the more material will be burned off.



Sample

a 1.5mm thick sheet is used to test different laser speeds and power



Sample needs to be taped in place

Engrave tests

Cutting 1: speed 500, power 20 Thickness +-
Cutting 2:"". ".", power 25 Thickness +-
Cutting 3:"". ".", power 30 Thickness +-
Cutting 4:"". ".", power 35 Thickness +-
Cutting 5:"". ".", power 40 Thickness +-
Cutting 6:"". ".", power 40, double area as 5 Thickness +-

final cutting: speed 200, power 57: Depth 1mm exact
speed 150, power 57: Depth 1.25mm
speed 100, power 57: Depth 2mm

Laser engraving parameters library

Engraving	*Depth*	*Speed*	*Power*	*Repeat*
Repository	0.9mm	45	75	2
Repository	0.45mm	45	75	1
Channel	0.1mm	60	60	1

Figure 10. Laser engraving parameters library.

Safety data sheet

Silicone sheet adhesion

Silicone sheet adhesion

The goal is to 'glue' sheets together. For this, silicone mix itself will be used. The factors that need research are:

1. when adhesion is the optimal, considering the mix curing time.
2. engaving:

Adhesion test

Initial test to asses silicone as a bonding material. Result: sheets proved to adhere strongly, however, with enough force, these can be peeled-off/separeted

Adhesion test 2

Silicone mix is applied onto a base sheet. The engraved samples are placed onto this sheet. placing the engraved samples on top can reduce the chance of silicone mix blocking the channel due to gravity.

Better adhesion

10min 5min 3min 1min

Fluidic interface samples

Silicone Laser engraving

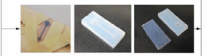
In this chapter a first fluidic interface will be made. This sample will be used as the starting point for upcoming variables tests

Sample

a 5mm thick sheet is used as a base, a 1.5mm sheet with a punted hole for the repository and a 1.5mm sheet for cover

Sample design size

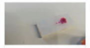
repository= 8mmD,
chamber=4mmD
Repository Ratio:
repository(mm2)/airchamber(mm2)=2



Engraved Depth:
1mm

Sample 1

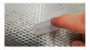
Fluid interface works, however:
1. Air bubles are present in the fluid repository thus the pressed force does not fully tranlate to fluid displacement
2. Viscosity of the coloring is too high, therefore liquid gets stuck in the channel



New video by pablo speijer

Sample 2

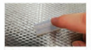
Coloring fluid is replaced with water. In addition, no bubbles are present in the repository.



New video by pablo speijer

Sample 3

Coloring fluid is replaced with water. In addition, no bubbles are present in the repository.



New video by pablo speijer

A.1 fluid repository ratio

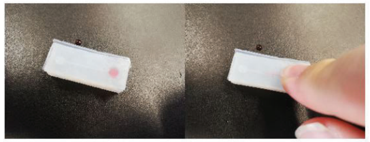
Test sensitivty of fluidic interface repository when integrating different repository sizes. Variables:
-Area and depth

However, for these tests just area is taken into consideration. As depth dictates the total volume necessary to fill the channel completely.

A.1.1 fluid repository small

Area of the repository is decreased by half.
repository= 4mmD,
chamber=4mmD
Repository Ratio: repository(mm2)/airchamber(mm2)=1

-The expected result is an increase of necessary pressure for interface actuation P=f*a.



A.1.2 fluid repository large

Area of the repository is increased by x1.5.
repository= 12mmD,
chamber=4mmD
Repository Ratio: repository(mm2)/airchamber(mm2)=3

-The expected result is an decrease of necessary pressure for interface actuation P=f*a.

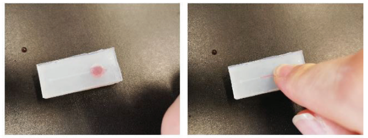
A.2 Air chamber ratio

Test sensitivty of air repository when integrating different repository sizes

A.2.1 Air chamber small

Area of the air chamber is decreased by x0.5.
repository= 8mmD,
chamber=2mmD
Repository Ratio: repository(mm2)/airchamber(mm2)=4

-The expected result is an increase of necessary pressure for interface actuation as the pressure in the chamber will become larger p1*v1=p2*v2.



A.2.2 Air chamber Large (skipped test)

Area of the air chamber is increased by xx.

-The expected result is an decrease of necessary pressure for interface actuation as the pressure in the chamber will become larger p1*v1=p2*v2. This test is skipped as the expected outcome can be guaranteed with test A.2.1.

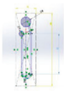
A.3 Fluid channel ratio

Test results of changes in length, width, height of fluid channels
- Length
- Section area
- Number of channels

These variables can play together, as the repository determines the amount of fluid displaceable, and the air chamber the pressure sensitivity. However the longer the channel, the more air that needs to be compressed. Therefore two tests will be done:

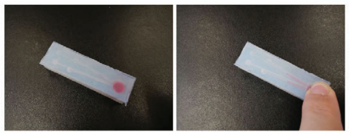
A.3.1 Channel long

Same Air chamber size as sample 2, longer channel and a larger repository (to fit enough displaceable fluid)



A.3.1 Multiple channeling

2. Same repository size and air chamber size as sample 1., but with and increased number of channels.



Appendix 2: Literature research method

During the literature, innovations are researched resembling what could be achieved or be replaced by a fluidic system. For this, three main search engines are used, finding sources, with or combining different keywords:

Research database search engines used

- Scholar.google.com
- Sciencedirect.com
- Youtube.com

Keywords used in search engines

- Fluidic system
- Hydraulic system
- Fluid channelling
- Fluid product
- Visual stimuli

- Physical output
- Soft mechanism
- Flexible mechanism
- Soft robotics
- Force transfer product
- Shape transformation
- Shape morphing
- Material memory
- Material healing
- Transforming material properties
- Transforming part properties
- Variable stiffness
- Dynamic stiffness
- Soft pumps
- Dynamic texture
- Transforming product
- Transforming material
- Controlled robotics
- Flexible robotics
- Stiff flexible robotics
- Hydraulic flexible robotics
- Dynamic magnetism
- Programmable magnetism
- Ferrofluid product
- Micro fluid
- Micro fluidic chips

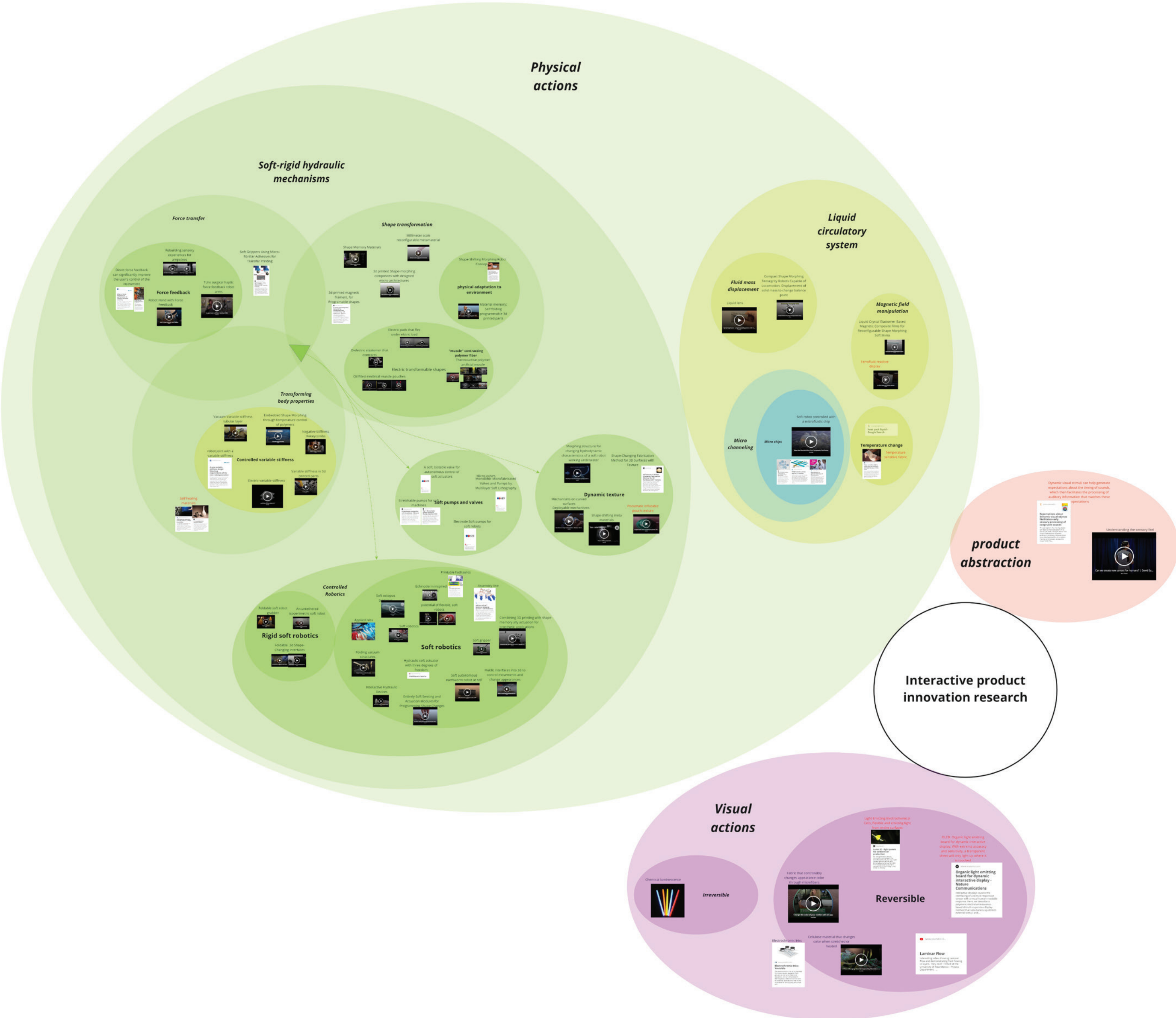
- Dynamic visual properties
- Dynamic appearance
- Programmable appearance

- Visual reversibility
- Product reversibility
- Reversible properties
- Material reversibility

- Haptics
- Product haptics
- Product abstraction
- Visual stimuli
- Sorority feel

Appendix 3: Literature classification of findings

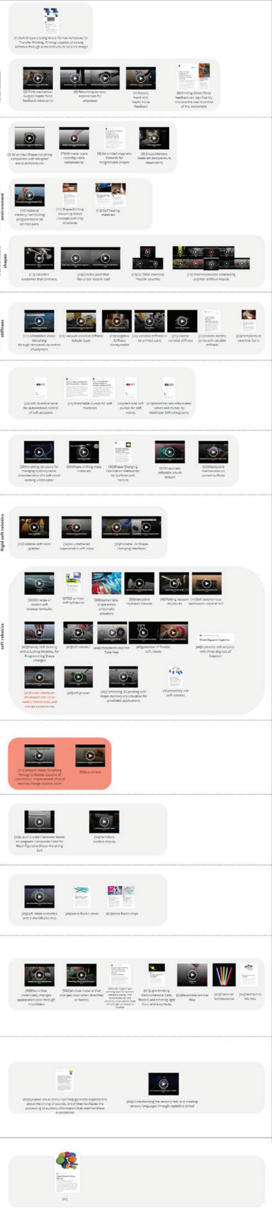
Scources clustered

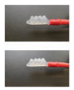
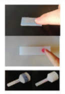


Classified scources

Literature Research summary

Existing research and innovation, regarding visual and physical actuators, and fluid channeling



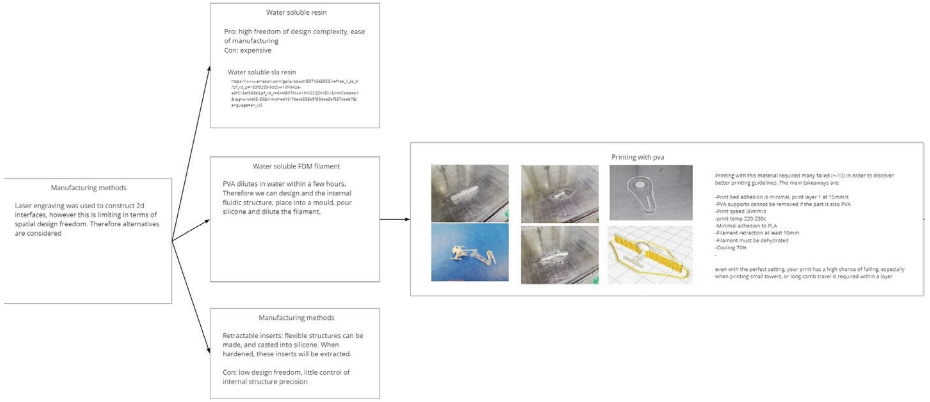
Group	Category	Research	Samples in this field	Where is being innovated	Missing knowledge or downsides	Innovation gaps
Physical output – Soft-rigid hydraulic mechanisms	Force transfer			• Research on 3d printed micro-structures that can serve as natural adhesives doe to their geometry	Very complex geometries, limited regarding manufacturing possibilities (extremely small), and application is case specific	
	Force transfer (Force feedback)			• Research to provide sensory feedback to user when controlling robotics, though either electric signals or motorized forces (pneumatic). forces are measured with force sensors	force feedback depends on motoric actuators	Non-electronic force feedback in soft bodies
	Shape transformation			• Research on materials that can be programmed (shape) during the manufacturing and be 'activated' through a trigger	Programmable bodies required yet very special materials	
	Shape transformation (physical adaptation to environment)			• Research on materials that can 'shape shift' to fit the surrounding environment, roll over, or actuate as pumps.	Shape shifting bodies are currently relatively very slow actuators	Bodies that can shape shift into different models
	Shape transformation (Electric transformation shape)			• Research on polymers that can contract under an electric load, delivering fast contractions and high strengths	Polymers fiber create lots of heat when contracted, in addition to requiring high voltages	
	Transforming body properties (Controlled variable stiffness)			Research on variable stiffness within a part through either: • Design of inner structure arrangement • Electric induced loads to soften the base material • Change stiffness through vacuum	- Systems are designed to change stiffness or absorb loads only in 1 direction (xyz) - When using vacuum, it can be either stiff or soft with no range between	Multi directional stiffness control (example: carbon fiber layers) Apply the vacuum and buckling methods into product design (non-adjustable)
	Soft pumps and valves			• Research on electrically activated pumps which are soft and stretchable structures, pumping liquid through pressing and stretching the body	Valves need to be electronically controlled and automated, therefore not autonomous	Independent and one way soft valves
	Dynamic texture			• Research on changing surfaces, through deploying shifting parts, or pneumatic inflated bubbles	Currently changing textures are comprised of assembled parts or complex metamaterials. Inflating textures are not precise nor able withstand force (unless high pressures are used)	Single body smooth controllable dynamic surfaces, including soft and rigid parts
	Controlled robotics (Rigid soft robotics)			• Research on foldable structures, that can bend in a desired direction through pneumatics. Though solid inner structures or high pressures they can retain strength	Currently folding structures are predesigned, and can be considered as rigids except for the intended application, Lacking in freedom and softness	
	Controlled robotics (soft robotics)			• Research on pneumatic actuators to control soft robots. Innovation regarding programming and sensing of actions, acquiring locomotion • Research being done to acquire 3-dimensional freedom of motion	- Lack of precise directional control in a 3d space yet (systems need to de computed for different actuators) - Soft robotics lack overall rigidity and therefore strength	Soft and rigid single body robotics, while providing strength and precision in 3 dimensions
Physical output – Liquid circulatory system	Fluid mass displacement			• Research on deformation of liquid inside objects to control the visible focal length • Prototype that can shift its inner center of mass (solid rather than liquid) in order to achieve locomotion		
	Magnetic field manipulation			• Research on actuated magnetic shapes, that can shape ship and move under a magnetic field	Currently on a micro scale	
	Micro channeling			• Research on the field of fluid micro-chips, which can be used to study biological and chemical analysis, but also computation of small tasks		
Visual	Reversible and irreversible actions			• Research on material variable material appearance along with innovation on reversibility of these		3d Appearance reversibility
product abstraction				• Research on the understanding of communication through creating new senses by using repetitive stimuli		Utilize pressure form texture and stiffness to sensory communicate
	Texture product					

Key summary points

Fist of, it is important to acknowledge the magnitude of the different fields that are being researched, and therefore additional valuable research might have been looked over.

- Force feedback is being implemented into remote controlled robotics, however are relying on electric actuators as these facilitate design and assembly of the controller (product).
- Materials are being developed that can recover its ´programmed´ shape however these can only remember one specific shape. Moreover, early prototypes are available of strong contracting polymer fibers, however these need to be electronically controlled and powered. In addition, concepts are in development to alter a shape through combing multiple strands on the exterior and work cohesively.
- Different concepts present methods to vary stiffness within a body, either through structural design, layered vacuum or raising the part temperature. However these are not adjustable with an extensive range nor offer distinction in direction.
- There are designs of foldable geometries, however these are case specific and cannot be applied to extensive fields.
- There is extensive research and developments regarding controllable soft robotics, these use mainly pneumatics, and are become more and freer in terms of 3-dimesional range of motion. However these lack strength and overall precision.
- There are little to no findable examples of products with variable centres of mass/inertia, except for spherical rolling robots.
- Dynamic visual appearances are in early stages of product design, relying mostly on computerized systems. Yet, there is a gap for dynamic reversible appearances non reliant on chemicals or electronics.

Appendix 4: Manufacturing fluidic silicone PVA prototypes



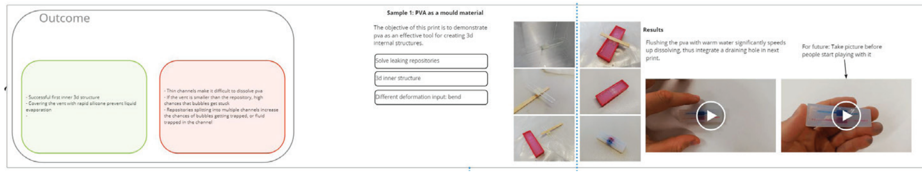
How to improve

- Silicone moulding
  - PVA
    - Pva needs to be supported/fixed from at least 2 points
    - Hollow 3d printed PVA structures can significantly speed up dissolving in water
    - Extraction of PVA parts becomes easy when previously soaked
    - PVA in channels smaller than 2mm are difficult to extract and dissolve
  - Mould
    - mould extraction is facilitated when the mould can be taken apart
    - mould extraction is facilitated when the mould is oiled
    - Silicone transparency is higher when the mould surface is smooth
- Silicone
  - More elastic silicone will reduce the chance of wall tears

New manufacturing techniques
Printing the soft model with a soft filament (tpu), then proceed to print, when the encasing is almost complete, pause the print and fill with fluid. Then resume the print to close the print.

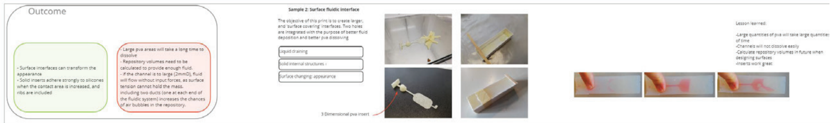
Appendix 5: Lo-fi material research prototypes

First 3D system



tinkering

Appearance: *Can we change how a part surface cover appears? How is fluid flow affected?*



How to improve?

- Width of fluidic surface affects the backflow of fluid (<1.5mm)
- Too wide of a channel incentivizes air bubbles into the interface
- Height of the channel has impact on fluid flow, too high lower the effect of surface tension (<1mm)
- volume of the repository MUST be calculated to provide enough fluid through the surface channel

Tactile: *can we change the shape of a surface?*

How to improve?

- Pva molding should be supported from multiple point to avoid differences in silicone surface thickness
- Air bubbles, and all round soft body reduce the effect on force feedback
- multiple opening can facilitate the pva extraction and reduce the chance of silicone tearing

Irreversability: *can we 'freeze' a fluidic interface (replicate existing concept)*

How to improve?

- with the use of a mesh, fluid will get trapped during the retraction, as a result of allowing less resistant channels
- Fluid will get flow into the meshes that have the same channel height (to be investigated)

Mechanism: *can we*

How to improve?

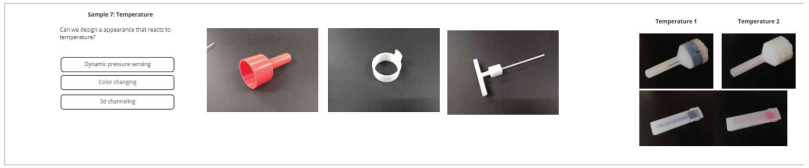
- Pva molding should be supported from multiple point to avoid differences in silicone surface thickness
- Repairing silicone tears has a big impact on the functional outcome, due to and increase in the part stiffness
- Silicone adaptor onto a hydraulic pump work good

Hydraulics: *can we control the direction of force and deformation when making a soft hydraulic system?*

How to improve?

- Pva molding should be supported from multiple point to avoid differences in silicone surface thickness
- Repairing silicone tears has a big impact on the functional outcome, due to and increase in the part stiffness
- Epoxy cannot be used to glue silicone
- A Silicone adaptor for a hydraulic pump is required, or else the system will leak

Temperature



How to improve?

- Silicone is a very good insulator, therefore surface thickness must be taken into account when

stiffness*: can we dynamically change the stiffness of a part?*

How to improve?

- Pressure must be significant to result in an increase in stiffness (with current dimensions)
- Epoxy cannot be used to glue silicone
- beforehand calculations must be done (the physics are there already)

Appendix 6: Robert mcCurdy design guidelines

Design constraints

Design constraints

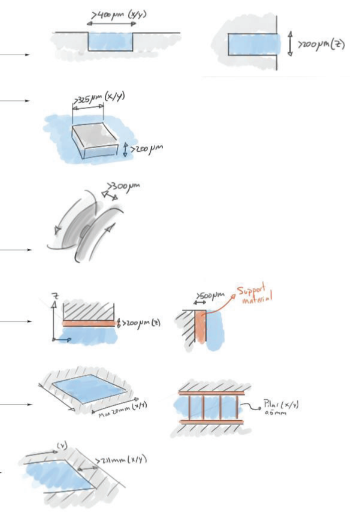
- Solid supports cannot be removed with ease at long narrow channels, closed channels, or channels with large volumes at the end, The solution is to add multiple purge ports that must be manually sealed in a time consuming post-processing step.
- The use of solids with varying stiffness allows certain portions to be more flexible, enabling prescribed strain in response to applied fluid pressure.
- Compared to previous work employing kinematic linkages or gears in active 3D printed assemblies, printed hydraulics offers low-friction, low-backlash, high force transmission elements.
- Objet Studio, automatically inserts several supporting layers underneath the model as it is being printed. Objet Studio will attempt to print the very first layers, the "carpet", with a hard model material, if available
- the inkjet nozzles can very precisely deposit droplets of ink, the precise height of each droplet is difficult to control. Even very small deviations in droplet volume could accumulate over many layers, resulting in printed layer heights substantially different from the CAD model. As a side-effect, however, the roller tends to push uncured liquid in the direction of the head's travel, forcing liquid to move out of its intended region, contaminating adjacent curing layers.
- The Objet260 datasheet specifies an X/Y accuracy in the range of 20-85μm, and a Z accuracy of 30μm when printing with multiple materials. However, we observed that the resolution at liquid-solid interfaces when printing liquids is substantially coarser.
- The most common failure mode occurs when unbonded cured material is swept up by the roller and deposited in the roller bath, clogging the drain that removes liquid. When this occurs, cured and uncured print material will often be deposited haphazardly over the build area, necessitating cleaning. It is critical that users become familiar with cleaning the roller bath assembly, the waste area, and the model heads before each print to ensure that the printer is ready to use.

Design Guidelines

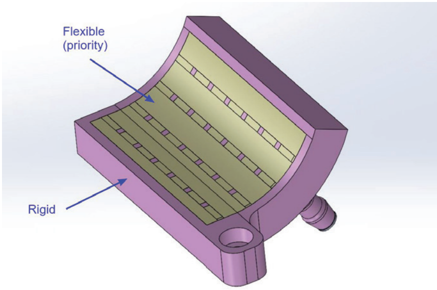
1	Separation (minimum along X/Y-axis):	0.4 mm
2	Separation (minimum along Z-axis):	0.2 mm
3	Feature thickness (minimum along X/Y-axis):	0.325 mm
4	Feature thickness (minimum along Z-axis):	0.2 mm
5	Feature growth (perpendicular to Y/Z-axis)	0.150 mm
6	Feature growth (perpendicular to X-axis)	0.2 mm
7	Solid-solid clearance at rotational joint	0.3 mm
8	Solid-over-liquid support thickness	0.2 mm
9	Solid-next-to-liquid support thickness	0.5 mm
10	Largest segment of liquid (dist in X or Y)	20 mm
11	Recommended width of support "pillars" inserted to connect model layers otherwise isolated by liquid; see Fig. 8 (X/Y-axis):	0.5 mm
12	Recommended solid feature thickness when adjacent to largest liquid segment (X/Y-axis):	2.11 mm

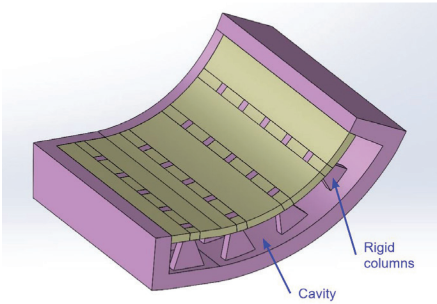
Design rules

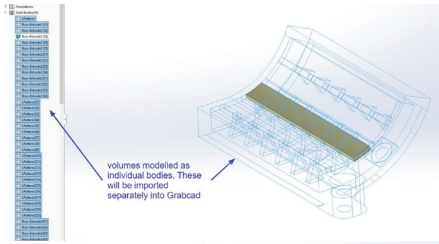
- The presence of the non-curing material inhibits the bonding between droplets of solidifying material within the current layer, and between subsequent layers. This effect is most pronounced at solid/liquid boundaries perpendicular to the print-head's direction of travel (interfaces parallel to the Y axis), and is exacerbated by long unbroken segments of liquid.
- (1 and 2) Different solid features must be separated by at least 400 μm of liquid in X/Y or 200 μm in Z to remain distinct
- (3 and 4) Solid features adjacent to liquid must be at least 325 μm thick in X/Y or 200 μm in Z to remain intact
- (5 and 6) features finish larger than designed. This is the case whether or not liquids are being printed, and the typical value is 150 μm normal to the surface; however, when printing with liquids this value increases to 200 μm for surfaces perpendicular (or nearly perpendicular) to the X axis
- (7) Printed rotational joints are a key component of printed robots, but adequate clearance must be provided to ensure that adjacent solids do not fuse while minimizing backlash; we found 300 μm to be an adequate trade-off
- (8 and 9) We discovered that introducing a thin shell of support material (by creating voids in the model geometries) that separates the solid from the liquid regions improves build-quality. as thin as 200 μm when the layer is nearly perpendicular to the Z axis, but should be at least 500 μm when nearly parallel to the Z axis(8 and 9)
- (10) Finally, large contiguous regions of liquid in any particular layer should not exceed 20 mm. achieved by changing the model geometry or inserting 500 μm diameter support "pillars". These support pillars are also employed to anchor a new layer of solid when printed on top of a liquid layer
- (11) Solid features adjacent to large liquid regions should be as thick as possible, particularly in the X direction

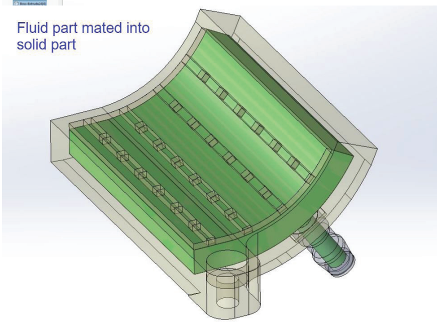


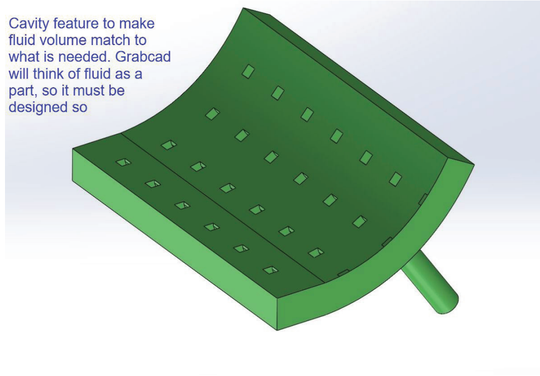
Appendix 7: Fluid print preparation

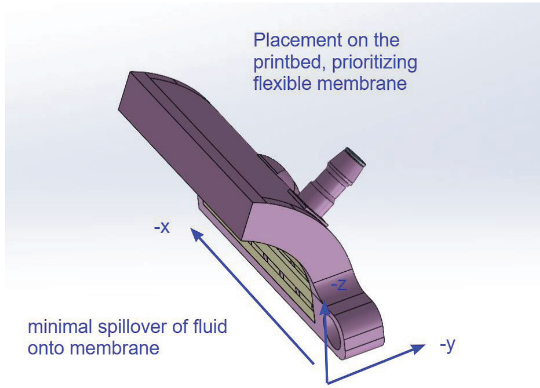


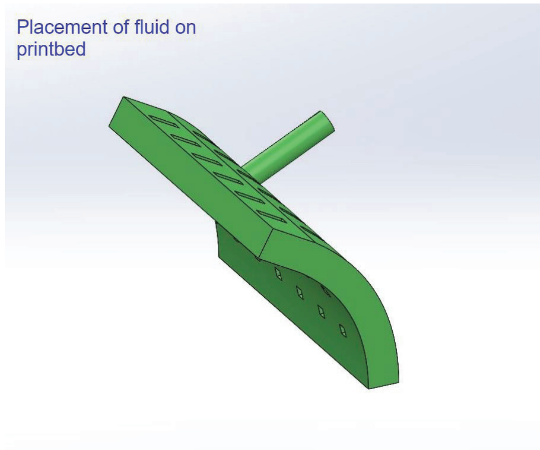


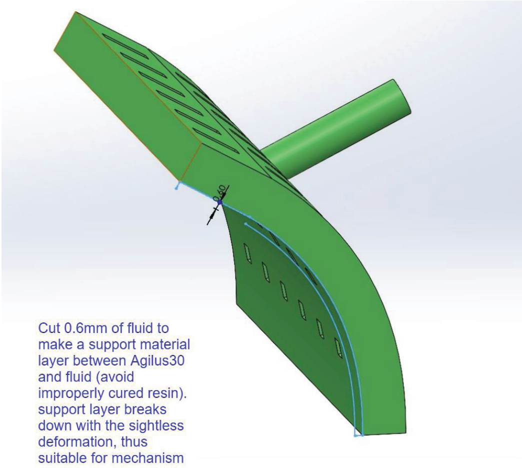


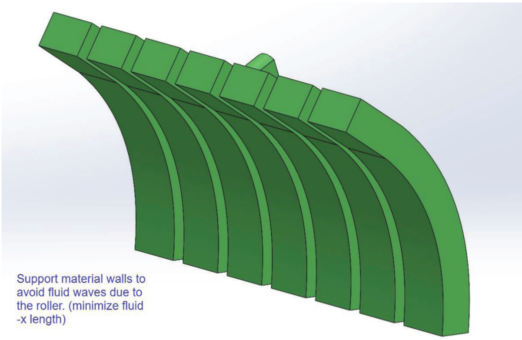


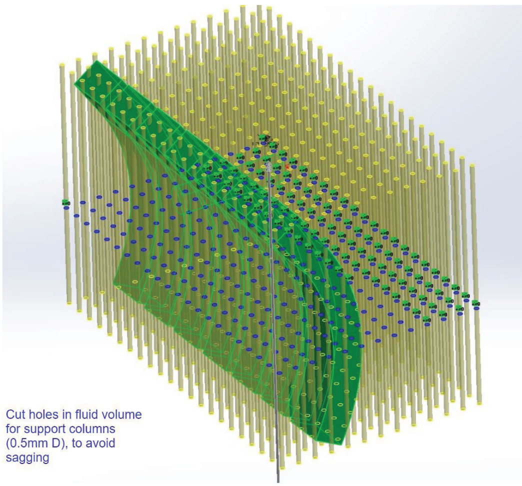


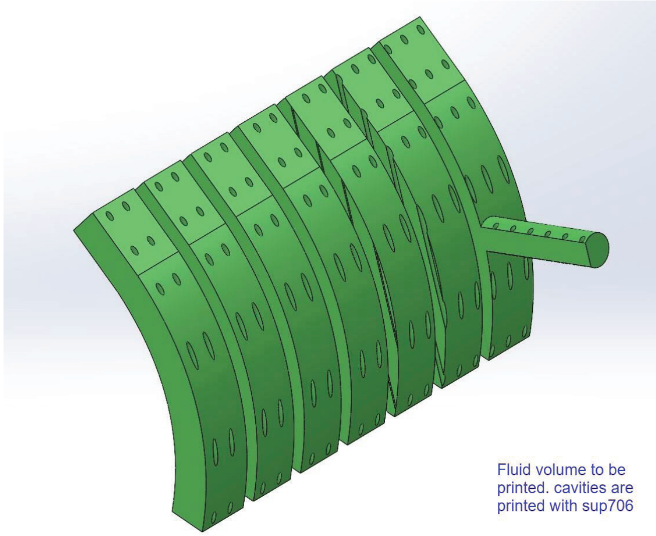


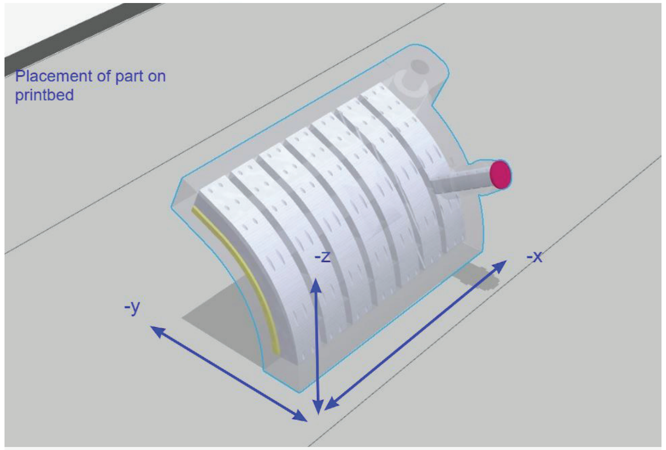


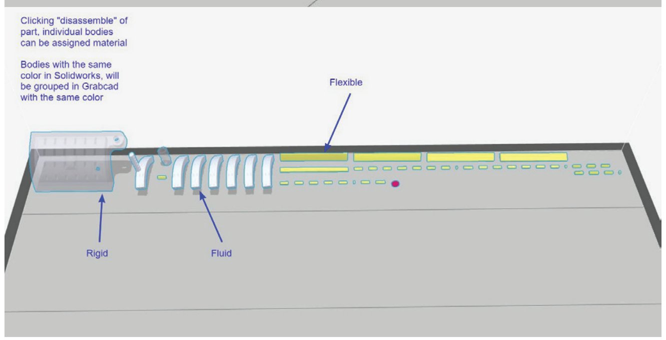

Cut 0.6mm of fluid to
make a support material
layer between Agilus30
and fluid (avoid
improperly cured resin).
support layer breaks
down with the sightless
deformation, thus
suitable for mechanism


Support material walls to
avoid fluid waves due to
the roller. (minimize fluid
-x length)


Cut holes in fluid volume
for support columns
(0.5mm D), to avoid
sagging


Fluid volume to be
printed. cavities are
printed with sup706


Placement of part on
printbed
-z
-x
-y


Clicking "disassemble" of
part, individual bodies
can be assigned material
Bodies with the same
color in Solidworks, will
be grouped in Grabcad
with the same color
Flexible
Rigid
Fluid

Appendix 8: 3D Printed fluid mechanisms analysis

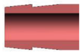
Hydraulic pressure measuring

Test force

Hydraulic pump diameter: 14.5mm
A=165mm2

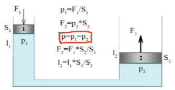
Manageable force before hydralic line expands and nozzle detaches: 2.2kg=21N

Force vs pressure



Hydraulic pump inner diameter=3mm
A=7mm2

4.9N (0.5kg) - 0.03N/mms
9.8N (1kg) - 0.06N/mms
21N (2.2K) - 0.127N/mm2



Expected forces:
F1/A1=F2/A2

F2=F1*A2/A1
F2=21N*3/165
F2=0.89N

P2=0.89N/7mm2=0.127N/mm2

Agilus 30 mechanical properties

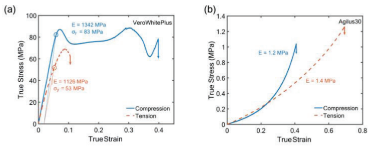
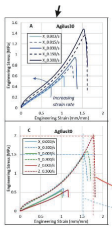


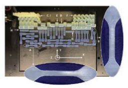
Fig 3. Tensile and compressive true stress – true strain curves for (a) VeroWhitePlus and (b) Agilus30.

Was not succesfully able to apply a elastic stress strain curve into a material simulation (crash everytime). Therefore introduced it as an linear elastic isotropic:

Elastic modulus E=1.4N/mm2
Poisson= 0
mass density= 1140kg/m3
Tensile= 2.4N/mm2
Compressive= 1N/mm2
Yield= 1.2N/mm2

Pressure: 50% of 0.127N/mm2= 0.063N/mm2





Elastic modulus E (z)=1.785/2=0.87N/mm2

Elastic modulus E (x)=1N/mm2

Surfaces will be printed algined on -x, assumming this for now:

strain= 1.5
Stress= 1.5N/mm2
Elastic modulus E=1N/mm2
Poisson= 0 (for now)
mass density= 1140kg/m3
Tensile= 2.4N/mm2 (assumming elastic behaviour till break)
Compressive= 1N/mm2
Yield= 2N/mm2 (assumming elastic behaviour till almost break)

Pressure: 50% of 0.127N/mm2= 0.063N/mm2

Property	Value	Units
Elastic Modulus	1	N/mm^2
Poisson's Ratio	0	N/A
Shear Modulus		N/mm^2
Mass Density	1140	kg/m^3
Tensile Strength	2.4	N/mm^2
Compressive Strength		N/mm^2
Yield Strength	2	N/mm^2
Thermal Expansion Coefficient		/K
Thermal Conductivity		W/(m·K)
Specific Heat		J/(kg·K)
Material Damping Ratio		N/A

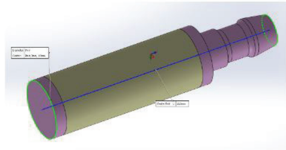
Big unknowns:
- **Actual exact force applied (pressure)**

Radial expansion

Sample 2.1

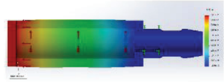
Model *Expected deformation*

Sample 1: 1.5mm shell, agilus30



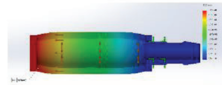
Sample 1: 1.5mm shell, agilus30,

- pressure: 0.03N/mm2 (0.5kg hydraulic pump)
- Expected deformation: 0.6mm

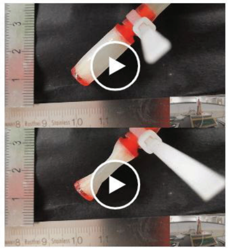


Sample 1: 1.5mm shell, agilus30,

- pressure: 0.12N/mm2 (2kg hydraulic pump)
- Expected deformation: 3.9mm at the tip



Printed sample and Results



Pressure

Vacuum

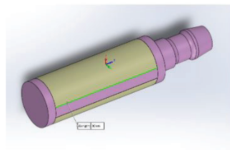
Result:
- Layer cracks occurred on the surface, as a result, one side is glued affecting the resulting deformation. Therefore, deformation cannot be compared to a simulation as it is affected by the repairs.
- Inward deformation (vacuum) is significantly larger than outward deformation (pressure)

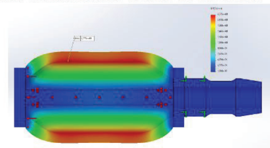
Sample 2.2

Model *Expected deformation*

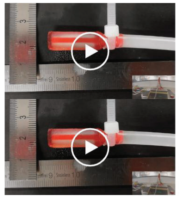
Sample 2: 1.5mm shell reinforced, agilus30,

- pressure: 0.3N/mm2 (0.5kg hydraulic pump)
- Expected deformation: 1.2mm at the width



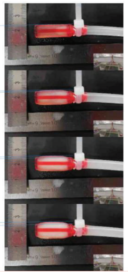


Printed sample and Results



Pressure

Vacuum



Result:

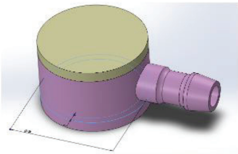
- Layer cracks occurred on the surface, as a result, one side is glued affecting the resulting deformation. However, deformation can still be compared to a simulation as the soft patched are individually separated.
- A 1.9mm deformation occurs under a load of 0.198Mpa. Deformation is linear

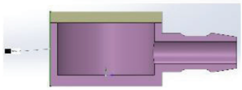
Sample 2.2: Printed vertically			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
1500	1340	0.07958787879	0.7
2400	2240	0.1330424242	1.2
3500	3340	0.1983757576	1.9

Dome inflation

Sample 1.1

Model

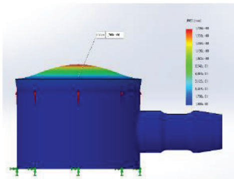


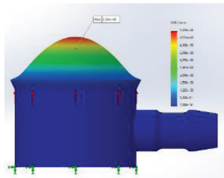


Expected deformation

Sample 1: 1.5mm top layer, agilus30,

- pressure: 0.01N/mm2 (0.16kg hydraulic pump)
- Expected deformation: 1.71mm





Printed sample and Results

1

Thin support columns (color cap)

Thin support columns (color cap)

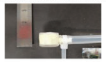
Result:

- The thin soft top layer deformed up to 2mm, under a load of 0.026MPa
- The thin soft top layer deformed up to 2.8mm before leaking, under a load of 0.043MPa
- Deformation occurs slowly as the soft layer is stretched

Sample 1.1 color cap			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
410	250	0.01484848485	1.3
600	440	0.02613333333	2
900	740	0.04395151515	2.8

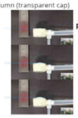
2

Thick support column (transparent cap)



Thick support column (transparent cap)

Irregularities on the surface are present



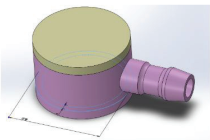
Result:

- The thin soft top layer deformed up to 1.8mm before leaking, under a load of 0.026MPa (equal as the other sample)
- Surface irregularities were present, as a result tearing occurred at low pressure, and initial deformation is slightly less than the one printed correctly
- Deformation occurs slowly as the soft layer is stretched

Sample 1.1 transparent cap (irregularities on the surface)			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
413	253	0.01502666667	1.1
613	453	0.02690545455	1.8

Sample 1.2

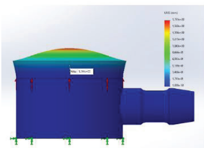
Model



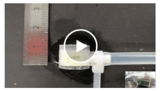
Expected deformation

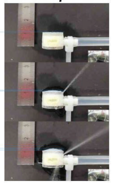
Sample 2: 2.5mm top layer, agilus30,

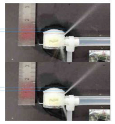
- pressure: 0.03N/mm2 (0.5kg hydraulic pump)
- Expected deformation: 1.73mm



Printed sample and Results







Result:

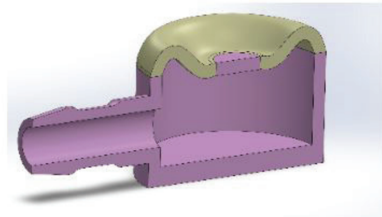
- The thin soft top layer deformed up to 2.2mm before leaking, under a load of 0.17Mpa
- As expected, the forces required are significantly higher than the 1.5mm thick sample. However the measurements cannot be taken into account, as the sample was leaking heaviliy during the test. As a result too much force is measured, compared to the actual pressure on the soft layer
- At the edges, outward deformation occurs. This has to be taken into account on a surface, as buckling may occur.
- Deformation occurs slowly as the soft layer is stretched

Sample 1.2: invalid measurement			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
1000	840	0.04989090909	0.7
1530	1370	0.08136969697	1.4
2465	2305	0.1369030303	2
3040	2880	0.1710545455	2.2

Displacement with minimal mechanical stress

Sample 3.1

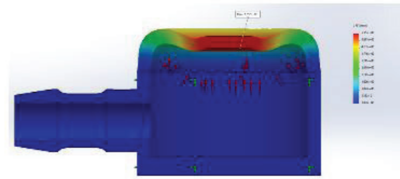
Model



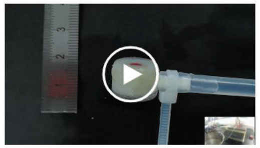
Expected deformation

Sample 1: 1.5mm layer, agilus30,

- pressure: 0.03N/mm2 (0.5kg hydraulic pump)
- Expected deformation: 5.3mm



Printed sample and Results



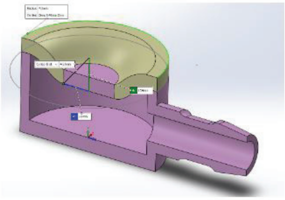
Result:

- Due to the geometry of the sample, direct measurements cannot be taken.
- Due to the geometry, a large deformation occurs with less force, compared to sample 1.1
- Deformation of 3mm under 0.016Mpa

Sample 3.1: Value not directly measured			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
430	270	0.01603636364	3

Sample 3.2

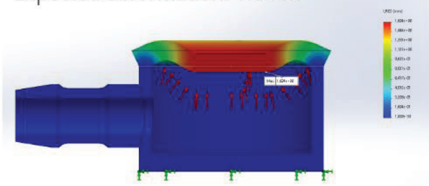
Model



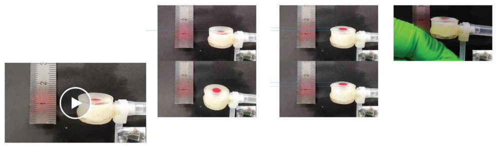
Expected deformation

Sample 2: 1.5mm layer, agilus30,

- pressure: 0.03N/mm2 (0.5kg hydraulic pump)
- Expected deformation: 1.6mm



Printed sample and Results



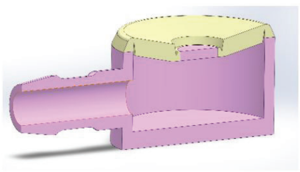
Result:

- Due to the geometry of the sample, direct measurements cannot be taken.
- Due to the geometry, a large deformation occurs with less force, compared to sample 1.1.
- Deformation of 2.1mm occurs at 0.017MPa
- Even though the deformation force required is higher than sample 3.1, the max deformation is larger.

Sample 3.2: Value not directly measured			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
450	290	0.01722424242	2.1
670	510	0.03029090909	3.1

Sample 3.3

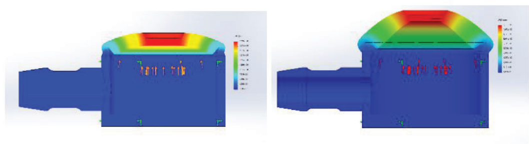
Model



Expected deformation

Sample 3: 1.5mm layer, agilus30,

- pressure: 0.01N/mm2 (0.16kg hydraulic pump)
- Expected deformation: 5.1mm



Printed sample and Results

Result:

- Due to the geometry of the sample, direct measurements cannot be taken.
- Due to the geometry, a large deformation occurs with little force, compared to sample 1.1. This due to the geometry, in which the layer is thinner where we want the bend. as a result, less stress is placed on that surface.
- Deformation of 2mm occurs at 0.007MPa

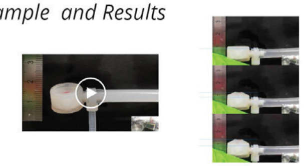
Sample 3.3 shore(A)30: Value not directly measured			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
290	130	0.007721212121	2
325	165	0.0098	3
645	485	0.02880606061	4

Sample 3.4

Printed sample and Results

Sample 3: 1.5mm layer, agilus30 shore 50,

- pressure: 0.03N/mm2 (0.5kg hydraulic pump)
- Expected deformation: ?mm



Result:

- Due to the geometry of the sample, direct measurements cannot be taken.
- Due to the geometry, a large deformation occurs with little force, compared to sample 1.1. This due to the geometry, in which the layer is thinner where we want the bend. as a result, less stress is placed on that surface.
- Deformation of 4mm occurs at 0.058MPa, significantly more than sample 3.3 (0.028). This is result of the higher shore value (30 vs 50).
- Both sample 3.3 and 3.4 have a significant higher tear resistance, due to emphasizing surface bend rather than elongation.

Sample 3.3 shore(A)50: Value not directly measured			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
1140	980	0.05820606061	4
2050	1890	0.1122545455	6

Results

Compare samples vs simulations

- Measure input force
- Measure deformation
- Take into account print direction and irregularities

Find the correct material properties, and with it estimate future model deformations!

Sample 1.1 color cap			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
410	250	0.01484848485	1.3
600	440	0.02613333333	2
900	740	0.04395151515	2.8

Sample 1.1 transparent cap (irregularities on the surface)			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
413	253	0.01502666667	1.1
613	453	0.02690545455	1.8

Sample 1.2: invalid measurement			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
1000	840	0.04989090909	0.7
1530	1370	0.08136969697	1.4
2465	2305	0.1369030303	2
3040	2880	0.1710545455	2.2

Sample 2.2: Printed vertically			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
1500	1340	0.07958787879	0.7
2400	2240	0.1330424242	1.2
3500	3340	0.1983757576	1.9

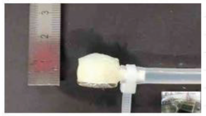
Sample 3.1: Value not directly measured			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
430	270	0.01603636364	3

Sample 3.2: Value not directly measured			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
450	290	0.01722424242	2.1
670	510	0.03029090909	3.1

Sample 3.3 shore(A)30: Value not directly measured			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
290	130	0.007721212121	2
325	165	0.0098	3
645	485	0.02880606061	4

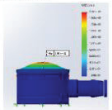
Sample 3.3 shore(A)50: Value not directly measured			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
1140	980	0.05820606061	4
2050	1890	0.1122545455	6

Sample 1.1



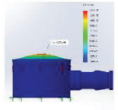
Sample 1.1 color cap			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
410	250	0.01484848485	1.3
600	440	0.02613333333	2
900	740	0.04395151515	2.8

Without using large displacement method, elastic modulus need to be raised beyond the indicated
ue
stic modulus: 2.15N/mm2
- Pressure 0.026N/mm2
- Deformation 2.16mm

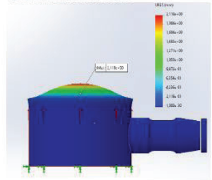


→ *Significant difference* →

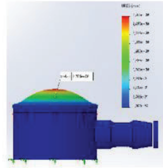
However, when using large displacement method the deformation is lower, and not relatable to the tensile tests, nor sample deformation
Elastic modulus: 2.15 N/mm2
- Pressure 0.026N/mm2
- Deformation 1.35mm



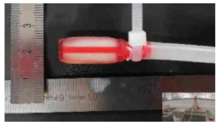
→ *Using large displacement method*
Elastic modulus: 1 N/mm2 (x-aligned)
- Pressure 0.026N/mm2
- Deformation 2.1mm



Using large displacement method
Elastic modulus: 1 N/mm2 (x-aligne
- Pressure 0.043N/mm2
- Deformation 2.76mm



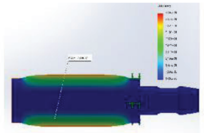
Sample 2.2: Vertically printed



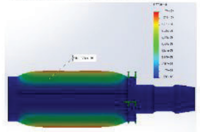
Printed vertically

Sample 2.2			
input weight (g)	actual weight (g)	Pressure N/mm2	Deformation (mm)
0	0	0	0
1500	1340	0.07958787879	0.8
2400	2240	0.1330424242	1.2
3500	3340	0.1983757576	1.9

Test 1
Using large displacement method
Elastic modulus: 0.87N/mm2 (y-aligned)
- Pressure 0.079N/mm2
- Deformation 0.72mm



Test 2
Using large displacement method
Elastic modulus: 0.87N/mm2 (y-aligned)
- Pressure 0.13N/mm2
- Deformation 1.57mm

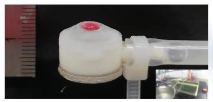


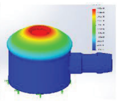
Conclusion

Fairly close representation of what will happen with a certain design when using FEM with large displacements activated. This can be used for:
- Finding the correct material thickness (knowing the intended deformation)
- Finding the adequate input force
- Finding the expected deformation (knowing the input force)

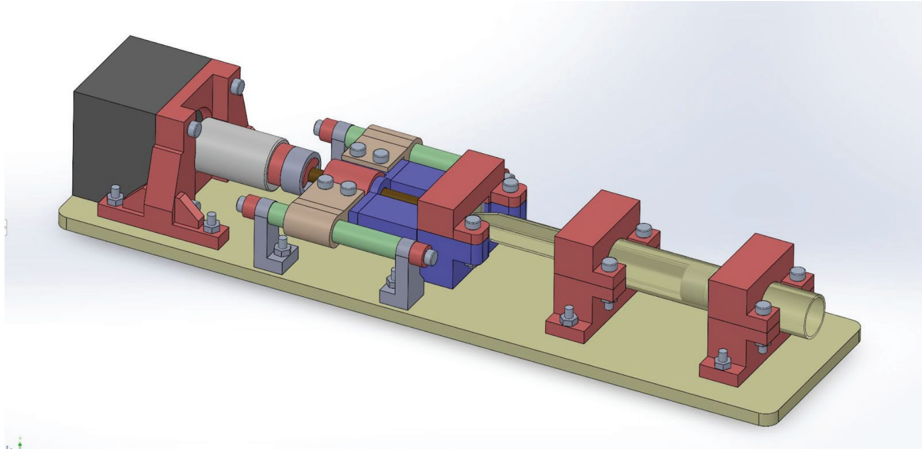
This method is valid when simulating models on a size of 10-15mm

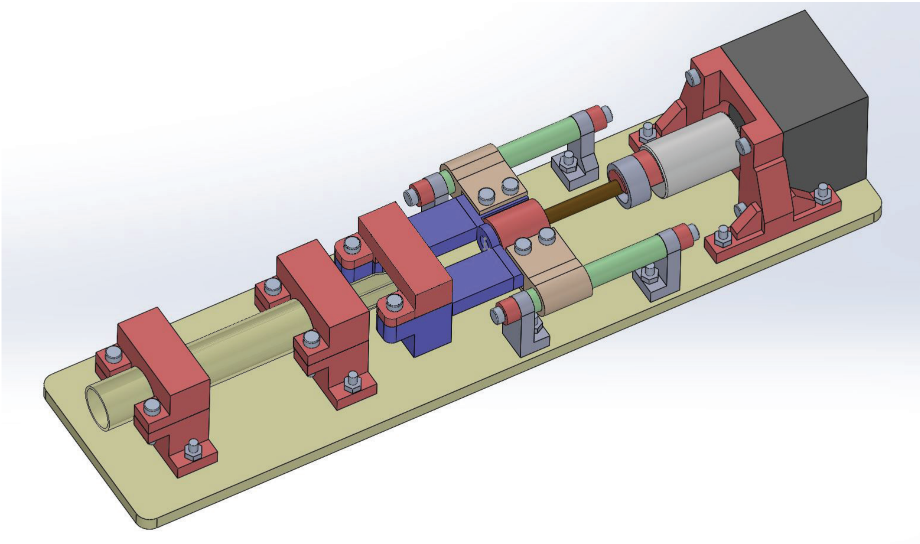
test 1: Sample 3.3 shore 30

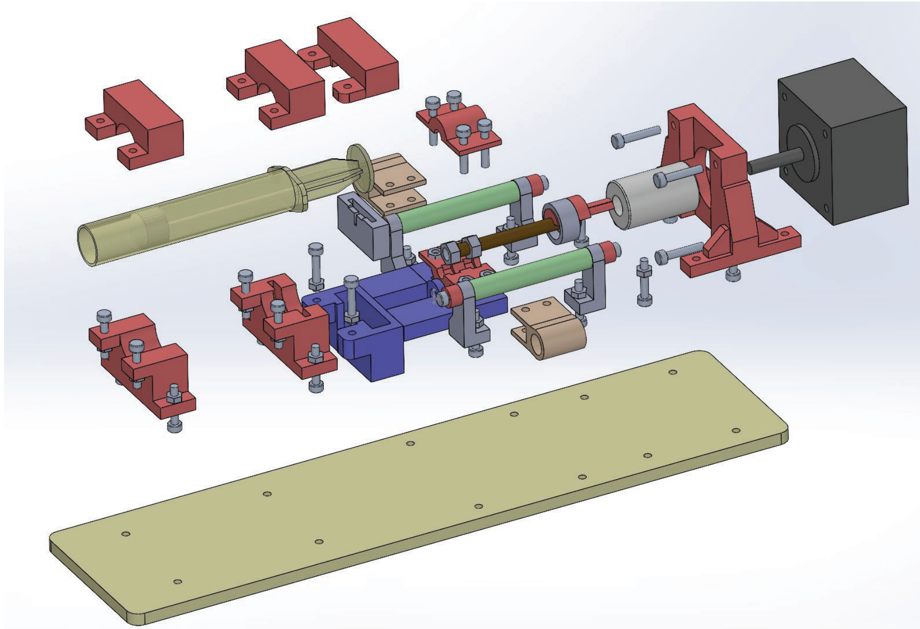




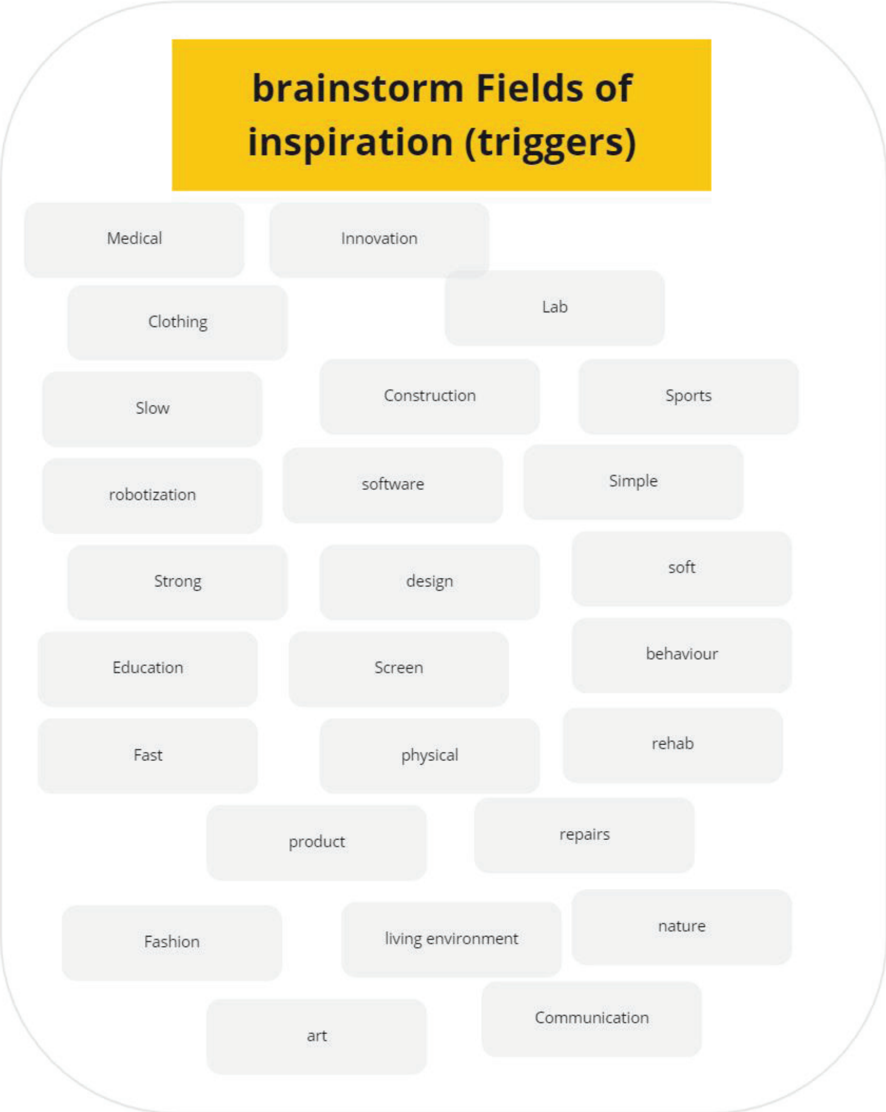
Appendix 9: Hydraulic printed system



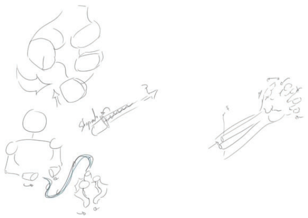
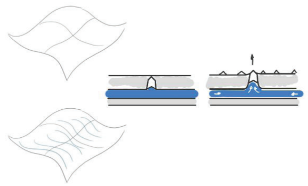
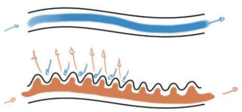
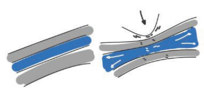
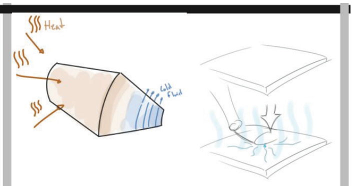
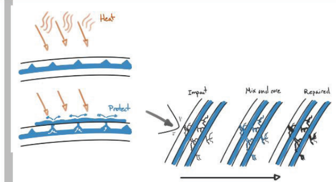
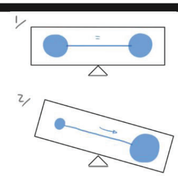
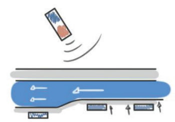
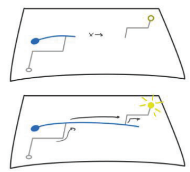




Appendix 10: Ideation triggers



Appendix 11: Fluid systems generated ideas

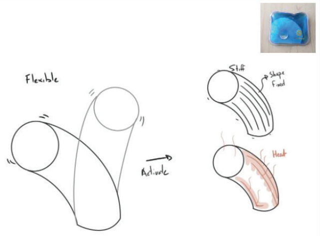
Idea name	Description:	visuals of the idea
Idea 1: Precise soft and rigid robotics	**Idea:** Through soft hydraulics, parts can expand, contract and deform. However, through multi-material printing we can determine the strength of each section. Therefore, the single body soft robotics can be soft and flexible, yet strong and rigid where needed. there are two design directions • electrically activated, fluid displacement is motorized, (motor, electroactive pads...) • *manually activated*, fluid displacement is manual, this means that a direct force feedback to the user can be achieved. This is useful for scenarios in which the users needs to feel the output forces (medical, lab, construction?) **Innovation:** high strength, precise and single body soft robotics. **Design value:** Extensive mechanical and design freedom through combining the actuator with the structure itself	
Idea 2: Tactile/texture transformation	**Idea:** Products changing their tactile texture, from a smooth surface, into a bumped, rougher or even sharper surface. Different patterns can be made, or even making use of multi-stiffness surfaces, solids can be used to stick out, for a 'sharper' texture, thus increasing grip in such case. **Innovation:** A single body with a flexible and variable dynamic texture, that can change the smoothness and sharpness of the surface. for a dynamic sensory product interaction. Design value: Customizable and variable surface patterns, without the need for assembly	
Idea 3: Dynamic cooling system	**Idea:** Liquid expansion (due to heat), or an hydraulic actuator, apply pressure on the circulatory system. When this happens, the surface texture changes, and thus an increase in contact surface. This increase will allow for more heat dispersion, and therefore acting as a variable radiator **Innovation:** Flexible and auto-regulatory radiator system imbedded into a product Design value: Autonomous and specific temperature control of a body	
Idea 4: variable impact absorption	**Idea:** With the use of multi-material 3d printing, we can to an extend design the absorption of an impact. In addition, fluid can be displaced within the body in order to dissipate the impact energy. As a result, we can design the amount of impact that will be absorbed from an impact, as well as act as an sensor. **Innovation:** Variable impact energy absoption within a body through fluid displacement. Design value: Impact loads can be displaced to different parts of the structure, where these might be useful	
Idea 5: Temperature control	**Idea:** 3d printing allowing for complex structures and channeling. through which cooling/heating channels can be integrated, both deep into the part or closely to the surface, while still being flexible/rigid where desired. Hot or could fluid can be pumped through these and therefore temperature can be controlled where desired. **Innovation:** Rapid cooling or heating of parts, and controlled temperature of a flexible body. Design value: Dynamic interactive temperature product can be designed (change when contact). Structures can be designed such that the temperature can be controlled.	
Idea 6: self-saving	**Idea:** 3d printing allows for designing inner channeling, in which specific fluids can be placed. Specific performance products can be designed such that they can protect itself from a temperature threat, or heal from a breaking impact. • The first, (protect from high temperatures), the system can be designed such as a bursting sprinkler system under threatening heat, in which the fluid system will burst and cool itself. • The second (heal from a impact), the systems can be filled with hardeners, which during a breaking of the structure can be released and mixed with each other, thus providing a internal healing of the structure (probably useful for product in which cannot be repaired in certain conditions) **Innovation:** Self protection from external temperatures and healing from damaging impacts Design value: Product useful life can be extended in an extreme scenario	
Idea 7: Variable center of mass/buoyancy	**Idea:** Fluid can be displaced to change the cent of mass/buoyancy. As a result, a body can be tilted, or its balance point, moment of inertia and even floating position can be changed. **Innovation:** Dynamic center of mass/buoyancy of a fixed single part Design value: Physical properties can be altered without the need of a mechanical system. Different use scenarios can be modelled merged a single body	
Idea 8: Dynamic magnetic field	**Idea:** Through displacement of ferromagnetic fluid through micro channels we can alternate (to a certain extent) the magnetic field of a piece. This means that external magnetic inputs can impact the fluid displacement, but also the internal fluid can affect external sources. • Additionally, electro-magnetic pads/actuators can be placed near channels and 'pump' the fluid. • As a different approach, through integrating magnets into the body, around the fluid channels, we can transform slightly the shape when placed in a magnetic field, which will apply pressure on the channel, thus displacing fluid. **Innovation:** Dynamic and controllable magnetic field, either for internal fluid displacement or exterior magnetic attraction Design value: non-electric interactive magnetic field manipulation	
Idea 9: Fluid as a conductor	**Idea:** The internal fluid can be considered as an electrical conductor. Therefore, an electrical conductor can be designed which will only work when fluid is in a certain position (closing the loop). **Innovation:** Interactive and flexible, fluidic electronic circuit, embedded into a body Design value: Electronic chips can be become imbedded into products itself	

Idea 10: Reversible solid fluid

Idea: Crystalline fluid can be used in the system. When activated (input), the fluid will solidify. this can have wo purposes:
- Solidify and retain firmly the shape of a flexible part.
- Provide instant heat from within the part itself.

Innovation: Flexible shapes which can be locked into a stiff shape, and provide instant heat

Design value: Through supercooled fluid, lasting heat can be released while stiffening a shape

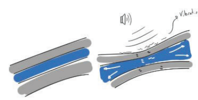


Idea 11: vibration sensor

Idea: When placed near a sound source, the encasing material will absorb vibrations coming from sound waves. During these vibrations, the fluidic interface can be designed such to displace (probably a very small amount) of fluid. Fluids with different densities can be used, as these can have different sound propagation characteristics and therefore display differently.

Innovation: Sound vibration transformation into a physical hydraulic actuator

Design value: Analog sound and vibration sensor

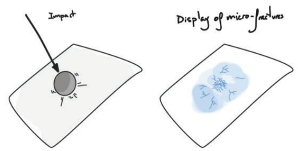


Idea 12: Visual communication of a broken product

Idea: Micro-fractures in a part can be fatal, yet difficult to identify. Therefore through internal structure design, it can be possible to change appearances when these micro-fractures occur.

Innovation: Visual feedback of a part mechanical health

Design value: Parts can be modelled such that excessive overloads can be recognized

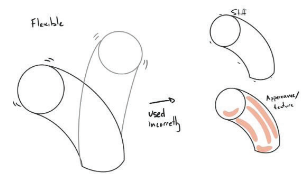


Idea 13: Product signaling its incorrect use

Idea: A product can be designed such that it changes certain properties when not being used correctly. This can increase user self-awareness, which might be useful for rehab product or tools. The changes that can be made are a change in specific stiffness, texture or appearance. To do so, we can consider the 'incorrect' usage as the input and determine the intended product property change (output).

Innovation: Visual and sensory feedback of human-product behaviour

Design value: Correct usage behaviour can be modelled into the structure itself

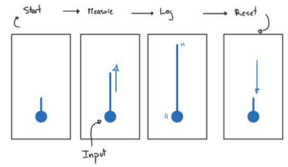


Idea 14: (Resettable) analog sensors

Idea: A interface can be designed that measures occurrences (inputs), and record these through fixing the ' value' of the interface (or even shape of it). However, after its use, the ' value' or shape can be reverted to the initial position so it can be used again. This could be designed through internal valves.

Innovation: Reversible sensors without the need of electronics

Design value:: non-electrical sensor that can be reused

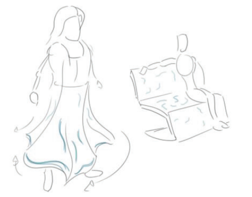


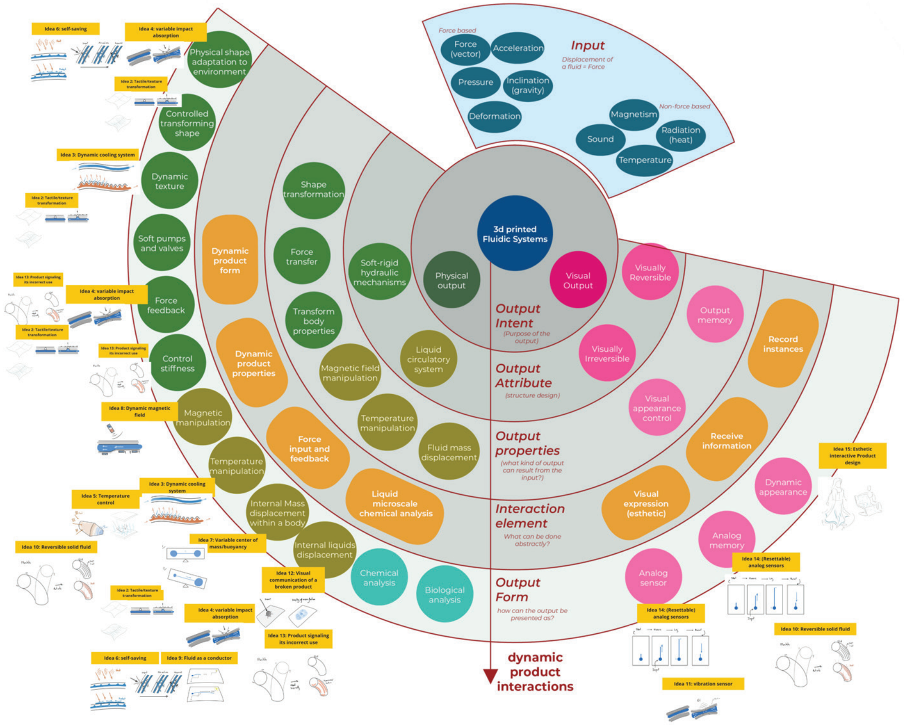
Idea 15: Esthetic interactive Product design

Idea: Designing concepts for esthetic reasons (while creating a added dynamic interactive value to products):
- Through utilizing an opaque fluid, we can displace this fluid in front of a light source, and achieve dynamic lighting integrated into 3d objects
- Integration into clothing that reaction to motion
- Integration into public spaces (benches, waiting spaces, traffic,...)
- interactive paintings that consist of small hidden fluid channels that are released under contact (painting is hidden until touched)

Innovation: Dynamic interactive product-human expression

Design value: Extensive interaction can be designed, while embed into products as a whole material





Appendix 12: Ideas scoring

Ideas evaluation

Quality of the innovation

Value for design and manufacturing freedom

- Method:

look in which category the concept is, look at the research table and compare

Criteria		Weight	Idea 1: Precise soft and rigid robotics	Idea 2: Tactile/texture transformation	Idea 3: Dynamic cooling system	Idea 4: variable impact absorption	Idea 5: Temperature control	Idea 6: self-saving
Desirability	demonstrate that the result is desirable for stakeholder (applicable to the field), or creates new value/meaning for society in general. Why is this better than other existing things.	24P	13P	16P	16P	7P	10P	10P
	• What innovation value is being created?	2P	High strength, precise and single body soft robotics.	A single body variable and flexible dynamic texture, that can change roughness and sharpness of the surface, for a dynamic sensory product interaction.	Flexible and auto-regulatory radiator system imbedded into a product	Variable impact energy absorption within a body through fluid displacement	Rapid cooling or heating of parts, and controlled temperature of a flexible body	Self protection from external temperatures and healing from damaging impacts
	• what design value can be created (application, interaction, manufacturing, 3d printing, materials, modelling...)?	3P	Extensive mechanical and design freedom through combining the actuator with the structure itself	Customizable and variable surface patterns, without the need for assembly	Autonomous and specific temperature control of a body	Impact loads can be displaced to different parts of the structure, where these might be useful	Dynamic interactive temperature product can be designed (change when contact). Structures can be designed such that the temperature can be controlled.	Product useful life can be extended in an extreme scenario
	• How developed is this field already regarding innovation and knowledge? (competitors).	3P	Extensive research and innovation is being done. However complexity is limited do to manufacturing limitation (which 3d printing can overcome)	Folding and deployable meta structures are in development. However these are assemblies and not homogenous surfaces, and lacking in precision.	Existing cooling systems tend to be static and electrically reliant	Hydraulic shock absorbers are highly available, along with impact absorbing materials	Dynamic interactive temperature products are non-existing yet. Parts with imbedded cooling are common in automotive and aerospace industries, however not imbedded into flexible products	Technology exist already in automotive world
Viability	result can become viable, thus surviving on a longer term both physically as well as the use itself.	21P	8P	11P	9P	11P	10P	2P
	• Could this idea be replaced on a short term with a different/better technology/method (threads)?	4P	Advanced prototypes are in development, that could surpass 3d printing on a short term	Meta-material structures are the closest in terms of structure, however these are overly complex	Isolating materials, and electrically cooled systems are already on the market	Impact absorbing materails are highly available, however these are designed for failure, or do not transport the impact energy	Changing or mainting a product temperatures is achieved currenly on a superficial level (except on engines)	Self healing polymers and concrete are in development,
	• Beyond the Stratasys: could this concept be manufactured without the use of multi-material 3D printing? (very unclear yet)	1P	Structures could be 3d printed with soft and rigid filaments and filled with fluidics, however strength and durability can become an issue	Process can be achieved through pouring silicone into a mould with the solid inserts, however this would be complex, not custumizable and time consuming	Expanding textiles could replace the soft structure	Structures could be 3d printed with soft filaments and filled with fluidics	Flexible micro structures could be difficult to achieve	Flexible micro structures could be difficult to achieve
	• Could there room for future development and improvement? (is it a dead end or can it be explored further) (subjective)	2P	Concept can be applied into different fields of robotics, and replicate more 'organic' actuators	Idea can be applied into different fields, not only performance, but also human-product sensory understanding	Idea could be applied largelly into sports gear, or possibly into fabriks,	Aplications could be found where transporting impact energies can become usefull	Interactive changing surface temperatures imbedded into products	
Feasibility	the results are achievable, or a new method is presented to achieve this, within the project time frame.	15P		8P	4P			
	• Expected showstopper to be overcome?	2P Low score=complex showstopper		Focus the deformation on just the point of interest and not surrounding part of the structure, while maintaining its flexibility	Achieve significant fluid expansion and pressure for surface deformation. Achieve significant heat transfer Focus the deforation on just the point of interest and not surrounding part of the structure, while maintaining its flexibility			
	• Could this concept be developed, tested, and optimized within the given time frame? (subjective, yet indicative)	1P						
	• Can this concept be developed with the available materials, techniques and resources?	2P		Controllable hydraulic pressure pump might be needed	Fluid would need a specific volume expansion, that might not be commonly available			
	Scoring	n/23		35P	29P			

Idea 7: Variable center of mass/buoyancy	Idea 8: Dynamic magnetic field	Idea 9: Fluid as a conductor	Idea 10: Reversible solid-fluid	Idea 11: vibration sensor	Idea 12: Visual communication of a broken product	Idea 13: Product signaling its incorrect use	Idea 14: (Resettable) analog sensors	Idea 15: Esthetic interactive Product design
10P	3P	2P	10P	3P	16P	16P	14P	16P
Dynamic center of mass/buoyancy of a fixed single part	Dynamic and controllable magnetic field, either for internal fluid displacement or exterior magnetic attraction	Interactive and flexible, fluidic electronic circuit, embedded into a body	Flexible shapes which can be locked into a stiff shape, and provide instant heat	Sound vibration transformation into a physical hydraulic actuator	Visual feedback of a part mechanical health	Visual and sensory feedback of human-product behaviour	Reversible sensors without the need of electronics	Dynamic interactive product-human expression
Physical properties can be altered without the need of a mechanical system. Different use scenarios can be modelled merged a single body	non-electric interactive magnetic field manipulation	Electronic chips can be become imbedded into products itself	Through supercooled fluid, lasting heat can be released while stiffening a shape	Analog sound and vibration sensor	Parts can be modelled such that excessive overloads can be recognized	Correct usage behaviour can be modelled into the structure itself	non-electrical sensor that can be reused	Extensive interaction can be designed, while embed into products as a whole material
Idea exists in products and engineering concepts, through either displacement of a mechanical mass, or inflation of tanks	Idea exists extensively to attract or repel, through electronics. However lacking in a dynamic interactive environment	Better working solution have been developed in the field of electronics, thus not present. However the imbedded interaction function can become new	Principle has not been applied using this technique, possible due to complication with fluid encasing (needs to be extremely smooth)	Electric and accurate controlled analog sensor exist	No competitors could be found that can communicate the presence of microfractures	No competitors could be found that can communicate the incorrect use of a part without the use of electronics	2D Fluidic interfaces can achieve this same goal	No competitors could be found that can utilize hydraulics in a transparent medium for esthetic interactions
4P	3P	5P	11P	7P	12P	11P	7P	12P
Mechanical alternatives could replace this	Electromagnets are a highly developed field	Flexible circuit boards		Electric and accurate controlled analog sensor are the alternative	No competitors could be found that can communicate the presence of microfractures	No competitors could be found that can communicate the incorrect use of a part without the use of electronics	2D Fluidic interfaces can achieve this same goal	No competitors could be found that can utilize hydraulics in a transparent medium for esthetic interactions
Structures could be 3d printed with soft filaments and filled with fluidics	silicone and insert could be used	silicone and insert could be used	Structures could be 3d printed with soft filaments and filled with fluidics	Flexible micro structures could be difficult to achieve	Flexible micro structures could be difficult to achieve	Flexible micro structures could be difficult to achieve	Flexible micro structures could be difficult to achieve	larger scale 3D printing, laser engraving and soft transparent material could be used
Specific application would need to be found	Specific application would need to be found	Specific application would need to be found	Specific application would need to be found	Specific application would need to be found	Applicable to different fields and materials	Applicable to different fields and materials	Specific application would need to be found	Applicable to different fields and materials
					8P	8P		6P
					Calculate and design structures that will microfracture	Achieve significant change in properties (stiffness) to become noticeable		Achieve Consistent fluid flow at higher channel volumes. Overall complexity if patterns cannot be repeated
					Hydraulic presses are available			depends on the objective
					36P	35P		33P

Ideas scoring

			Precise soft and rigid robotics	Tactile/texture transformation	Dynamic cooling system	variable impact absorption	Temperature control	self-saving	Variable center of mass/buoyancy	Dynamic magnetic field	Fluid as a conductor	Reversible solid-fluid	vibration sensor	Visual communication of a broken product	Product signaling its incorrect use	(Resettable) analog sensors	Esthetic interactive Product design
		Weight	Idea 1	Idea 2	Idea 3	Idea 4	Idea 5	Idea 6	Idea 7	Idea 8	Idea 9	Idea 10	Idea 11	Idea 12	Idea 13	Idea 14	Idea 15
	Desirability		13	16	16	8	11	10	8	2	3	11	2	16	16	13	16
value of the core idea	What innovation is being created?	2	2	2	2	1	1	2	1	1	0	1	1	2	2	2	2
value of the design process	what design value is being created (manufacturing, 3d printing, materials, modelling...)?	3	2	2	2	2	2	2	1	0	1	2	0	2	2	2	2
	How developed is this field already regarding innovation and knowledge? (competitors).	3	1	2	2	0	1	0	1	0	0	1	0	2	2	1	2
	Applicability: Could this concept be implemented into a product? Subjective, therefore is an supportive score	1															
	Viability		8	13	10	12	12	2	4	3	5	13	8	14	13	8	14
If it can be replaced on a short term, continuing with this is not viable	Could this idea be replaced on a short term with a different/better technology/method (threads)?	4	0	2	1	1	2	0	0	0	0	2	1	2	2	1	2
	Beyond the Stratasys: could this concept be manufactured without the use of multi-material 3D printing? (very unclear yet)	1	2	0	1	2	0	0	2	1	1	2	0	0	0	0	2
	Could there be room for future development and improvement? (is it a dead end or can it be explored further)	2	2	2	2	2	2	1	1	1	1	1	1	2	2	1	2
	Score		21	29	26	20	23	12	12	5	8	24	10	30	29	21	30
	Feasibility																
	Expected showstopper to be overcome?	2		1	0									1	1		0
	Could this concept be developed, tested, and optimized within the given time frame? (subjective, yet indicative)	1		2	2									2	2		1
	Can this concept be developed with the available materials, techniques and resources?	2		2	1									2	2		2
	Final score			37	30									38	37		35

Appendix 13: Ideas scoring sensitivity analysis

v1

very doubtfull	slightly doubtfull																
what is my confidence of this score?score gets an +1 or -1	what is my confidence of this score (scored on the high side)? score gets a -1		Precise soft and rigid robotics	Tactile/texture transformation	Dynamic cooling system	variable impact absorption	Temperature control	self-saving	Variable center of mass/buoyancy	Dynamic magnetic field	Fluid as a conductor	Reversible solid-fluid	vibration sensor	Visual communication of a broken product	Product signaling its incorrect use	(Resettable) analog sensors	Esthetic interactive Product design
	round with no changes																
		Weight	Idea 1	Idea 2	Idea 3	Idea 4	Idea 5	Idea 6	Idea 7	Idea 8	Idea 9	Idea 10	Idea 11	Idea 12	Idea 13	Idea 14	Idea 15
	Desirability		13	16	13	8	11	8	8	5	5	11	2	16	16	13	16
value of the core idea	What innovation is being created?	2	2	2	2	1	1	1	1	1	1	1	1	2	2	2	2
value of the design process	what design value is being created (manufacturing, 3d printing, materials, modelling...)?	3	2	2	1	2	2	2	1	1	1	2	0	2	2	2	2
	How developed is this field already regarding innovation and knowledge? (competitors).	3	1	2	2	0	1	0	1	0	0	1	0	2	2	1	2
	Applicability: Could this concept be implemented into a product? Subjective, therefore is an supportive score	1															
	Viability		8	13	10	12	13	6	4	3	5	13	8	14	13	8	14
If it can be replaced on a short term, continuing with this is not viable	Could this idea be replaced on a short term with a different/better technology/method (threads)?	4	0	2	1	1	2	1	0	0	0	2	1	2	2	1	2
	Beyond the Stratasys: could this concept be manufactured without the use of multi-material 3D printing? (very unclear yet)	1	2	0	1	2	0	0	2	1	1	2	0	0	0	0	2
	Could there be room for future development and improvement? (is it a dead end or can it be explored further)	2	2	2	2	2	2	1	1	1	1	1	1	2	2	1	2
	Score		21	29	23	20	24	14	12	8	10	24	10	30	29	21	30
	Feasibility			8	4									8	8		3
	Expected showstopper to be overcome?	2		1	0									1	1		0
	Could this concept be developed, tested, and optimized within the given time frame? (subjective, yet indicative)	1		2	2									2	2		1
	Can this concept be developed with the available materials, techniques and resources?	2		2	1									2	2		1
	Final score			37	27									38	37		33

v2

very dout	slightly doubtfull																
score?s core gets an +1 or -1	what is my confidence of this score (scored on the high side)? score gets a -1		Precise soft and rigid robotics	Tactile/texture transformation	Dynamic cooling system	variable impact absorption	Temperature control	self-saving	Variable center of mass/buoyancy	Dynamic magnetic field	Fluid as a conductor	Reversible solid-fluid	vibration sensor	Visual communication of a broken product	Product signaling its incorrect use	(Resettable) analog sensors	Esthetic interactive Product design
	round with -1																
		Weight	Idea 1	Idea 2	Idea 3	Idea 4	Idea 5	Idea 6	Idea 7	Idea 8	Idea 9	Idea 10	Idea 11	Idea 12	Idea 13	Idea 14	Idea 15
	Desirability		11	14	11	8	11	6	6	0	3	6	0	16	16	13	13
value of the core idea	What innovation is being created?	2	1	1	1	1	1	0	0	0	0	0	0	2	2	2	2
value of the design process	what design value is being created (manufacturing, 3d printing, materials, modelling...)?	3	2	2	1	2	2	2	1	0	1	1	0	2	2	2	1
	How developed is this field already regarding innovation and knowledge? (competitors).	3	1	2	2	0	1	0	1	0	0	1	0	2	2	1	2
	Applicability: Could this concept be implemented into a product? Subjective, therefore is an supportive score	1															
	Viability		8	13	10	12	13	6	4	3	5	13	8	14	13	8	14
If it can be replaced on a short	Could this idea be replaced on a short term with a different/better technology/method (threads)?	4	0	2	1	1	2	1	0	0	0	2	1	2	2	1	2
	Beyond the Stratasys: could this concept be manufactured without the use of multi-material 3D printing? (very unclear yet)	1	2	0	1	2	0	0	2	1	1	2	0	0	0	0	2
	Could there be room for future development and improvement? (is it a dead end or can it be explored further)	2	2	2	2	2	2	1	1	1	1	1	1	2	2	1	2
	Score		19	27	21	20	24	12	10	3	8	19	8	30	29	21	27
	Feasibility			8	4									8	8		3
	Expected showstopper to be overcome?	2		1	0									1	1		0
	Could this concept be developed, tested, and optimized within the given time frame? (subjective, yet indicative)	1		2	2									2	2		1
	Can this concept be developed with the available materials, techniques and resources?	2		2	1									2	2		1
	Final score			35	25									38	37		30

v3

			Precise soft and rigid robotics	Tactile/texture transformation	Dynamic cooling system	variable impact absorption	Temperature control	self-saving	Variable center of mass/buoyancy	Dynamic magnetic field	Fluid as a conductor	Reversible solid-fluid	vibration sensor	Visual communication of a broken product	Product signaling its incorrect use	(Resettable) analog sensors	Esthetic interactive Product design
very doubtfu of this score?scor e gets an +1 or -1	slightly doubtfull the high side)? score gets a -1																
	round with +1																
		Weight	Idea 1	Idea 2	Idea 3	Idea 4	Idea 5	Idea 6	Idea 7	Idea 8	Idea 9	Idea 10	Idea 11	Idea 12	Idea 13	Idea 14	Idea 15
	Desirability		13	16	13	8	11	10	10	5	5	13	4	16	16	13	16
value of the core idea	What innovation is being created?	2	2	2	2	1	1	2	2	1	1	2	2	2	2	2	2
value of the design process	what design value is being created	3	2	2	1	2	2	2	1	1	1	2	0	2	2	2	2
	How developed is this field already regarding	3	1	2	2	0	1	0	1	0	0	1	0	2	2	1	2
	Applicability: Could this concept be implement	1															
	Viability		8	13	10	12	13	6	4	3	5	13	8	14	13	8	14
If it can be replaced on a short term, continuing	Could this idea be replaced on a short term with a	4	0	2	1	1	2	1	0	0	0	2	1	2	2	1	2
	Beyond the Stratasys: could this concept be manufactur	1	2	0	1	2	0	0	2	1	1	2	0	0	0	0	2
	Could there be room for future developme	2	2	2	2	2	2	1	1	1	1	1	1	2	2	1	2
	Score		21	29	23	20	24	16	14	8	10	26	12	30	29	21	30
	Feasibility																
	Expected showstopper to be overcome?	2		1	0									1	1		0
	Could this concept be developed, tested, and	1		2	2									2	2		1
	Can this concept be developed with the	2		2	1									2	2		2
	Final score			37	27									38	37		35

Appendix 14: interview with karina Driller, expert in tactile perception

Key points

- Every surface has a texture, even glass, as long as an -z axis exists.
- Textures can only be verified by touch testing.
- People have an expectation about how a surface feels, after it has been visually observed.
- Friction is the most important variable when touching surfaces (when there is movement) determining roughness.
- On a micro scale, one shape might not be noticed, however, when there are a multitude of shapes, these can be noticed due to sin vibrations.
- The sound a surface makes when being touched, plays a role on how this is perceived.
- Sound can modify roughness perception.
- Duplex theory: elements from a certain size, do not need sweeping to be noticed.
- Textures larger than 5mm are considered shapes.
- Humans touch surfaces either pressing or sweeping, however, unconsciously we choose the one that will provide the most information.
- When textures are rigid, these can be smaller in size than flexible surfaces.
- Humans are attracted to touching surfaces to obtain sensory information.

Appendix 15: Interview with visually impaired individual about tactile perception

General questions

- *How often do you read braille?*
  - Answer: started 14 years ago, and now on a daily basis, however now at university he prefers relying more on audio software because it is faster.
- *How fast can you read braille? (words),*
  - Answer: really depends on how often you practice, but in general less than 1sec for a pattern (one letter)
- *How fast do you think you could read it in a future?*
  - Answer: if you practice a lot maybe 2 patterns a second, but the limitation is more moving of the fingers correctly above the relief
- *How long did it take you to interpret the patterns? and* Directly understand the language?
  - Answer:
- *Can you use different fingers?*
  - Answer: you learn to be sensitive in the fingers you read with, but with enough time i could read with any finger.
- *Could you read with a different part of your hand if you trained?*
  - Answer: he need to keep track of the alignment line, and without knowing where it is, he wouldn't be able to
- *Identifying patterns:*
  - *Are there letters with more dots than others, do these affect reading speed?,*
    - Answer: not at all, exactly the same difficulty whether there is 1 dot or 5
  - *Does the arrangement effect reading speed?*
    - Answer: not at all
- *Numbness:*
  - *After reading a lot, do you need to take a break, due to skin insensitivity,*
    - Answer: after reading a lot i have to take breaks, but not because of insensitivity but because i am tired, the same as when you are watching tv
  - *How does rock climbing affect the readability?*
    - Answer: yes, right after it takes me more effort to distinguish the dots, and if i have blisters, sometimes i cannot read at all.

- *Has he seen/experienced alternate languages that make use of vibrations, touch...?*
  - Answer: yes, a tactile gnosis device of the company "Vitec". you place you palm on it and a relief appears on it with a shape or letter, and after a while training, i could directly understand without thinking what is written on the surface, and even play games. i used it experimentally for 1 year.

Concept related questions

- *is there braille that he has trouble reading due to small or large size?, or too close together?*
  - Answer: braille is in general the same size, so not really
- *In his opinion, what is the most important variable for reading, is it height, shape, smoothness, spacing?*
  - Answer: both all of them and none at the same time. if a relief is too high it cannot be read, but if it is also too small it cant be read either
- *If you could change something about how you read/, what would it be?*
  - Answer: letter combination is different for each language, so learning different languages is really difficult
  - *what would his ideal tactile language look like?*

Exercise

- *pressing into braille, is he able to make distinguishments? what if he practices?*
  - Answer: could directly identify the letter when pressing into the braille without any problems

Appendix 16: FDM 3D printed tactile tests

Rapid validation of texture elements

Sweeping

	Strip 1- change in groove width				
	narrow	2	3. starting point	wide (baseline)	wide and tall
Intended	2	3	5	7	8
Perceived roughness p1: L	4	4	5	8	9
Perceived roughness p2: P	3.5	4	5	8	8
Perceived roughness p3	2	5	5	7	9
Perceived roughness p4	1	3	5	8	8

	Strip 2 - change in shape				
	wide small	2	wide (baseline)	4	wide and long
Intended	8	9	5	4.5	4
Perceived roughness p1	7	8	5	4.5	4
Perceived roughness p2	7	8	5	4	4
Perceived roughness p3	8	9	5	6	7
Perceived roughness p4	7	9	5	4	4

	Strip 3- Change in height				
	narrow	2	3. starting point	4	wide and tall
Intended	3	4	5	6	6
Perceived roughness p1	6	6	5	5.5	4
Perceived roughness p2	4.5	5	5	5	5
Perceived roughness p3	6	6	5	7	7
Perceived roughness p4	3	5	5	6	6

Pressing

	Strip 1- change in groove width				
	narrow	2	3. starting point	wide (baseline)	wide and tall
Intended	1	3	5	7	7
Perceived rough	3	3	5	6	7
Perceived rough	1	2	5	7	7.5
Perceived rough	1	1	5	7	7
Perceived rough	2	3	5	8	8

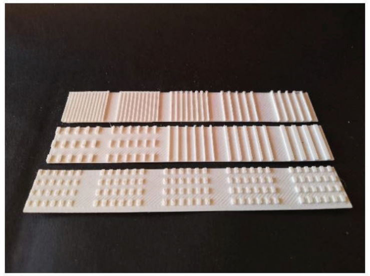
	Strip 2 - change in shape				
	wide small	2	wide (baseline)	4	wide and long
Intended	7	8	5	4	3
Perceived rough	7	8	5	4	3
Perceived rough	8	9	5	3.5	3
Perceived rough	7	7	5	6	4
Perceived roughness p4					

	Strip 3- Change in height				
	narrow	2	3. starting point	4	wide and tall
Intended	3	4	5	6	7
Perceived rough	3	3	5	7	7
Perceived rough	3	3	5	6	6
Perceived rough	1	2	5	6	7
Perceived rough	2	3	5	6	6

Sample 1
- varying groove width: test pressing and swiping, effect of spacing on perceived roughness

Sample 2
- Varying shape size (same spacing): test pressing and swiping, effect of size on perceived roughness

Sample 3
- Varying shape height (same spacing and shape): test pressing and swiping, effect of size on perceived roughness



Conclusions, most important factors

Roughness with movement:
- **Tighter surface curvature**, results in a rougher surface perception (more friction)
- Height could be neglected if the skin will not deform to the entire depth
- **Smaller shapes** will result in a rougher surface perception

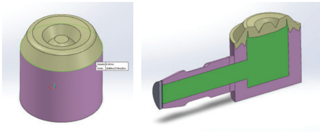
Roughness without movement:
- Spacing between shapes: the **further apart**, the surface roughness perception
- If shapes sufficiently apart, a **higher feature** will allow for a rougher surface perception
- **Smaller shapes** will result in a rougher surface perception

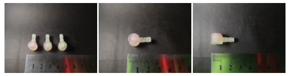
Appendix 17: Texture sensor and actuator design process

mechanisms

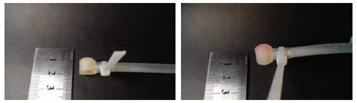
Model 1

Miniscule actuator

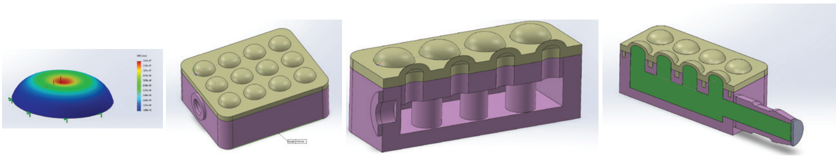


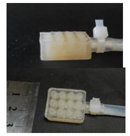


Miniscule actuator



Model 2



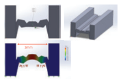


Method 1: displacing the flexible membrane

Model 3

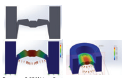
Applying the same working principle as the sample made with bending membranes

V1



Pressure 0.026N/mm2
Deformation 0.4mm
desired deformation +0.8mm

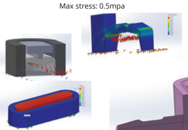
V2



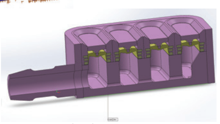
Pressure 0.026N/mm2
Deformation 0.55mm
desired deformation +0.8mm, however if negative pressure is applied to, this could be achieved

V3

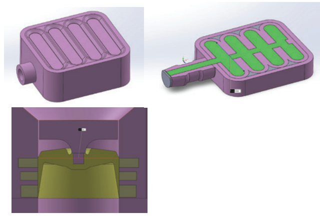
Max stress: 0.5mpa

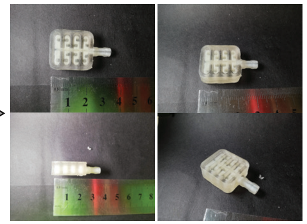


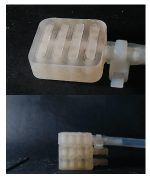
Model



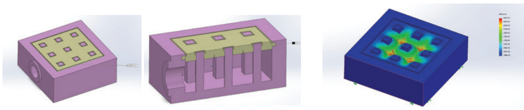
Printing with a shoreA 50, should give more strength, however less compliant

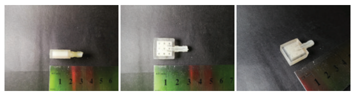


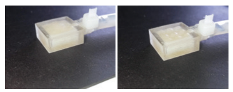




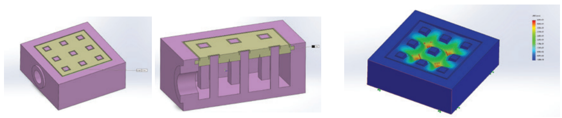
Model 4

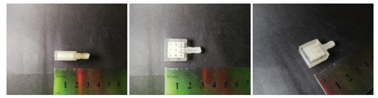


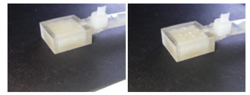


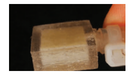


Model 4

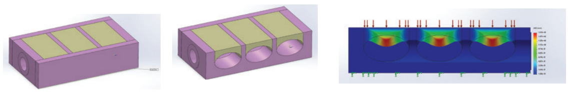


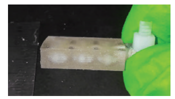






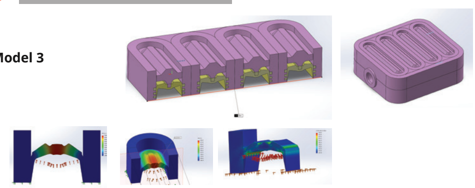
Model 5

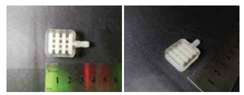




Method 2: displacing the rigid features

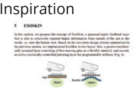
Model 3





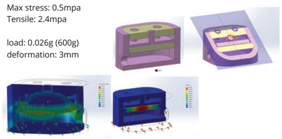
Model 6

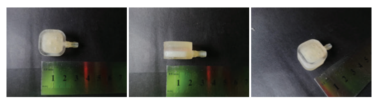
Inspiration

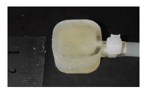


Max stress: 0.5mpa
Tensile: 2.4mpa

load: 0.026g (600g)
deformation: 3mm





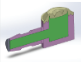
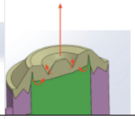
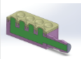
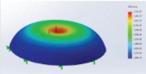
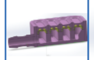
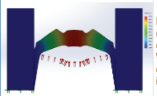
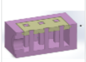
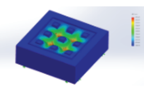
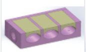
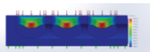
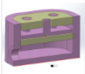
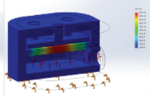


Not Works

Selection of mechanism

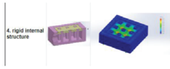
Scoring	
2	
1	
0	

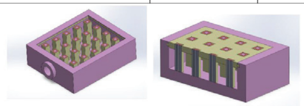
Rigid: puprle
Flexible: yellow

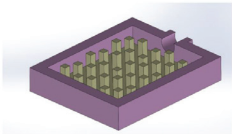
Mechanism			description	Expected durability	mechanism opportunities	Interaction feeling: mechanism actuation (product to user)	Interaction feeling: pressing interaction (user to product)	mechanism analysis: pros	mechanism analysis: cons
1. Soft actuator			circular shaped actuator (8mm D) . Soft membrane folds outwards when hydraulic pressure occurs. This membrane can fold slightly inwards with a correct design.	weakest point where the fold occurs. Very thin	- Large texture deformations (shapes)	When the membrane is actuated, it covers the entire area of the finger. When this membrane moves up, the deformation and change in shape/height is extemely noticeable.	When pressing into the membrane, there does not occur much noticeable deformation. This feels almost like pressing into a flat surface.	- Large displacements are obtainable (~2mm) - product to user signaling is very noticeable	- Minimum size is quite large (>5mm), therefore these will cover alomost the entirity of the a finger. - User to product interaction is minimal, as the membrane can barerely be pushed inwards
2. Curved membrane			Circular membrane domes (4mm D). which stretch the membrane when hydraulic pressure occurs. the dome can deform inwards but a buckling occurs.	weakest point along the outer surface, as the stretch is highest here	- Small actuated patterns	When the domes deform upwards, they press noticeably into the skin, and when retracting, a slight suction is felt at each dot. However when combining the range of these two, a very noticeable skin pressure-stretch occurs	When pressing into the membrane, there does not occur much noticeable deformation. This feels almost like pressing into a flat surface.	- Size of the actuators can be small (~4mm) - Paterns can be achieved with multiple dots on one finger	- The displacement is considerably small in each direction (up or down). however when combined, they can be very noticeable. - Stretching of the flexible membrane may cause rapid breakdown of the mechnism
3. folding square membrane			Folding membrane shape in any form (rectangular in this case). Soft membrane folds outwards when hydraulic pressure occurs. When this occurs, a rigid insert is pushed outwards. This membrane can fold slightly inwards with a correct design.	weakest point where the fold occurs. Very thin	- Small actuated patterns - Retactables rigids - rigid surounding structure on a roughness level (small) - Designing how the rigid structure needs to look for maximaum feel in the skin	When the rigid surfaces move upwards they can be felt individually	when pressing into the surface, a significant change in roughness is felt	- The displacement of the rigid structures is faily small (~1), however these are rigid, and as a result very noticeable. - Rigid structure can be designed to be smaller than the actuator itself. - Size of the rigid actuator can be small (~2mm)	- The small flexible membrane could be to small for long durability - The design of membrane can be complex
4. rigid internal structure			A soft membrane is placed on a rigid relief. When the membrane is deformed downwards, the rigid internal structure will create a reflief on the surface. the membrane could also be deformed upwards as a result of hydraulic pressure.	weakest point where the fold occurs. Very thin	- Medium deformation - rigid surounding structure on a roughness level (very small) - Designing how the rigid structure needs to look for maximaum feel in the skin	When the membrane is actuated, it covers the entire area of the finger. When this membrane moves up, the deformation and change in shape/height is extemely noticeable. When deflated, a change i surface roughness is felt	when pressing into the surface, a significant and sharps change in roughness is felt	- Displacement of the membrane upwards is small (1mm), however due to its large are, very noticeable. -Displacement of the membrane downwards is small (1mm), however due the rigid structure that appears, a change in roughness is highly noticeable. - Small size of the rigid structure obtainable (<2mm) - Shape freedom	- membrane might be fragile - stretching can occur if designed improperly reducing its durability.
5. Flat flexible membrane			A soft membrane is placed between rigid structures. When the membrane is deformed downwards, the rigid internal structure will create a reflief on the surface. the membrane could also be deformed upwards as a result of hydraulic pressure.	weakest point along the outer surface, as the stretch is highest here	- Medium deformation - rigid surounding structure on a roughness level (large) - Designing how the rigid structure needs to look for maximaum feel in the skin	When the membranes are actuated, they can be felt individually along the finger. When deflated, a slight change i surface roughness is felt	when pressing into the surface, a significant change in roughness is felt	- Displacement of the membrane upwards is small (1mm), however due tts number of actuators possible and size, very noticeable. -Displacement of the membrane downwards is small (1mm), however due the rigid structure that appears, a change in roughness is faily noticeable. - Small size of the rigid structure obtainable (<2mm) - Shape freedom	- stretching will occur reducing its durability.
6. Retractable rigid			A rigid structure is placed on a flexible membrane. when this deforms upwards, it will push the rigid structure out of the surface, and creating a relief. then the top surface is pressed down, this will deform around the rigid structure.					Mechanism does not work as intended	

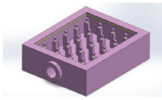
Appendix 18: Chosen 3D printed texture mechanism testing

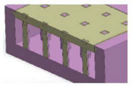
mechanisms

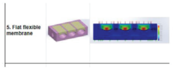
Mechanism		What can be improved?
Tactile roughness: Membrane folds around rigid structures 		Larger surface area More height displacement range better feel More durable?

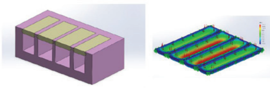
2.1  variable column stiffness

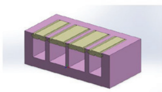
2.2  variable column height

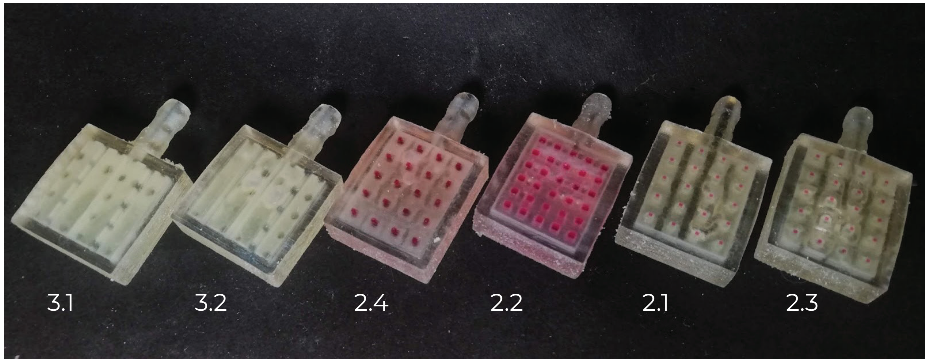
2.3  different membrane attachment

2.4 

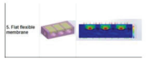
Mechanism		What can be improved?
Membrane folds in between rigid structures 		smaller membrane patches thicker/thinner membrane patches reduce stresses

3.1  Smaller area and smaller walls

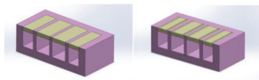
3.2  Smaller area and smaller walls + membrane folding

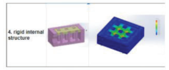


Selection

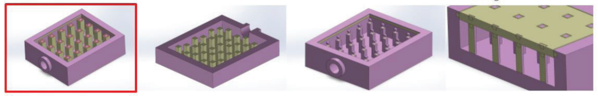


Reduce membrane area, and reduce rigid structure area





Variable structure stiffness | Variable structure height | membrane attachment | membrane attachment + folding



Appendix 19: User testing of concept mechanisms

Test steps

How to conduct the research

The research is conducted with participants with no prior experience in tactical environments not acknowledged about the project research.

Part 1: feeling roughness (observe variable roughness experience)

1. Give roughness block to the participant
2. Let them touch the item and allow them to press the surfaces (first impression), how do they react? (5min)
3. Signal to press into the different surfaces, can they feel differences in the design elements without me asking?
4. Signal to press into the different surfaces (instructed order), do they experience them differently?
5. Signal to press with different hand/finger positions
6. Questions

Part 2: feeling texture actuator (observe texture actuation experience)

1. Give roughness block to the participant
2. Let them hold the item without activating
3. Let them hold the item activating one single actuator. Experience?
4. Let them hold the item activating multiple actuators. Experience?
5. Let them hold the item activating multiple actuators, changing the design elements. How do they experience this?
6. Questions

Part 3: feeling roughness and texture actuator simultaneously

1. Give roughness block and texture actuator to the participant (one in each hand)
2. Allow them to press into the roughness surfaces and feel the texture actuators simultaneously. How do they experience this? Initial impressions?
3. While the texture actuators are activated in a cycle, can participants focus and feel the variance of surface roughness? (mental overload)

Observation points and interview questions

Part 1: feeling roughness (observe variable roughness experience) (15min)

1. *Give the roughness block to the participant. What do they notice?Anything special about the surfaces itself?*

When giving the testing sample to the participants without necessarily instructing to press into the designed mechanisms, participants moved their fingers over the different surfaces mentioning that different surface hardness can be felt to the touch. Beyond this first commentary no special characteristics can be attributed to the feeling of roughness itself, as participants assume in this first interaction surfaces to be constantly flat.

2. *Let them touch the item and allow them to press the surfaces (**first impression quickly**),*
    a. *how do they react?, (5min)*
    b. *First feeling ?*
    c. *Experience, intrigue?*

When instructed to specifically press into the surface samples, participants react surprised and intrigued due to feeling a change in texture. Participants feel a greater change in surface patterns the more they press into it. Participants mention that on a first instance the samples feel odd yet addicting to touch.

3. *Signal to press into the different surfaces, can they feel differences in the design elements without me asking?and when asking?*

Without asking, participants mention that some surfaces feel harder and flatter, meanwhile others are much sharper and softer.

4. *Signal to press into the different surfaces (instructed order), do they experience them differently?*
    a. *Difference in size:*
        i. *smaller shapes: the shapes can be identified better, signal is more intense, feeling detain*
        ii. *If size is to large, the surface will feel flat*
    b. *Difference in form:*
        i. *Participants were able to identify that shapes and pattern were different but not able to recognize how it actually looks*
        ii. *Narrow shapes are preferred as participants can press deeper into these (and feel less flat)*
    c. *Difference in space:*
        i. *More spaced felt better,because participants can press deeper into it, and therefore feeling more dynamic*
        ii. *The more spaced, the sharper the texture feels (even though it is the same)*
    d. *Convex (D) vs concave (E):*
        i. *A concave curve feels better*
        ii. *Patterns feel different (even when they are the same),*

5. *Signal to press with different hand/finger positions (flat, vs vertical)*
    a. *Preferences*
    b. *Feeling*
    c. *Comfort*
    d. *Feeling the roughness*

Participants mention that on a flat angle (0 degrees) they have the largest contact area, however, at this angle participants could recognize less of the roughness changes. On a 90 degree angle they mention they cannot feel the changes in roughness. However at a slight tilt, it is a pleasant pressing experience while being able to identify the variable roughness.

6. *Questions*
    a. *What is your overall experience of these surfaces, Intrigue? Did you like this experience?*

Participants mention being amazed by the tactile feeling, expressing how natural it feels. All participants express the urge to keep pressing into the dynamic surfaces. One participant describes the interaction as immersive.

b. *Discomfort of pressing into these surfaces?, skin Numbness, pain?*

Participants mention that they have no pain in their fingers (skin area of contact), however feeling slightly sensitive after the study (~20min).

c. *How do you think these surfaces could be improved? (feeling roughness)*

All participants mention that a larger height displacement results in a more pleasant experience.

d. *Can you find the roughest?*
    i. *A1 std*
    ii. *Concave 2 (more separation)*
    iii. *C2, more spaced out*

e. *Which feels the nicest to touch? Why?*
    i. *A1, balance between feeling pattern, and roughness, and depth*
    ii. *C2, because the most depth*

f. *Concave (E) vs convex (D) feeling? why?*

One participant mentioned a more pleasant experience with a convex surface, as the deformation is larger. Two participants mention a more pleasant experience with a concave surface, in addition, mentioning that this fits better on the finger too.

When concave a more separated pattern is preferred. When convex, a less separated pattern is preferred

Part 2: feeling texture actuator (observe texture actuation experience) (15min)

1. *Give roughness block to the participant without them looking at it*
2. ***Let them hold the item without activating (flat side)***
3. *Let them hold the item activating one single actuator. Experience? (up 1 sec, then down) (arduino code 1)*
    a. *how do they react?, (5min)*
    b. *First feeling ?*
    c. *Experience, intrigue?*

Participants react surprised when the actuators are activated for the first time, expressing how weird such signal is. Participants mention how the actuator signal feeling on the skin is initially a pinpoint dot, however, after a second it fades into an area.

4. *Let them hold the item activating multiple actuators. Experience? (up 1 sec, then down) (arduino code 2)*
    a. *how do they react?, (5min)*
    b. *First feeling ?*
    c. *Experience, intrigue?*
    d. *How does this feel different from only one?*
    e. *Distinguish the different actuators?*
    f. *Differences between them?*
    g. *How many actuators can they feel*

Initially participants are unable to recognize the different actuators, being too distracted by the actuation signal itself. However after a few cycles participants are able to recognize the different signal spots. Participants mention the feeling of the actuators as organic and natural, almost like a machine is breathing and living in the palm.

5. *Let them hold the item activating multiple actuators, changing the design elements. How do they experience this? Curved side*
    a. *Differences in height, how does this feel? (arduino code 3)*
    Press 6 low height, press 7 for high

Participants recognize a less intense signal strength.

b. *Changes in speed/duration , how does this feel? (arduino code 4)*
Press 6 slow, press 7 for high

Participants recognize a more intense signal strength when the actuator is fast. However when slow, the feeling is more calming. On the contrary when the actuation is too slow, participants mention discomfort as they cannot recognize whether the actuator is being actuated.

6. *Questions*
    a. *What is your overall experience of these surfaces, Intrigue? Did you like this experience?*
    b. *Discomfort when actuators pressed into the skin?, skin Numbness, pain?*
    c. *How do you think these surfaces could be improved?*

Participants mention the experience as feeling weird in the beginning, however after a few cycles it feels relaxing and almost organic.

Part 3: feeling roughness and texture actuator simultaneously (5min)

1. *Give roughness block and texture actuator to the participant (one in each hand)*
2. *Allow them to press into the roughness surfaces and feel the texture actuators simultaneously. How do they experience this? (arduino code 5, continuous)*
    a. *Initial impressions?*

Participants mention on a first impression an overwhelming number of stimuli, however after multiple cycles, participants mention being able to focus on the different actuators and while feeling the surface roughnesses

3. *While the texture actuators are activated in a cycle, can participants focus and feel the variance of surface roughness? (mental overload) (arduino code 5)*

Participants mention that it is harder to concentrate, however, focus improves rapidly.

4. *Questions*
    a. *Experience when these two textures are combined?*
    b. *How do you think these surfaces could be improved for feel both simultaneously?*
    c. *Do you think you could train to understand and recognize?*

Results involving the demonstrator design

Results from the user testing deciding the design of the demonstrator

Roughness mechanism

- Finger pressing angle: Participants mention that on a flat angle (0 degrees) they have the largest contact area, however, at this angle participants could recognize less of the roughness changes. On a 90 degree angle they mention they cannot feel the changes in roughness. However at a slight tilt (~20 degrees), it is a pleasant pressing experience while being able to identify the variable roughness.

- Placement of mechanism: Variable roughness mechanisms will be placed on the top of three fingers (thumb, index and middle finger). During the user tests, participants experienced a more ease and familiar pressing experience when pressing with the thumb and index finger. However a third mechanism is added to showcase the concept and observe the user interaction. One finger top (ring finger) will have no mechanism (texture actuator nor variable roughness), as this can facilitate holding the device firmly (ring finger and middle finger share the same tendon, therefore less independent control, and little finger has the least mind-muscle control of all five fingers).

- Design elements of the roughness actuator
    - Surface curvature: Participants mention a more pleasant experience when the finger fits into the curvature. Therefore, the surfaces will be slightly concave.
    - Mechanism area: for an optimal demonstration, the mechanism shall cover the entire tip of the finger. Therefore, the dimensions shall be 20 mm in width and 25 mm in length.
    - Rigid structure Form, size and spacing:
        - Size: Smaller better, cause a good signal (1.1mm good, 3m too large)
        - Shape: narrow shapes are preferred, causing a stronger signal and able to dig deeper in the skin
        - Space: larger space felt better allowing for a larger height displacement

Texture actuator mechanism

- Number of actuators: from the user test, participants demonstrated difficulty identifying multiple actuators, however this improved drastically with time. A major cause of this is the soft contact with the actuators itself. Therefore, three actuators on the palm will be implemented considering a strong surface contact due to an ergonomic shape. In addition, one actuator will be placed on the little finger to observe how participants experience texture stimulation on the fingers.

Demonstrator shape

- Shape for ergonomic hand contact: During the user test of texture actuators, skin contact with these actuators varied regarding the hand placement. Therefore, the demonstrator shall have an ergonomic shape in which skin contact with the concept surface is permanent.

- Controller type (joystick/mouse): The concept can be applied to controllers such as a mouse or joystick, however, to minimise unnecessary complexity, the demonstrator shall adopt the purpose/form of a mouse.

Appendix 20: Demonstrator design and testing

Test setup

Demonstrator User testing setup

***Qualitative research** relies on data obtained by the researcher from first-hand observation, interviews, questionnaires, focus groups, participant-observation, recordings made in natural settings, documents, and artefacts. The data are generally non-numerical, with an emphasis on understanding behaviour.*

Objective of the concept demonstrator user test:

The objective of this qualitative sample testing is to observe how participants experience the use of variable texture mechanisms embedded into a product interaction. The envisioned interactive product consists of a communication interface between user and product, making use of changes in surface texture to communicate and receive information.

With this research, a first-hand practical experience is conducted, through which participants can feel the varying tactile textures and reflect upon this impression. Meanwhile, the observer will gather information on the interaction behaviour between the participant and the tested material.

The purpose of conducting such research is to discover the experience that this concept could deliver in the short term, where it is successful, where changes are needed and which additional research might be essential.

Elements to observe:

Part 1: introduction to the texture actuators and sensors

During the mechanism user tests, the effective working of the different mechanisms have been validated. However, participants expressed a need for time to get acquitted with these variable textures, as these provoked a larger number of stimuli, and required multiple minutes time to get used to.

activities

In this first part, participants will firstly experience the roughness sensors, in which surface texture changes to more is being pressed, and digital visualisation of this interaction (arduino processing). This is followed with an experience on the texture actuators and how these can be actuated with different patterns and speeds. At last, these two are combined for participants to get used to the large number of stimuli.

Part 2: interacting with both mechanisms simultaneously simulating a product interaction

The purpose of this study is to discover how participants experience the use of dynamic surface textures for an interactive product-user tactile communication. In the previous first part, participants have experienced a first impression on these mechanisms. Now, in this second part we want participant to engage with these surfaces and observe the following:

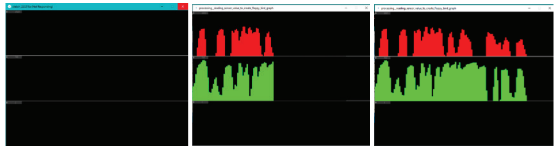
1. *How do participants experience these textures cohesively, when actively sending an intended signal to the "computer" (arduino visual), while simultaneously receiving ones too (texture actuators)?*
2. *How is participants' cognition affected when actively engaging with the signals from the surface sensors and actuators?*
3. *Can participants' feelings be influenced through different texture actuation patterns and speeds?*

With these research questions, it is important to establish how participants can be engaged in the product interaction in order to obtain qualitatively valuable results:

Each texture roughness sensor is connected to an analog force sensor (see demonstrator setup), in order to measure in real time the force being applied onto this surface. This real-time data can be converted into an onscreen visualisation (arduino processing, see demonstrator setup) from which participants can engage, mimicking a digital interaction on a basic level.

Sensor visualisation

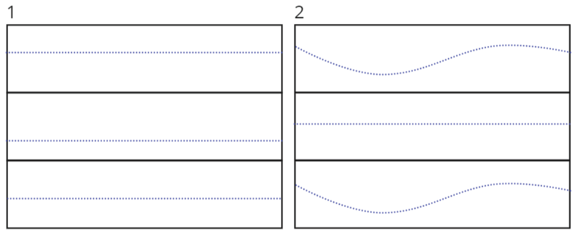
The chosen visualisation (with the time available and personal programming knowledge) for this interaction demonstration can be seen on the image below. In this image three continuous drawing screens are placed on top of each other. When the activity is started, the "drawing line" will move from left to right, and when the sensor is pressed, this drawing line can also move vertically. As a result, a drawing is screened from each sensor, which is used to establish the user test instructions. When the end of the screen is reached (on the right), the screen will be reset and immediately start again on the left.



Graphics are being improved

User Test

With the visual interaction established, the user test will be conducted through instructing participants what they have to "draw". These drawings will be variations of lines (see below), which will appear on the screen next to the drawing board, or on paper. With these instructions in mind, participants will actively engage with the roughness sensors, meanwhile different texture patterns are occurring simultaneously. Participants will be video and audio recorded, and the visual graphics will be saved to be used during the results analysis.



The blue line represents the drawing instructions (a better image will be made for the user test)

The three research questions will be addressed by the following:

1. *How do participants experience these textures cohesively, when actively sending an intended signal to the "computer" (arduino visual), while simultaneously receiving ones too (texture actuators)?*

   This will be answered (qualitatively) through recording the test itself and interviewing participants on the experience after the test. With this we focus on whether participants do (or not) like this product interaction, and what could be improved

2. *How is participants' cognition affected when actively engaging with the signals from the surface sensors and actuators?*

   Participants will be instructed to draw different curves, each more difficult. While simultaneously recognising the different actuators being actuated. This can be achieved through instructing participants to either stop or start drawing when a certain actuator signal or pattern occurs. As a result, we can observe how participants experience and handle the large number of stimuli.

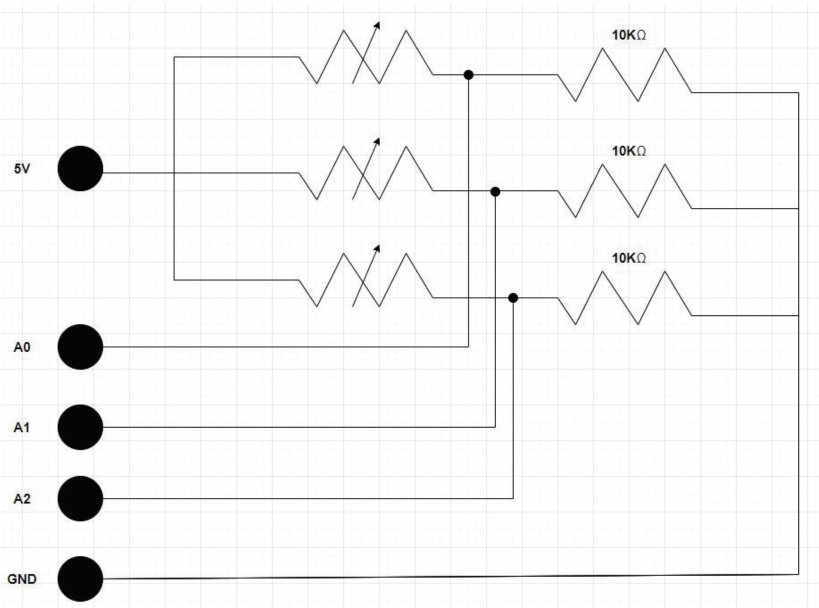
3. *Can participants' feelings be influenced through different texture actuation patterns and speeds?*

   Participants will be instructed to draw different curves, and after each curve, fill in a scoring sheet regarding how calm/stressed, focussed/distracted… they were during the drawing process. Even though multiple curves will be presented, each will be secretly repeated. However, the texture actuators for each curve will be different, as one will be slow, meanwhile the other will be fast, and twitching. As a result, we can observe whether different feelings can be evoked on the participant without changing the task.

Arduino code Force sensors

```
// rename these for your sensors:
int Apin = A0;     // analog
int Bpin = A1;     // analog
int Cpin = A2;      // digital pin
int A, B, C;

void setup()
{
  Serial.begin(9600);

}

void loop()
{
  A = analogRead(Apin);        // 0-1023 (in theory)
  B = analogRead(Bpin);        // 0-1023 (in theory)
  C = analogRead(Cpin);       // 0-1

  Serial.print(A);
  Serial.print(",");
  Serial.print(B-150);
  Serial.print(",");
  Serial.println(C-180);

  delay(20);                  // slight delay to slow down data flow
}
```

Force sensors circuit connection



Arduino code steppermotors

```
#define dirPin 2
#define stepPin 3
#define ROTARY_ANGLE_SENSOR A0

#define stepsPerRevolution 200


void setup() {
  // Declare pins as output:

      Serial.begin(9600);
      pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);
  pinMode(ROTARY_ANGLE_SENSOR, INPUT);
}
void loop() {

    int sensor_value = analogRead(ROTARY_ANGLE_SENSOR);


if (sensor_value<600) {
  // Set the spinning direction clockwise:
Serial.print(sensor_value);
 Serial.print(" , ");
 Serial.println("pump activated");

  digitalWrite(dirPin, LOW);
  // Spin the stepper motor 1 revolution slowly:
  for (int i = 0; i < 4*stepsPerRevolution; i++) {
    // These four lines result in 1 step:
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(500);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(500);
  }
delay(100);

  digitalWrite(dirPin, HIGH);
  // Spin the stepper motor 1 revolution slowly:
  for (int i = 0; i < 4*stepsPerRevolution; i++) {
    // These four lines result in 1 step:
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(500);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(500);
  }
  delay(500);}

  else{
        Serial.println(sensor_value);
    }

delay(50);
```

Processing visual code

```
// Graph Multiple Sensors in Processing

// Takes ASCII-encoded strings from serial port and graphs them.
// Expects COMMA or TAB SEPARATED values, followed by a newline, or newline and carriage return
// Can read 10-bit values from Arduino, 0-1023 (or even higher if you wish)
// Can also read float values

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import processing.serial.*;
Serial myPort;

int numValues = 3; // number of input values or sensors
// * change this to match how many values your Arduino is sending *

float[] values = new float[numValues];
int[] min = new int[numValues];
int[] max = new int[numValues];
color[] valColor = new color[numValues];

float partH; // partial screen height

int xPos = 0; // horizontal position of the graph
boolean clearScreen = true; // flagged when graph has filled screen


void setup() {
  size(1440, 1080);
  partH = height / numValues;

  // List all the available serial ports:
  printArray(Serial.list());
  // First port [0] in serial list is usually Arduino, but *check every time*:
  String portName = Serial.list()[2];
  myPort = new Serial(this, portName, 9600);
  // don't generate a serialEvent() until you get a newline character:
  myPort.bufferUntil('\n');

  textSize(10);

  background(0);
  noStroke();

  // initialize:
  // *edit these* to match how many values you are reading, and what colors you like
  values[0] = 0;
  min[0] = 0;
  max[0] = 900; // full range example, e.g. any analogRead
  valColor[0] = color(255, 0, 0); // red

  values[1] = 0;
  min[1] = 0;
  max[1] = 700;  // partial range example, e.g. IR distance sensor
  valColor[1] = color(0, 255, 0); // green

  values[2] = 0;
  min[2] = 0;
  max[2] = 400;    // digital input example, e.g. a button
  valColor[2] = color(0, 0, 255); // blue
  /*
 // example for adding a 4th value:
   values[3] = 0;
   min[3] = 0;
   max[3] = 400; // custom range example
   valColor[3] = color(255, 0, 255); // purple
   */
}


void draw() {
  // in the Arduino website example, everything is done in serialEvent
  // here, data is handled in serialEvent, and drawing is handled in draw()
  // when drawing every loop in draw(), you can see gaps when not updating as fast as data comes in
  // when drawing in serialEvent(), you can see frequency of data updates reflected in how fast graph moves
  // (either method can work)

  if (clearScreen) {
    // two options for erasing screen, i like the translucent option to see "history"
    // erase screen with black:
    background(0);

    // or, erase screen with translucent black:
    //fill(0,200);
    //noStroke();
    //rect(0,0,width,height);

    clearScreen = false; // reset flag
  }

  for (int i=0; i<numValues; i++) {

    // map to the range of partial screen height:
    float mappedVal = map(values[i], min[i], max[i], 0, partH);

    // draw lines:
    stroke(valColor[i]);
    line(xPos, partH*(i+1), xPos, partH*(i+1) - mappedVal);

    // draw dividing line:
    stroke(255);
    line(0, partH*(i+1), width, partH*(i+1));

    // display values on screen:
    fill(50);
    noStroke();
    rect(0, partH*i+1, 70, 12);
    fill(255);
    text(round(values[i]), 2, partH*i+10);
    fill(125);
    text(max[i], 40, partH*i+10);

    //print(i + ": " + values[i] + "\t"); // <- uncomment this to debug values in array
    //println("\t"+mappedVal); // <- uncomment this to debug mapped values
  }
  //println(); // <- uncomment this to read debugged values easier

  // increment the graph's horizontal position:
  xPos++;
  // if at the edge of the screen, go back to the beginning:
  if (xPos > width) {
    xPos = 0;
    clearScreen = true;
  }}

void serialEvent(Serial myPort) {
  try {
    // get the ASCII string:
    String inString = myPort.readStringUntil('\n');
    //println("raw: \t" + inString); // <- uncomment this to debug serial input from Arduino

    if (inString != null) {
      // trim off any whitespace:
      inString = trim(inString);

      // split the string on the delimiters and convert the resulting substrings into an float array:
      values = float(splitTokens(inString, ", \t")); // delimiter can be comma space or tab

      // if the array has at least the # of elements as your # of sensors, you know
      //   you got the whole data packet.
      if (values.length >= numValues) {
        /* you can increment xPos here instead of in draw():
        xPos++;
        if (xPos > width) {
          xPos = 0;
          clearScreen = true;
        }
        */
      }
    }
  }
  catch(RuntimeException e) {
    // only if there is an error:
    e.printStackTrace();
  }
}
```