Judgment of fabrics using haptic feedback technology

B. Sc. Thesis

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Abstract

The main goal of this thesis is to render fabrics in order to allow retailers and designers to judge these fabrics. Haptic feedback technology seems usable to do so, since it allows for tangible interaction. However, a literature review shows it is currently not feasible to render fabrics using haptic feedback technology. The technology cannot render precise and accurate enough. To explore more on the topic of haptics, a state-of-the-art review is made. The state-of-the art review shows rendering fabrics is currently not done with the use of devices. During this review also the Haptic revolver by Microsoft was explored. This device uses small pieces of fabric instead of rendering it completely without the use of actual fabric. An adapted version of this device could be able to render big sheets of fabrics with the use of just tiny pieces of fabric. Since the Revolver of Microsoft is not available to test, a controller is made with haptic wheels. These wheels hold a tiny piece of fabric on top, which, by rotating, gives the user the impression of touching a big sheet of fabric. This report describes the process of making the device, testing it, and it states possible improvements. The potential of the controller is present, however, iterations must be made in order to make the concept to a useful product.

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Contents

1 Introduction

1.1 Situation

Designing clothes and presenting new collections of clothes to retailers, are two events which return on structural base for companies in the clothing industry.

During the designing of clothes, designers want to present their ideas about fabrics, and so they must present a piece of the fabric they want to use. Currently this piece of fabric is either hand-made and so rather expensive, or represented with pictures, which does not allow for a proper judgment of the fabric. In order to allow the designers to save time, be more flexible, clarify themselves, and in order to save money, new ways of presenting the fabric must be found.

The way of presenting new collections used to be by making a batch of the complete collection and send them to the retailers. For every product the production machines need to be set-up, new sheets of fabric are needed, and the products also have to be transported. All of these actions cost the clothing companies a lot of money and time. In addition, by throwing away materials and transporting the products, the companies leave a big ecological footprint. In order to overcome these problems, a clothing company (PVH) came up with a digital showroom. These rooms are located in offices of the companies. Retailers can visit an office were they can see the new collection via digital displays. Using a big touchscreen the retailer can compose a collection out of the collection of the brand. Since retailers also want to judge the fabric of the clothes, still a batch of clothes needs to be made. Presenting clothes on screen allow the companies to make just 15% of the collection instead of the full 100% they used to make. This is a big improvement but leaves room for more developments.

The former stated company which came up with the digital showroom is PVH. This is a clothing company with brands like Tommy Hilfiger and Calvin Klein. PVH is a client of Hecla Professional, an audio and video systems company located in Hengelo. Hecla is the client for this graduation project, PVH is an indirect client.

1.2 Challenges

The goal of this graduation project is to develop a system which is able to haptically render fabrics in order to allow judgment of fabrics both by the designers and the retailers. As an inspiration for this system the Haptic Revolver of Microsoft [1] is used to build on. The system overcomes the problems of wasting materials and making big costs. The system is also able to provide the user a realistic fabric hand in order to allow judgment of the fabric. The system is developed within current technological limits. The system also allows for presenting different fabrics, since a lot of clothes are made with different fabrics. The system allows for quick switching between fabrics. The system also holds the possibility to accompany the haptic feedback with visual feedback.

1.3 Research Questions

Continuing the previous presented situation and challenges, two research questions are identified that will be covered by the following thesis:

- ***How to develop a haptic wheel interface which allows both designers and retailers of a clothing company to judge fabrics?***
- ***To what extent does this controller with a haptic wheel allow for judgment of the fabrics?***

To support the main research question and give a more elaborate answer, the following subquestions were formulated.

- *Does the use of a small piece of fabric allow for rendering a big sheet of fabric?*
- *How to construct a haptic wheel interface?*
- *Which features of fabric hand can, and which cannot be rendered using the haptic wheel?*

1.4 Report Outline

The report is organized as follows. In chapter 2 a context analysis, based on a literature review and a state-of-the-art review, is performed. In this chapter literature on the topic of haptic feedback is examined and a state of the art of haptic feedback devices is stated. Haptic feedback is explored and the conclusion is, that haptic feedback technology is currently not able to render fabrics in order to judge them. The precision of rendering is too low. However, developments regarding rendering small textures are nearby.

In order to find fitting solutions, chapter 3 examines other kinds of solutions. Using modern technologies, potential possibilities on the topic of rendering fabrics are examined. Preliminary requirements are formulated based on: a brainstorm session, stakeholder analysis, PACT analysis, scenarios and a meeting with the client. Using these preliminary requirements, a final concept is chosen: a haptic wheel interface based on the haptic revolver of Microsoft.

Chapter 4 tends to describe the envisioned system into more details by stating requirements prioritized using the MoSCoW method, the specification of the prototype. After formulating these requirements, chapter 5 describes the realisation of the system. All the steps taken in order to realise the prototype are stated, and a hi-fi prototype is made.

In order to evaluate the prototype's functionality and usability, both a functional test and an user test are conducted. These tests showed positive results, all of the functional requirements are met, and the user test shows the potential of the system. The hi-fi prototype is also presented to the client, PVH, they gave positive feedback and were enthusiastic about the final system.

Lastly conclusions are drawn based on the conducted research. Recommendations are stated in order to enlarge relevance and allow in-depth investigations on the topic of rendering fabrics, and the potential of the envisioned system in this field.

2 Context Analysis

This chapter covers a literature research which describes what haptic feedback is, what important features of fabrics are and it examines the possibilities of using haptic feedback technologies in order to judge fabrics. Leading in this chapter is the question: *To what extend do modern technologies/devices allow for rendering fabrics and their features.*

Technologies like force feedback, vibrotactile feedback, electrotactile feedback, ultrasound feedback, and thermal feedback are explored. Comparing the found features with these technologies allows to reason whether or not haptics are useful when rendering fabrics. Furthermore, this chapter will also cover a state of the art review describing which haptic devices already exist, and how relevant they are. The final part of this chapter is an overall conclusion on the context analysis. This conclusion tends to combine the findings in literature on the topic of haptic feedback technology with the found haptic devices, in order to state the potential of different technologies and devices.

2.1 Literature Review

This literature review covers a study on haptic feedback technology, and tries to answer the question: *To what extend does haptic feedback allow for accurate rendering of fabrics?*

This review contains four parts. The first part states a definition of haptic feedback. The second part regards a state-of-the-art of haptic feedback. In this part the current state and developments in haptic feedback technology are explored. The third part focuses on the use of haptic feedback in the judgment of fabrics. This part reviews some basic requirements of judging fabrics, and this requirements are compared with the possibilities of haptic feedback. Lastly, conclusions are drawn in an attempt to give a clear and concise answer to the question if haptic feedback is useful in the judgment of fabrics, so if it allows for accurate rendering of fabrics.

2.1.1 Definition of haptic feedback

In order to improve todays human computer interaction, haptic feedback technology can be used. Nowadays, a lot of this interaction is based on touch, which is often by sliding and tapping on a screen of glass that gives visual feedback. A big setback of the touchscreen is the lack of tangible feedback. Smart-phones are able to vibrate when receiving a message, but this functions as an alert rather than providing the user with tangible feedback. Paterson [2] states that people like to interact in a new way with their computer and their screens, this new way is based on haptic feedback and it's found on the idea of allowing people to interact with technology in a more active and exploratory way. The word 'haptic feedback' arises from the word haptic, which means the sense of touch [3–7]. Using haptic feedback technology, also called haptics, interaction with the virtual environment is no longer only visual and aural but it's also tangible [3, 8]. The words haptic feedback and haptics are used interchangeable in this review. In order to overcome todays limited manner of human computer interaction, haptic feedback can be used to make this interaction more active and exploratory by providing tangible feedback.

Haptic feedback implies a lot of different concepts, at a high level two kinds of haptic feedback can be distinguished. This two kinds of haptics are kinesthetic feedback and tactile feedback [3,5]. Kinesthetic feedback is based on the things a human can feel with the nerves inside his muscles and joints. By touching and carrying an object one can estimate its size and weight, and on top of that the user can also determine where the object is in relation to his body [5, 8]. Ravikanth et al. [5] and Saddik [8] also agree that tactile feedback is about the things one senses with his skin, often with the skin of the fingers. The skin of a human has a lot of nerves in it, which allows him to sense things such as texture, heat, pressure, and vibration. This tactile sensation allows a person to determine the shape and material of an object. Combining these two kinds of feedback allows a person to get an idea of the features of an object. This features can, for instance, be used to determine what the object is. Kinesthetic feedback and tactile feedback are two high level kinds of haptic feedback, and can be used both separately and combined based on what kind of feedback is needed.

In order to reproduce the physical features of a virtual object, a haptic interface can be used. This interface is a device which exchanges energy with users, either via mechanical movement or an electrical stimulus [4]. Via sensors the interface can determine the input of the user. Based on this input, the interface is able to calculate a fitting output and delivers it via actuators [4, 8]. Saddik [8] states that two major features can be determined which characterize haptic devices, namely, the degrees of freedom (DOF) and the refresh rate. The degrees of freedom indicate on how many axis the device can deliver force. 1-DOF for instance implies one degree of freedom. In the current existing haptic feedback devices 1-DOF, 2-DOF and 3-DOF are most common is agreed by Xia [3] and Salisbury et al. [7]. The relatively new and emerging 4-DOF and higher orders allow for more realistic feedback but are harder to produce [7]. The refresh rate refers to the maximum amount of individual forces the device can generate per time unit. According to Saddik [8] this is typical 1kHz to create a smooth feedback. Both of these properties, DOF and refresh rate, contribute to the realism of the haptic feedback.

Using the above stated characteristics of haptic feedback a definition of haptic feedback technology is formulated. This definition combines the different kinds of haptics at a high level, with the abilities of haptics, and the way of presenting the haptics. The formulated definition is as follows: *Haptic feedback technology is either one, or a combination of kinesthetic and tactile feedback, which allows a person to interact with the virtual environment by touching virtual objects which real-world features are recreated with the use of haptic feedback devices called haptic interfaces*. This definition is used throughout this literature review.

2.1.2 Types of haptics

Haptic feedback has a general definition, but haptics occur in different types. In order to get an overview of the current types of haptic feedback, the framework provided by Tesla is used [9]. This framework is used since it allows for a systematic exploration of the different types of haptics. In addition, this framework gives an elaborate view on the topic of haptics. According to this framework [9], haptics consist out of five basic types of feedback, namely, force feedback, vibrotactile feedback, electrotactile feedback, ultrasound feedback, and thermal feedback. Only force feedback depends on kinesthetic feedback, the four other types of feedback are based on tactile feedback. Each of the five feedback types is based on a certain physics phenomenon. Since the characteristics of these phenomena are different, the different types of feedback currently only fit for specific applications.

2.1.2.1 Force feedback

Force feedback is a very basic type of haptic feedback and uses the principle of kinesthetic feedback. Force feedback aims to reproduce the information which can be sensed by the human kineasthetic system [2]. Proximity and intimacy are often related with touch in the real world. Using force feedback, touch gets a whole new definition. Touch is no longer just something to experience nearby, but can be reproduced over a distance using a network, like the Internet for instance. Force feedback can occur through a combination of pressure and movement in space. Paterson [2] states that the force feedback devices affect the muscles and limbs in contradiction to other types of haptic feedback technology which only affect the skin and its receptors. For a realistic and pleasant experience of touching and manipulating a virtual object, the user must be provided sufficient freedom of movement. Since the user needs this freedom of movement, the force feedback devices are often big and expensive to make [10]. Additionally, to create the most realistic experience, the user should also be able to see the object. By accompanying the haptic model of a virtual object using visual representations on either a screen or via AR/VR technology, the user can both see and feel the object which creates a better user experience. Paterson [2] argues that the haptic feedback conforms the visuals and vice versa. Force feedback aims to reproduce touch using pressure and movement, it is based on kinesthetic feedback, and requires freedom of movement for the user to be realistic.

2.1.2.2 Vibrotactile feedback

Different from the above stated force feedback, vibrotactile feedback affects the skin and its receptors. Kaczmarek et al. [11] state that vibrotactile stimulation is based on mechanical vibrations which arouse tactile sensations. An example of vibrotactile feedback is the buzzing of a mobile phone when receiving a call [12,13]. Hayward et al. [12] state that this kind of feedback is the most used type of all haptic feedback technologies. This is most likely the case since this technology is cheap, simple and easy to use. In addition, this technology does not require a lot of parameters and it has a relatively small power consumption. The technology lends itself particularly for hand-held devices with applications like invisible alerts, warnings, messages, and feedback in games [12]. Vibrotactile feedback is concerned with stimulating the receptors in the skin of the user with the use of vibrations.

Besides the stated advantages of this technology, also some disadvantages can be distinguished. To explain these disadvantages, a closer look must be taken to the principal vibrotactile feedback technology uses. The two most used manners of evoking vibration is by either using an eccentric mass motor or using an electromagnetic moving coil [13]. One disadvantage is that it's hard to make these actuators small enough to deliver specific and detailed tactile feedback on the skin. Therefore this kind of feedback is less useful for applications where small-scale feedback is needed. In addition, these actuators have a relative confined area. So in order to give feedback on larger parts of the skin, multiple actuators are needed [12]. Besides this practical disadvantages, also some physical properties of this technology are challenging to control and may cause problems. This troubling physical properties are the time it costs to adapt the frequency, the bandwidth of the actuator and the difference in reaction time between stimulus and response compared to the real-world [13]. Vibrotactile feedback interfaces are cheap and relative easy to use, however, they also offer some challenges regarding small-scale feedback and parameter management..

2.1.2.3 Electrotactile feedback

By stimulating both the receptors and the nerve fibers using electric current, one can provide feedback. This feedback using electric current is called electrotactile feedback [11]. By either applying electric charge directly on a finger or via a conductive surface, an electrostatic field is created. Kaczmarek et al. [11], Bau et al. [14] and Meyer et al. [15] agree that this electrostatic field can be experienced as friction due to the attraction force developed between the finger and the (conductive) surface. Kaczmarek et al. [11] call this kind of friction between a finger and an adapted touch surface the 'electrostatic friction'. Based on the amount of voltages applied to the surface, the electrostatic friction changes. This change in friction results in a broad variety of different shapes and textures which can be experienced by the user [14, 15]. This kind of feedback can be applied to very small surfaces, but can also be used for bigger surfaces. The technology can be shaped as a new device, added to objects or be added to existing devices like phones and tablets. Combining the visuals of an object with a tactile sensation allows users to experience an object virtually and over a distance. One big advantage of this kind of feedback is the lack of moving mechanical parts, which allows the device to be small and solid [14]. Using electric current one can provide feedback based on electrostatic friction, which can be used to render objects, shapes, and textures.

2.1.2.4 Ultrasound feedback

Using ultrasound on bare skin one can get haptic feedback in free space. Ultrasound feedback uses high frequency sound waves and its acoustic radiation pressure phenomenon to provide feedback [16]. The ultrasonic vibration envelope is the most important concept used in this type of feedback, since the finger friction mechanics associates the envelope of the vibration with friction [15]. Iwamoto et al. [16] state that airborne ultrasound seems to be the best candidate for this type of feedback, because of its ability to reflect almost all the ultrasound on the skin. This ultrasound based technology allows the user to use the feedback on bare skin, so without the use of a reflective film to feel the pressure caused by the ultrasound.

2.1.2.5 Thermal feedback

Using temperature and thermal conductivity, thermal feedback provides a user with the thermal characteristics of the object the interface is rendering. Thermal feedback is based on the use of temperature in order to give feedback to the user [17, 18]. When the fingertip of a user touches the surface of an object, a simulation of the heat transfer gives the user the idea of feeling the temperature which fits the object. In order to give a realistic simulation of the heat, Kyung et al. [17] state that controllability of the heat and a fast response is essential. Thermal feedback can be used to give feedback over a bigger surface, but this requires a lot of energy since heat needs to be generated or be taken away. Kyung et al. [17], and Jones and Berris [18] agree that regardless of thermal feedback not being the primary concern in tactile feedback research, it's a crucial part of realistic feedback. When two objects have the same shape and texture, one can distinct between the two objects based on their different thermal characteristics. Two important concepts in thermal feedback are, according to the research of Kyung et al. [17], heat capacity and thermal conductivity. These concepts as a product, but also the differences between them, describe the heat transfer of materials. These differences and products allow thermal feedback to simulate the thermal behavior of objects, in order to make them feel more realistic [17]. The concepts heat capacity and thermal conductivity are important in thermal feedback, since they provide the user with thermal characteristics of the rendered object.

2.1.3 Implementation of haptics

In order to tell whether or not haptic feedback technology can be used in the judgment in fabrics, the physical properties and characteristics of fabrics are needed. After formulating these features, the formerly stated different haptic feedback technologies can be examined to be suitable for judging fabrics.

2.1.3.1 Features of fabric hand

Fabrics come in different kinds, shapes, and each fabric has other features. Because of its physical properties and characteristics, each fabric is unique. These differences occur due to the great amount of variance of material, processing and finishing. This great diversity makes fabrics both interesting and complex, especially to describe and model. In order to be able to know and judge a fabric, one must see and feel the fabric. According to the AATCC [19] and Hassan M. Behery [20], the tactile sensations a person gets when touching and rubbing a fabric is called the 'fabric hand', sometimes also referred to as the 'drape of the material'. Using the features of fabrics, one can describe fabric hand. At all times this process of describing fabrics is a subjective process, since it's associated with personal tactile sensations which are translated into the features [20]. Using the Guidelines for the Subjective Evaluation of Fabric Hand [19] in combination with a chapter of the book by Behery [20] and the information portal of Textile School [21], table 1 is composed. This table holds a list of features to describe fabric hand. The physical properties of fabrics stated in table 1 contribute together to the texture of the fabric. Altinsoy and Merchel [13], Hu et al. [22], and Culbertson et al. [23] agree that texture is one of the most important features of fabric hand, since humans use texture observation to identify objects and their properties. For that reason, the bottleneck of using haptic feedback technology will be to what extent the interfaces is able to render the features of the textures.

Table 1 – Features of fabric hand *

Kind of feature	Description
Physical properties of Fabrics	- Type, size and length of fiber - Diameter, twist and size of yarn - Fabric structure - Woven, knitted or non-woven - Finishes (chemicals and mechanical effects)
Physical characteristics of Fabrics	- Thermal conductivity - Light Permeability - Moisture transmission - Transformation characteristics such as elasticity, flexibility and elongation
Other features	- Smoothness - Softness - Firmness - Thickness - Warmth - Weight - Stiffness

* table is composed using [19] [20] [21]

2.1.3.2 Haptic feedback technology applied to the features of fabrics

Currently there is a lot of research on the topic of rendering the textures of surfaces, using haptic feedback interfaces. In this section the five different types of haptic feedback technology stated in chapter 2.1.2 will be examined.

2.1.3.2.1 Force feedback

Because of its characteristics, force feedback is not very useful when rendering fabrics. Textures are basically differences in height on a detailed level. One could argue that using force feedback, this differences can be generated in order to render the texture. However, force feedback is based on perceiving feedback via the nerves inside muscles and joints, as stated in chapter 2.1.1. The texture of fabrics is experienced by tactile sensations [19], which means it's too small and detailed to experience with the nerves inside muscles and joints. This means that texture is too small to render using force feedback. However, the transformation characteristics from the physical characteristics of table 1 could be rendered, since they do rely to some extent on ones kinesthetic sensations. For example, the elasticity and flexibility of a big sheet of fabric. In order to render fabrics force feedback cannot be used to render fine textures, but it might be useful to render other features of fabric hand.

2.1.3.2.2 Vibrotactile feedback

An interface using vibrotactile feedback allows for rendering of fabrics, but is not ideal. A lot of the existing interfaces to examine textures utilize a pen-based vibrotactile tool, which the user can hold and touch a surface with [3,5,22,24,25]. Using vibrations with different frequencies, the pen can render the texture of a surface to some extent. Despite the ability to render this technique has a big setback, namely, it is not very intuitive. The definition of fabric hand suggests that one wants to touch the fabric using his finger in order to get the tactile sensation. This sensations can be linked to different properties and characteristics of fabrics. It can be argued that using a pen-based device to experience a fabric is not intuitive, since a tool is used to touch the fabric. On top of that, when one drags a tool across a rock and a wooden table he can feel the difference, but when he drags an item across two fairly similar fabrics he will not feel the difference, since the two textures are too much alike [22]. When rendering fabrics, vibrotactile feedback does render the fabrics to some extent, but due to the not intuitive interaction it is not very useful.

2.1.3.2.3 Electrotactile feedback
Using electrotactile feedback, textures can be recreated using electrostatic friction. To a certain extent, this will cover the physical properties of fabrics given in table 1, also referred to as the texture [13–15]. This electrotactile feedback provides feedback when the user moves his fingers over the interface. This feedback exists due to electrostatic fields which induce friction. Currently no electrotactile device exist which can render such small details as needed for accurate rendering of the texture differences between two similar fabrics. Todays most advanced devices render up to 1mm. This is detailed, but not sufficient for rendering fabrics, which usually have highly detailed textures and finishes [26]. To some extent electrotactile feedback is able to render textures, using electrostatic fields.

2.1.3.2.4 Ultrasound feedback
Ultrasound on its own is not sufficient to render fabrics, however, in combination with other types of haptic feedback this type might be useful. According to Meyer et al. [15], ultrasound feedback is able to support an electrostatic interface to render textures. Electrotactile feedback interfaces can produce forces on a wide-bandwidth, which allows to render textures to some extent, but the range of friction it can produce is not very wide. Adding an ultrasonic device to the interface may solve this problem, since the ultrasound feedback is able to generate this wider range of friction. Currently no proper solution is found but the idea seems promising [15]. Ultrasound feedback might be useful in combination with other types of feedback when rendering fabrics.

2.1.3.2.5 Thermal feedback
Next to rendering the actual and expected temperature of the fabric, thermal feedback also allows to render some of the physical characteristics stated in table 1. Kyung et al. [17] state the relevance of thermal cues to people, since they use them in order to discriminate among materials. Both the characteristics thermal conductivity and moisture transmission heavily depend on temperature and its behavior. These characteristics can be rendered using thermal feedback [27]. The haptic interface must have a fast heating and cooling rate in order to simulate a realistic heat transfer between the fingertip and the rendered fabric. Kyung et al. [17] state that a cooling rate of 2°C/s and a heating rate of 4°C/s are sufficient, this is possible to realize with todays technology. Since thermal feedback is able to render some of the physical characteristics of fabric hand, this type of feedback might be useful when rendering fabrics.

2.1.4 Conclusion Literature Review

This review states a brief overview on the topic of haptic feedback and the different types of technology used to create interfaces. Subsequently, important features of fabric hand are described and the stated types of technology are compared to these features.

Currently no haptic feedback interface exists which can render fabrics and all of its features, however a combination of types may apply. In order for a person to judge fabrics, he must be able to experience different features of the fabric. Most haptic feedback technologies can only render one of the features stated in table 1. Since texture exists out of multiple properties and characteristics, the interface must be able to render more than just one of these features. A combination of electrotactile, ultrasound, and thermal feedback may allow for a tactile feedback interface which can simulate fabrics to a certain extent. Combing electrotactile feedback and ultrasound feedback allows for rendering physical properties, the texture, of the fabric. Adding thermal feedback allows for rendering some of the physical characteristics of fabric. One type of haptic feedback on its own does not render sufficient features of a fabric, however, combing different types of haptic feedback do render multiple features of fabric to some extent which may allow for judging. Nonetheless, this render is with todays technology not elaborate and complete enough to be used for judging fabrics. The features may be rendered, but not precise and detailed enough to allow the user to distinguish the features of the fabric.

Force feedback and vibrotactile feedback do not seem to apply for rendering fabrics for judgment. Both of the types allow for rendering one feature to some extent, but either the way of interacting is not good, or the desired feature is not rendered sufficient. These technologies are, with todays technology, not useful when rendering fabrics for judgment.

Current techniques does not allow to render at such precision as needed, but the potential is big. Especially electrotactile feedback, which is a fairly new type of feedback in the field of rendering textures, allows for rendering small details. Further investigation is needed to be able to use haptic feedback technology to judge fabrics.

The focus of this review is on haptic feedback in general and gives an overview of current types of haptic feedback technology. At this moment the main principal of a type of feedback may not seem to be applicable to judge fabrics, a further elaboration of this technology may give new solutions which do apply. Combining different haptic feedback technologies in one device in combination with AR/VR to provide high quality visual feedback could be useful to some extent in order to judge fabrics. More investigation is needed on the topic of combining haptics with AR/VR in order to render fabrics for judgment.

2.2 State Of The Art Review

This review describes which products already are available and developed in the field of haptic feedback with relation to rendering textures, it tends to answer the question: *Which haptic interfaces are already developed on the topic of rendering fabrics and/or textures?*

This state of the art review contains six sections which cover developed haptic feedback interfaces. In the last section conclusions are drawn with respect to the stated question.

2.2.1 Teslasuit

The Teslasuit by Tesla is a full body suit which holds a haptic feedback system, motion capture system and it is temperature controlled [28]. The Teslasuit system is based on a combination of Electrical Nerve Stimulation and Electrical Muscle Stimulations. This combination ensures a high density of sensations to the user. Next to this nerve and muscle stimulation, the suit also holds a thermocontrol which allows for thermal feedback. Using this feature the suit can both heat up and cool down according to the virtual environment or object. This suit is stretchable, breathable, durable and washable.

The suit (figure 1) itself is not made with the purpose of rendering either fabrics or textures. However, the technology used does allow to render the thermal conductivity of materials. Other features of fabric hand can not be rendered since the density and precision of actuators do not allow for such precise rendering as needed.

Figure 1 – Teslasuit, picture from Teslasuit.io [28]

2.2.2 Ultrahaptics

Ultrahaptics uses ultrasound feedback to create three-dimensional shapes and textures to some extend [29]. This device (figure 2) allows to add haptics to virtual objects, to develop holographic interfaces and enlarges gesture control with the use of tactile feedback. This device creates a tactile sensation in mid-air, this means without the need for controllers and wearables.

If rendering with Ultrahaptics at a very high density was possible this device might be interesting to render the texture of fabrics. However, the density and accuracy of rendering is low and only allows for rendering basic shapes in mid-air rather than very detailed textures.

Figure 2 – Ultrahaptics, picture from Electronicdesign.com [30]

2.2.3 HaptX Gloves

The HaptX Gloves (figure 3) are haptic gloves which add touch, force feedback and motion tracking to virtual reality [31]. The glove let the user feel the shape, movement, texture and temperature of digital objects while it simultaneously tracks the movement and positioning in space. The main concept used for this device is microfluidic technology, this is processed in textile. This textile contains a network of high-displacement pneumatic actuators and a number of microfluidic air channels. By pushing against the user his skin, the actuators give feedback. By controlling the amount of pressure and the precise spot, the gloves can create a big amount of sensations (which imply texture, size, shape and movement). Additional thermal feedback can be integrated into this gloves as well. Combining the microfluidic actuators with an exoskeleton which provides force feedback to each individual finger, allow for a realistic rendering of objects.

The HaptX Gloves can render with a high accuracy due to its high actuator density. According to their website [31] only the flat of the hand already holds up to 120 actuators. Although this is a very high density, this is by far not enough to render the detailed texture of fabrics. The thermal properties, which will be added in the near future this device, can be used to render thermal conductivity of a fabric.

Figure 3 – HaptX Gloves, picture from HaptX.com [31]

2.2.4 Tanvas

Tanvas is a device which enables the user to add a sense of touch to a touch display using haptic feedback technology [32]. Using ultrasonic vibrations and electrostatic fields this technology allows the user to feel different materials on a touchscreen (figure 4), which enables one to feel what he sees on screen. This technology aims to provide tactile feedback to the fingertips in order to enable interaction with the virtual environment.

According to reviews of people who used this technology at the CES 2016, the experience is not very good. The device is able to render rough shapes, but it does not allow for rendering detailed textures since it is not accurate enough. This technology might be interesting in the future but currently does not seem to be useful in order to allow judgment of fabrics.

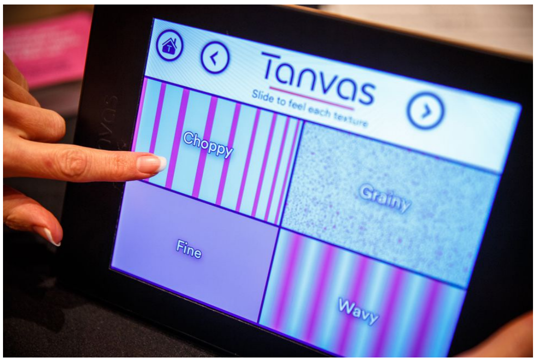

Figure 4 – Tanvas, picture from Cnet.com [33]

2.2.5 Haptic Revolver

The Haptic Revolver by Microsoft is a hand-held controller which can render haptics at the users fingertip when interacting with virtual objects [1] (figure 5). The Revolver consists out of a wheel which can rotate and move up and down in order to render touch contact with a virtual environment. By spinning the wheel the device renders both shear forces and motion while the user moves along the virtual surface. The index finger of the user rests on a groove directly above the wheel's axis. When the user touches the virtual surface, the wheel moves up and touches the fingertip. By rotating the wheel when the user moves his finger, a friction is rendered based on the speed of the movement along the surface. The wheel can be changed, so different materials can be used in order to provide different tactile sensations to the user. By adding edges and other elements to the wheel, objects on top of the virtual surface can be rendered as well.

This technology does not allow to completely render the fabrics without using any existing fabrics. Yet this means that is does allow to provide an accurate fabric hand since it uses the actual fabric. This technology seems suitable for the rendering of fabrics.

Figure 5 – Haptic Revolver, picture from MSpoweruser.com [34]

2.2.6 SensAble Phantom Omni

The Phantom Omni (figure 6) is a 6-DoF haptic device and has a pen-based interface, its handle is connected to the base using one chain with different joints [35]. The device uses force feedback in order to render objects and textures. The Phantom Omni currently can be used in combination with the Penn Haptic Texture Toolkit (HaTT) developed by Penn Engineering, which offers 100 haptic texture and friction models [36].

The Phantom Omni can render very accurate due to its 6-DoF and the accurate actuators used. One very big down-side to this technology is the use of a pen-based interface, which, as stated before, does not provide an intuitive interaction. Since the user is not able to experience the tactile sensations with his fingers, this may feel odd.

Figure 6 – SensAble Phantom Omni, picture from delfthapticslab.nl [35]

2.2.7 Conclusion State Of The Art Review

Currently no device exist which is able to render fabrics accurate enough to be used to judge the fabric. Some of the devices are able to render for instance the thermal conductivity of a material, but other features of fabric hand seem to be not possible. Even devices like the HaptX Glove and the Phantom Omni, which both can render with a very high accuracy, don't seem to apply for this application. The Haptic Revolver of Microsoft seems to be a good option since it renders the fabric at the highest accuracy as possible, because it uses the actual fabric.

2.3 Conclusion

This chapter states a context analysis on the topic of haptic feedback. Both a literature review and a state of the art review are included in order to provide a complete overview on the topic of haptic feedback with respect to the judgment of fabrics.

The stated literature review tries to answer if and to what extend haptic feedback allows for accurate rendering of fabrics. This section concludes that currently the technology is not developed enough to allow for sufficient rendering of fabrics for judgment. Some techniques allow for rendering certain features of the fabric to some extend, but none allows for rendering multiple features. Maybe a combination of multiple types of haptic feedback do allow for rendering multiple features of the the fabric. Even if this is possible, the quality of the render is not sufficient yet due to the technology which still not allow for high quality rendering. The potential of using haptic feedback is big, but it is not ready yet.

The state of the art review examines which haptic interfaces are already developed regarding rendering fabrics and/or textures. Currently no device exist which is able to render fabrics detailed enough to be used for judging the fabric. No device exist which actually aims to render fabrics. Some devices have the ability to render textures to a certain extend, and some are able to render thermal conductivity. As stated, only a combination of multiple features will allow for a sufficient fabric hand, this is not achieved by any of the devices. However, the Haptic Revolver of Microsoft seems to be interesting since it uses the actual fabric, but tends to reduce the amount of needed material. By building this device and adapt it to the use case of judging fabrics, this device might be useful.

Todays haptic feedback technology is immature to allow for accurate rendering of fabrics. Also, no device currently exists which can render fabrics. The Haptic Revolver seems to be an interesting device to explore and adapt to the use-case.

3 Ideation

This chapter describes the ideation phase of this project. The ideation phase is the first phase of the design method for Creative Technology, it is used to generate ideas, and based on certain aspects choose one final concept to build. This chapter contains multiple aspects, which lead to the final concept. First a brainstorm is stated which includes eight ideas. Some of these ideas are based on ideas and devices found during the context analysis. After brainstorming, a stakeholder analysis is conducted. This analysis tends to give more insight in the involved parties, and how to treat them during the whole project. After conducting a stakeholder analysis, a PACT analysis is performed. This PACT analysis allows to formulate different aspects of the current situation, which enables the developer to gain more insight in this situation. Using the PACT analysis, a scenario is made from the user's perspective. Combining all of the finding during the context analysis and the ideation, a list of preliminary requirements is made. The ideas of the brainstorming session are treated using the preliminary requirements, this leads to a fitting solution, the final concept: a haptic wheel interface.

3.1 Brainstorming

Idea 1
Create a fabric which can be modified in order to reproduce different properties of a fabric. By using special fibers, which change when applying electricity to them, a fabric can be changed real-time. With this special fibers, properties like the elasticity, roughness, and the way the clothes fall can be changed. This fibers can be woven to create a small sheet of fabric, parts of clothes like a sleeve, or complete pieces of clothes.

Idea 2
Create advanced weaving machines which can locally weave small sheets of fabric which allow for judgment. Computer models for the weave pattern of a fabric are generated and send to the weaving machine. By defining a set of basic fibers with all specific characteristics, different properties of fabrics can be generated. These machines are small and portable so they can be placed at the locations of the different end-users.

Idea 3
Create a surface with very tiny needles which can move up and down in order to generate properties of a fabric. These needles are small enough to not be experienced as sharp, painful and disturbing. By moving these needles with different speed, resistance and in different patterns, these needles allow for generating specific properties in compliance to the fabrics.

Idea 4
Use a pen-based interface which uses vibrotactile feedback to render the properties of a fabric. By holding a pen which vibrates in specific patterns, the feeling of scraping a pen over a fabric can be generated. First one piece of the fabric has to be created and using measuring devices a model of the fabric can be made. This model can be send to the end-users and be transported on to a pen, which then provides vibrotactile feedback.

Idea 5
Use electrostatic fields on a surface which allow for rendering fabrics. By creating fields in a certain patterns, different textures can be generated. A device which allows for generating such fields is needed, the surface can differ. By creating these fields on top of an interface which displays the fabric itself allows for an experience which combines tactile sensations with matching visuals.

Idea 6
Use a 3D-model to create an exploded view of the fabric. For instance the weave pattern can be displayed, which allows the viewer to see how the fabric is made (using an exploded view for instance). This tells experienced people in the field of fabrics how the fabric feels and behaves. In combination with sophisticated shaders, this model allows for a visual judgment of the fabric. Adding physics allows for accurate modeling of clothes around a virtual person. This concepts tends to show both the way the material is made, and how it behaves.

Idea 7
Create an interface which uses a small piece of the fabric in order to render a bigger piece of the fabric. This can be done using a wheel which rotates in the opposite direction of the user's movement. The device can be hold in one hand and can be used as an extension to a visual representation of the fabric. Using the existing piece of fabric allows for an accurate feeling of the fabric since the actual fabric is used. Wheels can be changed to render different sheets of fabric.

Idea 8
Create mood-boards which represent a fabric. Using colors, objects, textures and shapes, a certain impression of the fabric can be given. By defining different characteristics using specific images, a fabric can be presented. This requires people who are trained to read this mood-boards.

3.2 Stakeholder analysis

Using a stakeholder analysis, the parties involved in the development of the prototype can be found. According to Freeman and Reed [37], a stakeholders is either an individual, a group or an organisation that has an interest in a project. Stakeholders affect or are affected by certain decisions and outcomes of the project. Neither of the stakeholders are the same nor equal. Sharp et al. [38] state that stakeholders can be categorised based on their role in the project. The four concepts of main stakeholders are: users, developers legislators and decision-makers.

By mapping the stakeholders into a stakeholder matrix, the importance of the different stakeholders can be determined. Based on this matrix the way of managing the stakeholders can be determined. The stakeholder matrix of Mendelow [39] adapted by Thompson [40] is used, which provides a matrix with two axis: a power-axis and an interest-axis. Figure 7 holds the adapted matrix, mapping all the stakeholders. This matrix follows from the analysis stated below. Both the power and the interest of the stakeholders are examined.

3.2.1 Users

The users are the people who will interact with the system, the ones who will use the system. This project recognizes two main users, the designers of clothes and the retailers who are representatives of retail companies. For this project both of this groups are involved with the brand Tommy Hilfiger, part of the clothing company PVH [41]. Also a third user can be distinguished, the buyers of the fabrics.

The first group of users are the retailers of companies who tend to sell clothes of a collection by a clothing company. They will visit a clothing company and choose a collection of clothes, based on the looks and fabric hand of the clothes. This process currently works, so for the retailers there is no need for commissioning the system. However, when a clothing company chooses to commission this system, this may have influence on the experience of judging the product. This group of users have a high interest but their power is low.

The second group of users are the designers of a clothing company. During the process of designing clothes, choices regarding the fabric have to be made. The choices a partly based on the fabric hand, which this system tends to render. Currently the designing is already working and there is no direct need for commissioning the system. However, when this system is commissioned by a clothing company this may have influence of the experience. The judgment of fabrics could either improve or become worse, both having a major influence on the work of the designers. This results in a high interest, but since they do not have the last word, their power is medium.

A potential third group of users can be distinguished, these users are the buyers of the fabrics in name of a clothing company. Next to the designers, also a group of people is present which buy fabrics. This group could also use the envisioned system when the producer of the fabrics uses this system to present a lot of fabrics without the need of bringing big sheets of fabric. However, in order to narrow the scope of potential users, this group is not taken into account.

3.2.2 Developers

Developers are all the people that are involved in the developing of the project. In this project the researcher performs this role. The interest of the researcher is high since he executes this project himself. The influence of the developer is medium. He is able to make decisions, but these are for a big part based on the interests of the users and decision makers who have a lot more power.

A co-developer for the judgment of fabric project is Juliette Hoedemakers. Her focus is on the visual aspect of judging fabrics, so she is not involved in developing this particular concecpt. She is involved in the bigger concept of he idea, she has a high interest but low power.

3.2.3 Legislators

There are no legislators involved in this project.

3.2.4 Decision-makers

Decision-makers are the ones who have high power in the development of the system. This group of people is responsible for the project and/or the system. This group of people set requirements and state goals. They must be involved in major steps in the development since they have a final say in the decisions that are made.

The client for this graduation project is Hecla Professional. They do not have the intention to commission the system themselves, but are highly interested in the development since it is for one of their clients. The system is a potential product for Hecla which they can sell to clients like PVH. Besides, the techniques involved are relative new technologies which may be interesting for their company, so gaining information is interesting for this group. The interest of Hecla Professional is high as well as their power.

Another decision-maker is the supervisor from the University of Twente, from the bachelor program Creative Technology. He has medium interest and a high power. Next to the supervisor also a critical observer is present. He has medium interest and medium power.

A client of Hecla Professional is the clothing company PVH. This is the group which actually tend to commission the system. This group is interested in the use of new technologies in order to render fabrics. They have motives like saving money and speeding up certain processes. Their interest is high, their power is medium.

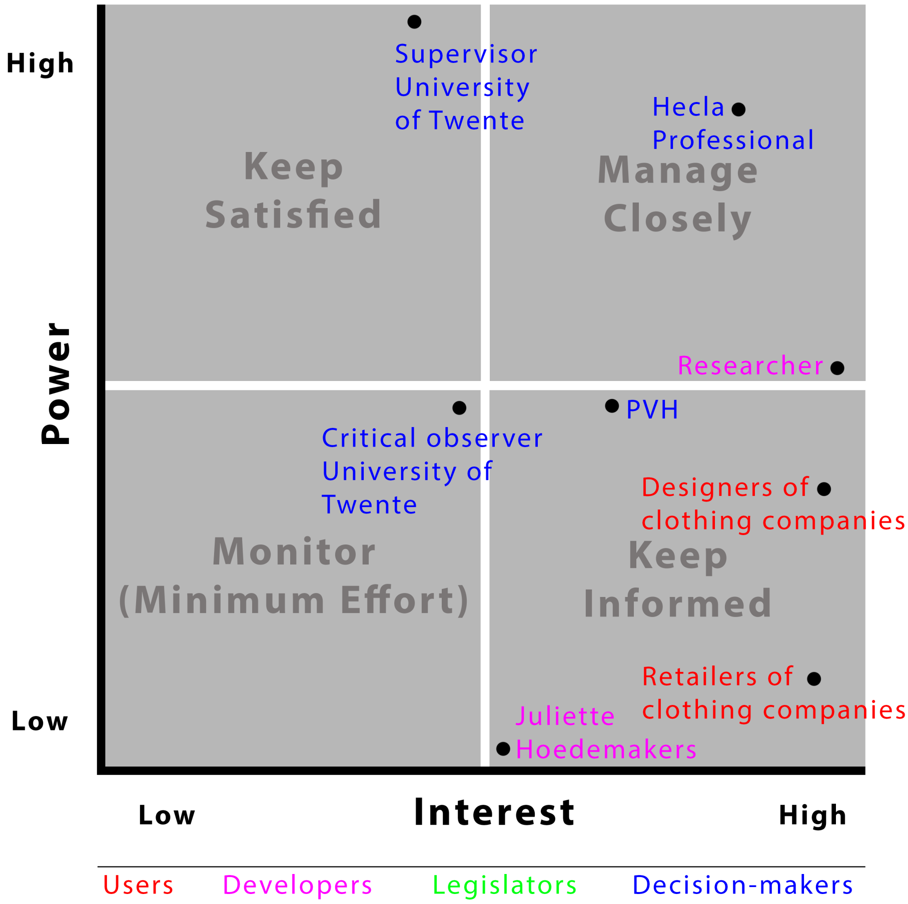

Figure 7 – Matrix with stakeholders. Showing their interest on the x-axis and their power on the y-axis

3.3 PACT analysis

The aim of designing a system is to create it in such a way, it meets the needs of specific users, who execute certain activities in a certain context using specific technologies. PACT is a framework which can be used to specify these users, activities, context, and technologies [42]. PACT is an acronym, which stands for the words: People, Activities, Context and Technologies, according to Trulock [43]. Based on this PACT analysis, iPACT adds an 'i' which allows to state the 'intention' of the system [44].

Intention
The intention of this envisioned system is to allow for tangible judgment of fabric without the need of making clothes or big sheets of fabric. Yet, it must allow the user to experience a big sheet of fabric in order to be able to judge the fabric.

People
People entails all relevant physical and cognitive user characteristics, motivations, experience and skills. The above stated user groups are the people using the system, these are the retailers and the designers.

Retailers
The retailers are, as stated before, representatives of companies who retail the clothes of clothing companies. Out of all of the clothes of a brand, they compose a collection which they will sell to their costumers. In order to make funded choices in the selection of clothes they must judge the clothes on different aspects. The look, the colors, the way the clothing folds, the reflection in light, the texture and fabric hand. All of these aspects contribute to how well the clothes will be sold by the retailer, and how well the clothes fit into the collection of the retailer.

The motivation of the retailer to use system is to judge the quality and hand of the fabric. If a clothing company he visits chooses to use visuals and an interface to transfer the fabric in order to present their clothes, the retailer simply has no other choice than to use it.

The retailer sees a lot of different clothes and fabrics, so he is experienced in the field of judging fabrics. Since he tends to both judge and buy clothes, he has skills in both judging clothes and in sales..

Designers
The designers of a clothing company are, as stated before, responsible for the design of the clothes and for the material choice. The fabric they tend to use must fit both the design and the theme of the collection. The designers are often experienced in the field of fabrics but still need to see and feel a lot of specific details to judge if the fabric is good enough to be used. All the properties must be felt and experienced to get a good impression of the fabric.

The designers are motivated to use an interface which renders the fabric because this allows for a more precise judgment of fabric, compared to currently used systems. Nowadays this is often done using images, which are spread to other designers all over the world. By creating an interface which allows for a more tangible but yet quick way of communicating the fabrics will improve the design-phase.

Since designers are responsible for the theme of a collection, designing clothes, and choose fabrics they are good in judging fabrics. They work with fabrics on daily base, and small details are important since they either strengthen of weaken their designs.

Activities
The users of the system want to judge the fabric of a garment. The reason they want to judge is either because they determine if they will use the fabric in their design (designers), or to determine if they want a garment in their collection (retailers).

The frequency of judging by the retailers depends on how often the clothing company tends to present a new collection, usually this is 4 times a year. For each of these collections the retailer visits the clothing company only once, so the retailer will use the system only 4 days per year. Yet these interactions are very important since based on these interactions the retailer decides whether or not he will buy clothes of the collection.

The designers will use the system more frequent since they have multiple fabrics to judge per garment. This means they will interact more frequent with the system compared to the retailers.

Context
The judging of the fabrics will be in an office, so inside a building. There is a lot of space to move and electricity is at hand. The setting is in case of the retailer formal and in case of the designer somewhat informal yet professional.

Technologies
Recently, clothing companies have integrated technology in presenting their clothes to retailers. A big touch interface is used in combination with a wall filled with screens. The presentation rooms also include audio, which allows for a presentation of the theme of the collection. The touch interface and screens are also used to present the clothes themselves. To get a tangible feeling of the fabrics the clothing companies offer a swatches book, with real sheets of fabric.

The designers use pictures and drawings of fabrics and their textures. Sometimes a piece of existing fabric is used. Currently, the designers don't use a lot of technology, the designing process tends to be traditional and analog.

Figure 8 – Digital showroom of Tommy Hilfiger, by PVH. Image from knight-interactive.com [45]

3.4 Scenario from the user's perspective

By defining a concrete description of a use-case, a scenario, design implications can be formulated and substantiated. A scenario describes how the user uses the envisioned system, what he wants and what he needs. This gives insight in the requirements based on concrete situations. The base of this scenario is the performed PACT analysis. Since the scenarios describe the situation from the user's perspective, the intention was to use both the retailer's and the designer's perspective in order to create a scenario (or multiple scenarios). However, after contacting the clothing company PVH, it is concluded that a scenario from the designer's perspective is not feasible. The designers of clothing companies are very busy, and an appointment was impossible. Besides , the contact persons did not have enough knowledge about the design process to give enough information for a scenario. For that reason there is no scenario present from the designer's perspective, the retailer's perspective however is explored.

Retailer

Jim is a 30 year old men who is a representative for a big clothing retail-company. He got an invitation to come to the clothing-company PVH in Amsterdam to see the new collection of Tommy Hilfiger. So this morning he woke up and drove to Amsterdam, and now is ready to enter the office of PVH.

The office is a high building, located in the port of Amsterdam. The building is modern, nice looking and quite impressive. Jim enters the building via a revolving door and the receptionist greets him. After telling who he is and why he is here, the receptionist calls Peter, the representative of Tommy Hilfiger who is going to present the collection to him. While waiting for Peter to arrive, Jim gets a cup of coffee and a nice seat.

When Peter arrives, he and Jim take the elevator to the 14th floor where they have an astonishing view over the port. The 14th floor is separated in rooms by walls made of glass, this allows you to see everything going on and allows you to see a part of the collection presented. The clothes are displayed on mannequins, and Peter tells they are just a selection of this winters' collection.

Jim and Peter walk towards a nice walnut desk with a big integrated touchscreen. On this screen Peter shows some of the inspirations for the collection and tells something about the choices made. After giving this brief introduction they walk to the digital showroom, where an even bigger walnut desk is present. Again with a big touchscreen mounted on the desk, but now also a big wall with screens is present at the end of the desk. Peter presses a button and the showroom goes into theater-mode, a movie with information about the collection is presented.

After the elaborate introduction to the collection, Jim has a good impression of the theme and inspiration of the collection. Peter briefly explains how the interface works, and now Jim is free to explore the collection himself using the touchscreen. Another cup of coffee is brought into the room. By dragging and sliding on the screen, Jim can compose a collection, and review clothes on the big wall with screens.

Peter then also points at a small controller which lays on the table. Next to the controller a nice box is located which holds a stack of wheels. It seems like there is fabric on top of the wheels. Peter explains to Jim that whenever he wants to feel the fabric of a garment, he can tell him and he will change the wheel accordingly. After Jim tells Peter he wants to feel the fabric of a specific shirt, Peter easily clicks a wheel of the controller and hand it over to Jim. The controller has two grooves in which Jim puts his fingers, so that his fingertips touch the wheel. When Jim moves the controller around, the wheel starts to spin which give him the impression he is moving his hand on a big sheet of fabric. On the screen he sees the fabric in detail, and next to it a model on screen wearing the shirt.

When finished with experiencing the shirt, Jim wants to feel the fabric of a pair of jeans. Peter switches the wheel with a new wheel, and within seconds Jim is able to experience the fabric of the jeans. The controller allows him to feel a big sheet of fabric with just a small device in his hand.

After Jim is done composing a collection which his company can sell, Peter clicks on the finish button on screen. Jim enters his e-mail address and the invoice is sent to him via an e-mail. Jim and Peter shake hands and Jim is guided towards the exit. Jim heads home after composing a collection via a pleasant experience.

Designer
Further investigations needed, not enough information present to state a proper scenario in which the envisioned system is used.

3.5 Meeting PVH

During the ideation phase, also the client PVH is visited. They gave information about the process, and the current developments. The client did not have a lot of requirements, since they want to explore possibilities rather than obstruct creative ideas. They would like to be able to render fabrics without the need of physical fabrics, and the rendered fabrics must allow for judgment. In order to fit into the style of PVH, the system should look neat and luxurious.

3.6 Preliminary requirements

A list of preliminary requirements is made, using the results of the PACT analysis, the user scenarios and a meeting with the client (PVH), see table 2. The table is split in two columns, left states the functional requirements (actions and things the system does), right the non-functional requirements (what the system is). Using the MoSCoW method, the importance of the requirements is given. The MoSCoW method developed by Dai Clegg of Oracle UK in 1994 is a method used to create a prioritised list or requirements [46]. Based on this prioritised list one can determine the sequence of completing requirements. According to Haughey [46], the acronym MoSCoW stands for Must have, Should have, Could have and Won't have. Where the 'must-haves' are non-negotiable, the 'should-haves' should be delivered as many as possible and the 'could-' and 'won't-haves' are nice but do not have direct impact on the success of the project.

Table 2 – Preliminary requirements of the system *

Functional	Non-functional
MUST	
	System must be realizable with current technology
	Experience must be intuitive, tangible and be of added value to the presented visuals
	System must be realized within the given timespan
	The system must allow the user to judge the fabrics
	The system must allow for reduction of fabrics
SHOULD	
	The system should look neat and luxurious, in line with the style of PVH
	The system should be able to render a big sheet of fabric, which the user can freely experience
COULD	
	The system could allow for judgment of fabrics without the need of making a piece of fabric
WON'T	
	The system won't be able to render fabrics without the use of the actual fabric

* table is composed using the PACT analysis, the scenarios and a meeting with the client (PVH).

3.7 Concepts

When comparing the ideas of the brainstorming section with the preliminary requirements, choices can be made. Both the dropouts and promising ideas are stated. A short recap of the ideas:

- Idea 1: Fabric with fibers which can be modified in order to generate specific properties
- Idea 2: Weaving machines which can locally weave custom sheets of fabric
- Idea 3: Surface with tiny needles which move up and down to generate tactile sensations
- Idea 4: Pen-based interface which uses vibrotactile feedback to render fabric
- Idea 5: Use of electrostatic fields in order to generate texture
- Idea 6: Use visuals like a 3D-model of the weaving pattern
- Idea 7: Controller with a rotating haptic wheel, which holds a tiny piece of fabric
- Idea 8: Mood-boards which represent fabrics

3.7.1 Dropouts

Looking at the requirements eight different reasons for an idea to fail can be formulated. Namely, technology is not developed enough, poor experience, and not realizable in the timespan given for this project. Each of this reasons are treated in a different paragraph, and ideas which dropout because of this reasons are assigned accordingly. The three most applicable reasons are listed below. In figure 9 all of the non-functional 'must-haves' are listed and for each idea a cross is placed when applicable. This matrix emphasizes that idea 7 is the only idea which meets all the requirements.

	idea 1	idea 2	idea 3	idea 4	idea 5	idea 6	idea 7	idea 8
System must be realizable with current technology	x	x		x		x	x	x
Experience must be intuitive, tangible and be of added value to the presented visuals	x	x	x		x		x	
System must be realized within the given timespan				x		x	x	x
The system must allow the user to judge the fabrics	x	x	x	x	x	x	x	
The system must allow for reduction of fabrics	x		x	x	x	x	x	x

Figure 9 – Matrix with the ideas and the non-functional 'must-haves'. Idea 7 is the only idea which meets all of the requirements.

Technology is not developed enough
Both the ideas 3 and 5 seem interesting and promising. However, current technology is not developed enough to allow for such a way of rendering fabrics. Idea 3 requires a surface of needles with a diameter of 1mm or smaller, which must be controlled separately. This requires mechanics on a very small scale, yet the needles must be quite strong to compensate the applied pressure of the user. This does not seem to be possible with current technology. Idea 5 requires electrostatic fields which are made with a precision of 1mm or even smaller. Based on literature it can be concluded that current technology is not developed enough to allow for such precision and yet be tangible.

Poor experience
The ideas 4, 6, and 8 dropout since they do not allow for an intuitive and tangible interaction. One of the requirements of the client is to allow for judgment based on tangible interaction, which is not the case for the ideas 6 and 8. Idea 4 is in concept good-working, and should allow the user to feel the texture of a fabric whilst the fabric is not present. However, the experience is similar to judge a fabric when rubbing across the surface using a pointed pen-like tool. This is not a logic and intuitive way to experience a fabric.

Not realizable due to the given timespan
Idea 1 and idea 2 use another approach to render fabrics and some of its properties. However, the ideas are too complex and elaborate to realize in the given timespan. For this reason the ideas dropout. Creating a new kind of advanced fibers requires elaborate and time consuming investigation. The same holds for creating weaving machines which are portable, and can locally create a custom fiber. These machines must be able to set-up themselves, and advanced weaving patterns must be integrated. This requires a lot of knowledge on the topic of weaving, fibers, and weaving machines. Both of this ideas are time consuming and not realizable given the timespan.

3.7.2 Promising idea

One idea meets almost all the requirements, this is idea 7. This idea uses a simple motor, a microcontroller, a tracker to track the position, and a 3D-printer to make the casing. At first glance the system does seem to provide an experience which meets the requirements. To what extend the experience is sufficient must be investigated. The idea is not very complex and elaborate, so it should be possible to be finished within the given timespan. After iteration it is possible to make the system look neat and luxurious. The only requirement this idea does not meet is the use of no fabrics at all to allow for judgment, although it does reduce the amount of fabrics needed very substantially. Since this requirement is a 'could', it is not a reason to dropout this idea.

3.8 Conclusion and final concept

This part states the final concept based on the findings in this ideation phase. As stated previously, idea 7 seems to be most promising, for this reason this idea will be used as base for the concept. The idea is funded on the idea of Microsoft which is stated in the context analysis, the Haptic Revolver. This haptic device, however, is not available to use and test, so a prototype has to be made.

The concept consist of different parts; a motor, a casing, a wheel with fabric on top, a sensor to track the movement and a controller to process the data. The device holds at least the motor and the tracking sensor. The user takes the device into his hand with his fingers touching the haptic wheel with fabric on top, and moves over the horizontal-axis. The movement is tracked, using a sensor, and send to a processing unit (a micro-controller). This unit processes the data and tells the motor at what speed and in which direction it should rotate. The haptic wheel is attached to the axis of the motor. When the user moves the device, the motor starts to rotate in order to give the user the impression he moves his fingers over a sheet of fabric. The haptic wheel can be removed from the axis, and a different haptic wheel can be attached which holds a different fabric on top.

4 Specification

The specification phase is the second phase of the design method for Creative Technology. The found requirements of the ideation phase are specified in to more detail. Also, based on the final concept (which is stated in chapter 3.7), requirements are formulated. Taken the context analysis and the ideation into account, requirements can be formulated. A sketch is made in order to specify into more detail what the envisioned system should look like.

Similar to table 2, table 3 distributes the requirements with respect to functional and non-funtional requirements. Also, the requirements are prioritised based on the MoSCoW method. The MoSCoW method developed by Dai Clegg of Oracle UK in 1994 is a method used to create a prioritised list or requirements [46]. Based on this prioritised list one can determine the sequence of completing requirements. According to Haughey [46], the acronym MoSCoW stands for Must have, Should have, Could have and Won't have. Where the 'must-haves' are non-negotiable, the 'should-haves' should be delivered as many as possible and the 'could-haves' are nice but do not have direct impact on the success of the project. The 'won't-haves' state possibilities, but which are not included in the design because the were not feasible. Table 3 can be found on the next page.

Combining all of the requirements, the envisioned system looks like the sketch in figure 10. The haptic wheel is present, and can rotate in two directions. Also grooves for the fingers are present. The device is handheld and allows for quick switching of fabrics. In this design the ability to move up and down is included, this ability however, is not realizable due to a short of both time and money. Also a wire is present at the back of the controller. This wire is preferable not present, but given the time and complexity of the design it is not a major point of interest.

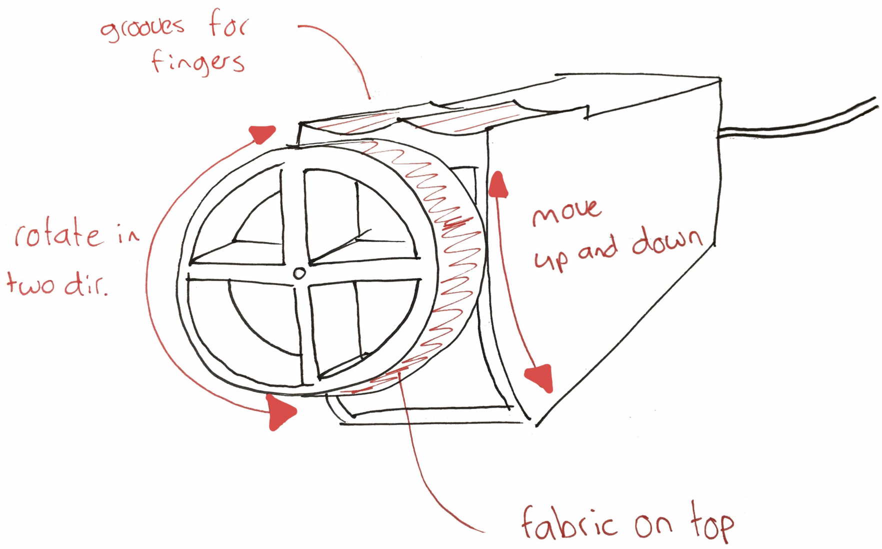

Figure 10 – Sketch of the envisioned system. With the haptic wheel which can spin in two directions, fabric on top of the haptic wheel, ability to move up and down, and grooves to keep the fingers of the user in place.

Table 3 – Requirements of the system *

Functional	**Non-functional**
MUST	
The wheel must be able to spin at both low and high speed	The system must allow the user to judge the fabrics
The wheel must be able to rotate at a speed matching the movement of the user	The system must render a big sheet of fabric, which the user can freely experience
The wheel must be able to rotate in two direction and quickly switch from rotation direction	Experience must be intuitive, tangible and be of added value
The system must have a speed limit to prevent the wheel from spinning too hard (which may cause burning wounds)	The controller must be light and handheld
The system must allow for a wide range of motion	The system must allow the user to feel a flat surface using a rotating wheel
The system must track the movement of the user with high precision	It must be easy to switch wheels (which have different fabrics)
The system must be designed in such a way, the user's fingers touch the wheel without effort	Diameter of the haptic wheel must be big enough to give the impression of a flat surface (but must be as small as possible)
The device must, at least, allow for judgment by rotating in the x-direction	The system must allow for reduction of fabrics
The tracker-system must be robust	
Wheel must rotate, even at small movements of the user (1cm/s for instance)	
SHOULD	
The wheel should rotate even when the user presses fairly hard on the wheel	The device should be rounded and ergonomic
The grooves for the fingers should offer guidance and aid to the user	The system should be easy to set-up
	The system should look neat and luxurious, in line with the style of PVH
	The system should allow to be combined with visuals
	The tracking sensor should not bother the user
	User should not experience any hindrance from the attachment of the fabric to the wheel
	The controller should feel solid and reliable
COULD	
The system could allow for rotation in both x-direction and y-direction	The system could be wireless
	The system could be stand-alone
	The system could be plug-and-play
WON'T	
The haptic wheel won't be able to move up and down	The system won't be able to render fabrics without the need of actual fabric

* table is composed using ideation chapter and the final concept.

5 Realisation

The realisation phase is the third phase of the design method for Creative Technology. The specification phase leads towards design choices which are used to state the required and used components for the hi-fi prototype. These components consist of hardware, software and the casing. All components are analysed to be consistent with the requirements before realised and added to the prototype. This chapter describes which technologies are used to build the prototype, why certain design choices are made and states the final prototype. First the hardware is treated, components like the motor, tracking device, and the casing. Different motors are tested in order to find the right one, a motor with 80 rpm an a big torque. Also different trackers are tested, the HTC VIVE came out most stable and yet easy to implement. For the casing also a few iterations are stated. The final design consists of deep grooves for the fingers to rest in, nice round shapes and a beam to attach the tracker to. For every component the iterations are stated when applied. Since problems occurred during different phases of the realisation, the iteration is a process which is done constantly. This results in iterations for individual components rather than iterations of the complete prototype.

Next to the hardware, also the software is explained in some detail. Major tasks of the system are treated: motion tracking and the rendering of fabrics. The complete and final prototype is presented in its final setup, including different haptic wheels with seven different fabrics.

5.1 Software and hardware components

The requirements, as stated in chapter 4, are interpreted in order to make them meaningful for the component at hand. However, due to limited time, not all requirements are treated extensively for all different components. In order to illustrate how his interpreting of requirements can be performed, this is done for one hardware component: the motor. The functional requirements are translated to technological requirements. This kind of requirements is measurable, and so the components can be compared to measurable specifications. Abilities and functions of the motor are calculated, and compared to the technological requirements. This will lead to a motor which meets all the defined needs.

5.1.1 Hardware

Different hardware components are used for this system. Each of the components are explained in more detail belows. The components used are a motor, H-bridge module, Arduino UNO, tracking device, servo, power-supply, haptic wheel, and a casing.

Motor
In order to find a fitting motor, some requirements need to be taken into account.

- The motor must be able to rotate in two directions. Using a brushed motor is preferable since this kind of motors is able to rotate in two directions.
- The motor must be strong enough to rotate even while the user applies some pressure to the wheel.
- The motor must rotate with a certain speed. This is based on a number of variables: The speed is calculated by stating some variables. The maximal distance to cover in one movement, this is assumed to be 100cm. The diameter of the wheel, which is 6cm. This diameter gives a circumference of 18.84cm (found using $6*\pi$). Dividing the maximal distance (100cm) by the circumference of the wheel (18.84cm), gives the number of rotations needed to cover the maximal distance. Namely, 5.31 rotations ($100/18.84$). As a guideline for the desired time the motor takes to make this 5.31 rotations, is 2-5 seconds.
- The motor must be affordable.

- The motor must rotate smooth in order to allow for a stable and fluent interaction.

In order to find the correct motor, different models are examined. Since stepper-motors rotate fairly stuttering at lower speeds, these motors are not taken into account. The first two motors where not strong enough and/or able to rotate at the right speed. Motor 3 seems to be the most promising motor since it is both strong and rotates at the desired speed, for that reason motor 3 is chosen to be used for this system.

Motor 1, Adafruit 5V DC Toy / Hobby Motor [47]

- The torque at the shaft of the motor is 0.20Ncm, which means that it can lift approximately 0.02kg ($0.2Ncm/10$*(gravitational acceleration approx.)*) when a shaft with a radius of 1cm is used. With the wheel, which has a diameter of 6cm, the torque is 0.003 Kgcm ($0.02/6$. This is not strong enough since the user is able to stop the motor when pushing his finger against the wheel.
- This motor has a max. speed of 9100 rPM when 5V is applied. This means that the motor can cover the distance of 100cm in 0.035 seconds when a wheel with a diameter of 6cm is used ($5.31/(9100/60) = 1.01$). This is too fast, covering a distance of 100 cm in just 0.035 seconds does not seem to be use-able for the proposed task.
- This motor costs €1,69 on the website adafruit.com, this is cheap, so affordable.

Motor 2, Conrad 12V MFATransmissiemotor 540 50:1 [48]

- The torque at the shaft of the motor is 30Ncm, which means that it can lift approximately 3kg ($30Ncm/10$*(gravitational acceleration approx.)*) when a shaft with a radius of 1cm is used. With the wheel, which has a diameter of 6cm, the torque is 0.5 Kgcm ($3/6$. This seems to be strong enough. Yet, after trying this motor, the torque does not appear to be sufficient. The motor can easily be stopped when it rotates at lower speeds.
- This motor has a max. speed of 316 rPM when 12V is applied. This means that the motor can cover the distance of 100cm in 1.01 seconds when a wheel with a diameter of 6cm is used ($5.31/(316/60) = 1.01$).
- This motor costs €26,49 on the website Conrad.nl, this seems to be a reasonable price.

Motor 3, Pololu 12V 131:1 Metal Gearmotor [49]

- The torque at the shaft of the motor is 180Ncm, which means that it can lift approximately 18kg ($180Ncm/10$*(gravitational acceleration approx.)*) when a shaft with a radius of 1cm is used. With the wheel, which has a diameter of 6cm, the torque is 3 Kgcm ($18/6$. This torque is big enough to ensure the user is not able to stop the motor when pushing it. The motor is able to rotate at lower speeds with sufficient torque.
- This motor has a max. speed of 80 rPM when 12V is applied. This means that the motor can cover the distance of 100cm in 3.98 seconds when a wheel with a diameter of 6cm is used ($5.31/(80/60) = 3.98$). This top-speed is sufficient to render the fabric with a distance of 100cm within the desired time.
- This motor costs €42.70 on the website Pololu.com, this seems to be a reasonable price.

H-Bridge module
The H-bridge module used is the L298N. This module can be controlled using a PWM signal and two digital signals. Using the two digital signals the direction of the motor can be controlled (this is the H-bridge), using the PWM signal the speed of the motor can be controlled. A 12V power-supply must be attached to the module as well, this enables the module to provide the required power to the motor.

Arduino UNO
In order to control the motor using the H-bridge module an Arduino UNO is used. This Arduino UNO is able to send digital signals and PWM signals. It can also receive data from the tracker via the serial port which allows the Arduino to control the motor compliant with the movement of the tracker.

Tracking device
The tracking device must be able to track the movement of the user with the device. It should be easy to attach to the controller. It does not need to provide the exact location in free space, it must track the direction (over one axis) and velocity of the movement.

Accelerometer
First, an accelerometer was used since it is fairly small, easy, cheap and it measures the acceleration which can be transformed to velocity. After testing the sensor it appeared the sensor does not return a constant value. The measured acceleration has to be integrated over time in order to return the velocity (which can be used to calculate movement). When starting to measure, the values it returns instantly starts to drift. This occurs since also the errors are integrated over time, and so the errors enlarge every integration. This sensor is not accurate enough to be useful for this system.

HTC VIVE tracker
In order to find a more stable way to track the movement, the HTC VIVE tracker is used (figure 11). This tracker enables to track very accurate the movement of the user. It is easy to attach using a default camera screw, a M6 screw in the Netherlands (which are used on tri-pods for example). The HTC VIVE tracker can only be used in combination with a base-station of HTC. This base-station must be located at a distance of at least 2.5m from the tracker, and must be aimed towards the tracker.

Figure 11 – The HTC VIVE tracker.

Servo
In order to move the 12V DC motor up and down, which allows to choose whether or not to let the wheel touch the user's finger, a servo motor can be used. However, after testing, the servo motor is found not to be strong enough to lift the 12V DC motor. Next to that, the protocol used to control the servo violates the protocol used to control the 12V DC motor. Since it is both practically as programming-wise a challenge, and it does not directly influence the success-rate of the concept, it is decided to leave the servo out of the concept and leave the idea for further investigations.

Power-supply
A 12V power-supply is needed to allow the motor to rotate at it's max. speed, also a minimum current of 5A is required for the motor from Pololu [49]. Besides, the power-supply should be affordable. For this reasons, the Mean Well LRS-75-12 AC/DC [50] from Conrad.nl is chosen. This is a 12V power-supply with 6A max. output and costs €20,49.

Haptic wheel
The haptic wheel must be attached to the motor. This attachment must allow to switch the wheels with different fabrics. Preferably to switch without the need of screwing, or other time consuming proceedings. Figure 13 displays a breakout of the attachment of the haptic wheel to the motor. The gray part is the motor, the green part is the attachment, which must be screwed to the axis of the motor, the blue part is the changeable haptic wheel which can hold fabrics on top. The grooves inside the haptic wheel fit into the ridges of the green attachment (figure 12) and provide firmness when the motor starts to rotate. The diameter of the haptic wheel is 60mm. This is chosen since this provides a circumference which feels fairly flat, yet, creates a wheel which is not colossal. This is tested by trail and error, using jars, lids and cardboard tubes. Diameters varying from 20mm up to 100mm are tested. Another reason to use a diameter bigger than 50mm is the size of the motor. When the motor is placed inside a casing and the user must place his finger on top of the casing in order to make contact with the wheel, the casing must be at least 25mm above the axis of the motor. This results in a haptic wheel with a diameter of at least 50mm.

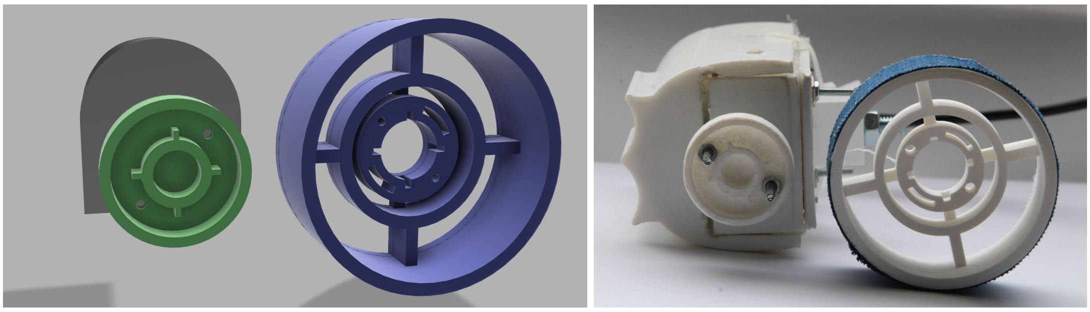

Figure 12 – Left image, 3D-render: breakout of the attachment of the blue haptic wheel to the green base which is attached to the motor. Right image: breakout of the same attachment when 3D printed. Note in both the 3D-render and the 3D print the gaps and ridges which fit into each other.

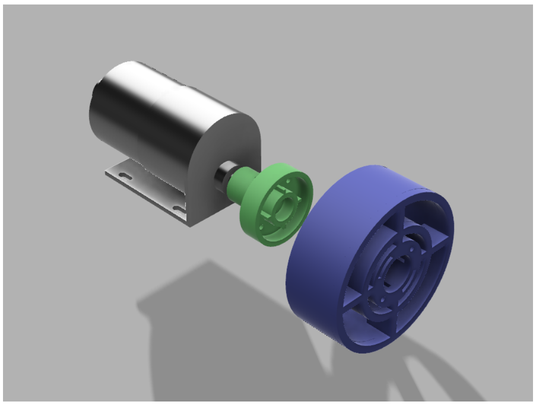

Figure 13 – Breakout of the attachment of the haptic wheel to the motor, front view.

Casing
In order to rotate the wheel with fabrics on top, a motor is used. This motor is placed inside a casing in order to allow the user to easily hold the system. Besides some room to hold the motor, the casing should also include grooves to guide where the fingers must rest, and it should be compact enough to be held in one hand.

Version 1
The first version of the casing is shown in figure 14. This version includes the 12V DC motor

in a red bin, the blue haptic wheel, and a gray casing. The red bin can move up and down in order to press the wheel against the finger of the user, or to remove the wheel from making contact with the finger. The servo motor needed for this movement can be placed inside the left rectangle, which is sticking out of the main body. This version is not very ergonomic due to its rough and rectangular shapes. Also, as stated in the part about servo motors, the servo motor will be removed from the design due to the lack of power to lift the 12V DC motor. For this reason the slot in which the servo motor could be placed, can be removed. The compartment in which the red bin can move up and down can be removed as well, since this movement is not possible after removing the servo.

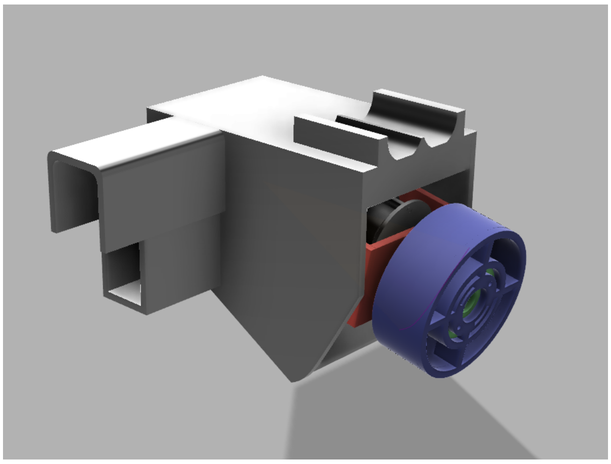

Figure 14 – Version 1 of the casing.

Version 2
The second version of the casing is shown in figure 17. This version also includes the 12V DC motor in a red bin, the blue haptic wheel, and a gray casing. Using round shapes and rounded edges, an attempt is made to make a more ergonomic design. The grooves allow the user to place his fingers on the correct place, and hold them in place. Since the servo is removed from the design, the height of the case with respect to the haptic wheel should be taken into account. It is chosen to make the casing in a way, that when the user rests his fingers in the grooves, this is the exact same height as the haptic wheel (this can be seen in figure 16). This prevents the user from the need to push down or the need to bend his fingers up in order to stay on top of the wheel.

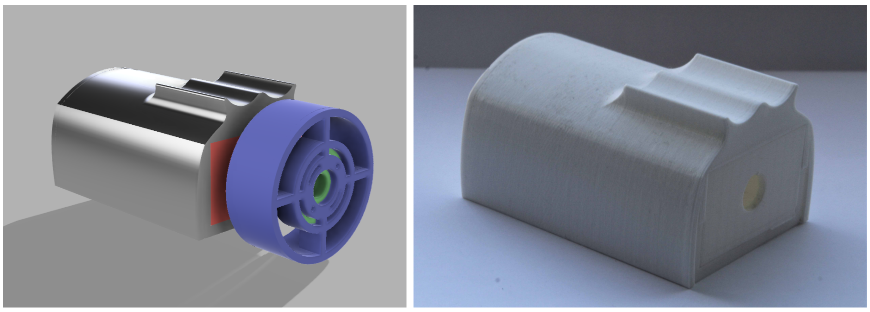

Figure 15 – Version 2 of the casing, servo is removed, edges are more smooth. Left the 3D-render of the case, right the 3D printed case.

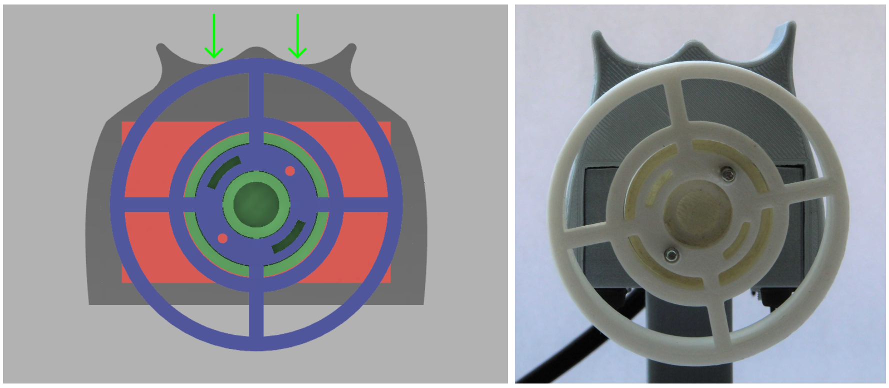

Figure 16 – Version 2 of the casing, the height of the haptic wheel and the lowest point of the grooves are the same. The left image is the 3D-render where the green arrows indicate points of interest. The right image is the realisation.

Version 3

The third version of the casing is shown in figure 17. This version holds the 12V DC motor in the casing without the use of the previous used red bin. Also the blue haptic wheel, and a gray casing can be found. The ergonomic round shapes, and the supporting grooves are preserved. Removing the red bin for the 12v DC motor allows to reduce the size of the controller. Both the width, height and length are reduced over 10mm, this allows the user to hold the controller more easily in his hands. This version still does not allow for attaching the tracker, in order to do so an additional part is made, figure 18.

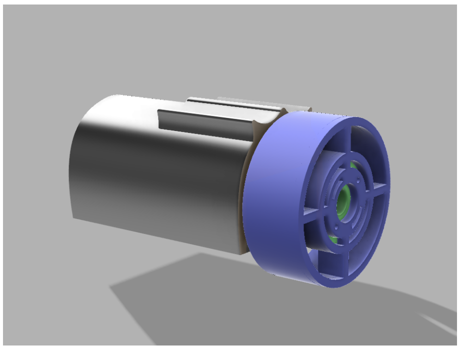

Figure 17 – Version 3 of the casing, an improved design of version 2. More efficient usage of the space by removing unnecessary parts.

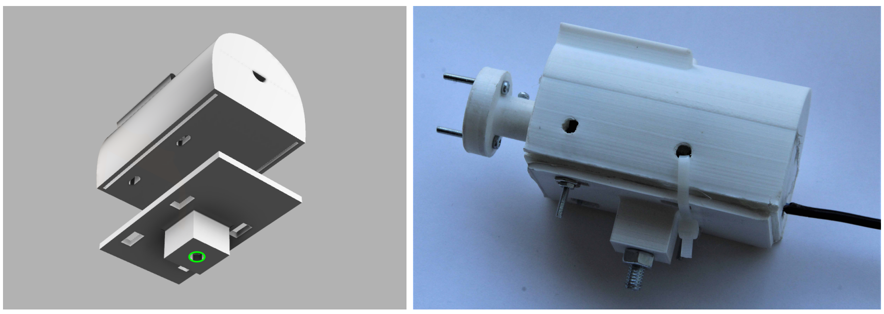

Figure 18 – Plate which can be attached to the casing. Left image, 3D-render: placing a screw inside the hole (bright green circle) on the end of the beam allows to attach the tracker. Right image: 3D printed version 3 of the case, the screw is at its place on the bottom.

Version 4

The fourth version of the casing is shown in figure 19. This version combines the designs from figure 17 and figure 18. Also the 'walls' of the casing are made thicker, from 2mm to 3mm, in order to made the controller more solid. The grooves at the top are deeper compared to previous designs. This is done in order to prevent the fingers from moving when using the device, this appeared to be a problem in previous designs during functional testing. In all of the four corners of the casing holes are made. These holes are used for the attachment of the top to the bottom. This attaching is done using tie-wraps in order to have the possibility to open the casing if necessary. A breakout of version 4 can be found in figure 20, this figure also hold a picture of the final prototype.

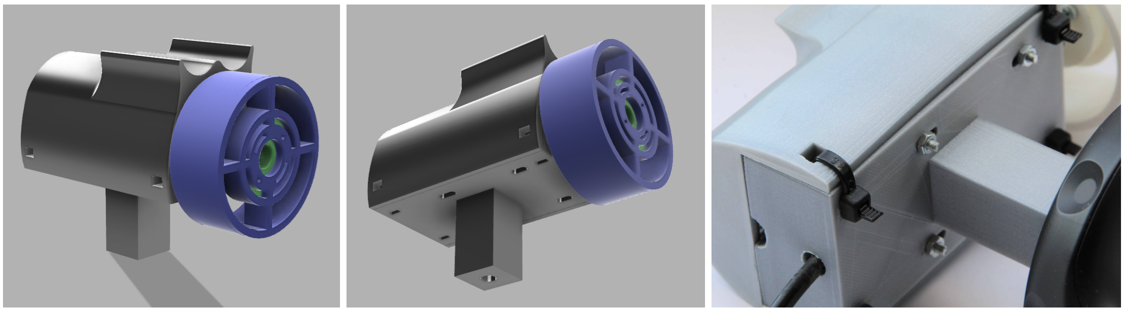

Figure 19 – Version 4 of the casing, different view-angles are used to show different sides of the design. The holes in the corners (left image) are made to attach the top to the bottom. The hole on the bottom of the beam (middle image) allows to attach the tracker using a screw, the holes under the bottom-piece (middle image) are used to attach the motor to the casing. The left image is the actual 3D printed version 4 case, note the tie-wraps which attach the top and bottom to each other. Also the screws can be found which attach the motor to the case. The black item in the right-bottom corner of the right image is the HTC VIVE tracker.

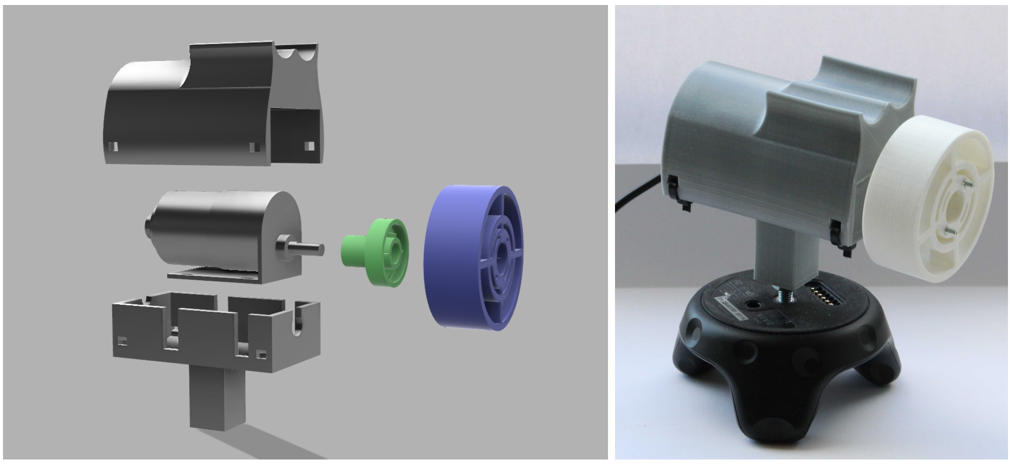

Figure 20 – Left is a 3D-rendered breakout of version 4 of the casing, right is the actual 3D-printed case of this version 4. Regarding the left image: Left top corner is the top of the casing, left bottom corner is the bottom of the casing, at the bottom of the beam the tracker can be attached. The motor can be found left in the middle. Right in the middle is the haptic wheel, the object in the center of the image is the attachment of the haptic wheel to the motor, this part is screwed to the axis of the motor. Regarding the right image: the top and bottom are attached using tie-wraps, the black object in the bottom is the HTC VIVE tracker.

5.1.2 Software

On the PC-side the programming language Python is used to read the measurements of the HTC VIVE tracker and convert it to the rotation-speed and direction of the motor. To read data of the HTC VIVE parts of code by Luke Beno are used, this can be found on the website of Road to VR [51]. Using the serial-port, this speed and direction are send to the Arduino Uno, which uses the programming language Arduino which is based on C/C++. All Arduino code used can be found in Appendix A, all Python code used can be found in Appendix B.

5.2 Motion tracking

The motion tracking is done using the HTC VIVE tracker. One base station of HTC, part of the HTC VIVE VR system, must be placed in front of the user. In order to render a sheet of fabric only the movement over the x-axis is used. The tracker returns the x-position based on the center axis of the base station. By calculating the difference between the current position and the previous position, the velocity can be calculated. This is done dividing the traveled distance by the time it took to travel that distance. This is calculated using the programming language Python. Measuring 50 values at a rate of 250Hz and taking the mean of the found values allow for a more accurate velocity, which can be interprented by the Arduino. Movement to the left is considered velocity in the positive direction, to the right is considered to be velocity in the negative direction. This is necessary in order to determine the direction of rotation of the motor.

5.3 Render of fabrics

Rendering fabrics is done using the haptic wheel. These haptic wheels hold a piece of fabric, and rotate with a certain speed in a certain direction.

Fabrics
Placing a piece of fabric on top of a haptic wheel allows the user to experience a fabric. This piece of fabric must be attached before the user uses the system.

Rotation
The Python script returns the magnitude of the velocity and the direction of the velocity. The velocity of the movement is from 0 up to values around 600. These values are send via the serial-port to an Arduino. Python returns positive values for movement to the left and negative values for movement to the right. Since the protocol used for the serial-communication does not support a minus-sign, the value 888 is used for positive numbers and 999 for negative numbers. These values are never reached as velocities, so it is safe to use them without confusing the program. When a 999 is received, the Arduino sends a signal to the H-bridge to close two switches, when a 888 is received, these switches open and the other two switches close. This results in rotation either clock-wise, or counter clock-wise.

Since the 12V DC motor needs a certain voltage to start rotating, this voltage is used for the lowest velocities the system senses. Sending a PWM signal of 50 let the motor rotate at its lowest speed. The mapping of the velocities to PWM-values can be found in table 4. These values are found be trail and error, using calculations improvements can be made, in order to make the system more accurate. The direction chosen is as following, when the user moves the controller to the left, the wheel rotates clockwise, and vice versa. This is done because, when one moves his hand to the left over a static surface, reasoning from his hand, the surface moves to the right.

Table 4 – Mapping of the velocity to the PWM signal

Velocity of user	PWM signal to control motor
$Velocity < 5$	PWM = 0
$Velocity \geq 5$ and $Velocity < 50$	PWM = 50
$Velocity \geq 50$ and $Velocity \leq 250$	Map velocities (50,250) to PWM (50,255)
$Velocity > 250$	PWM = 255

* PWM signals are values between 0 and 255, these values tell the H-bridge what portion of the 12V he must provide the 12V DC motor with.

5.4 Prototype

5.4.1 Set-up

In figure 21 the set-up of the system can be found. This image holds all of the components included in the system. The power supply, Arduino UNO and H-Bridge module are placed inside a lasercutted wooden box, in order to keep them protected. The 12V DC motor is located inside the controller, and is with two wires connected to the H-Bridge. Using a M6 screw, the HTC VIVE tracker is connected to the controller. At a distance of approximately 3 meter from the HTC VIVE tracker, a base-station is placed. This base-station projects an infrared field which is used by the tracker to provide the displacement of the controller. The Arduino UNO is connected to a laptop via USB. The HTC VIVE tracker and base-station are wireless connected to the laptop.

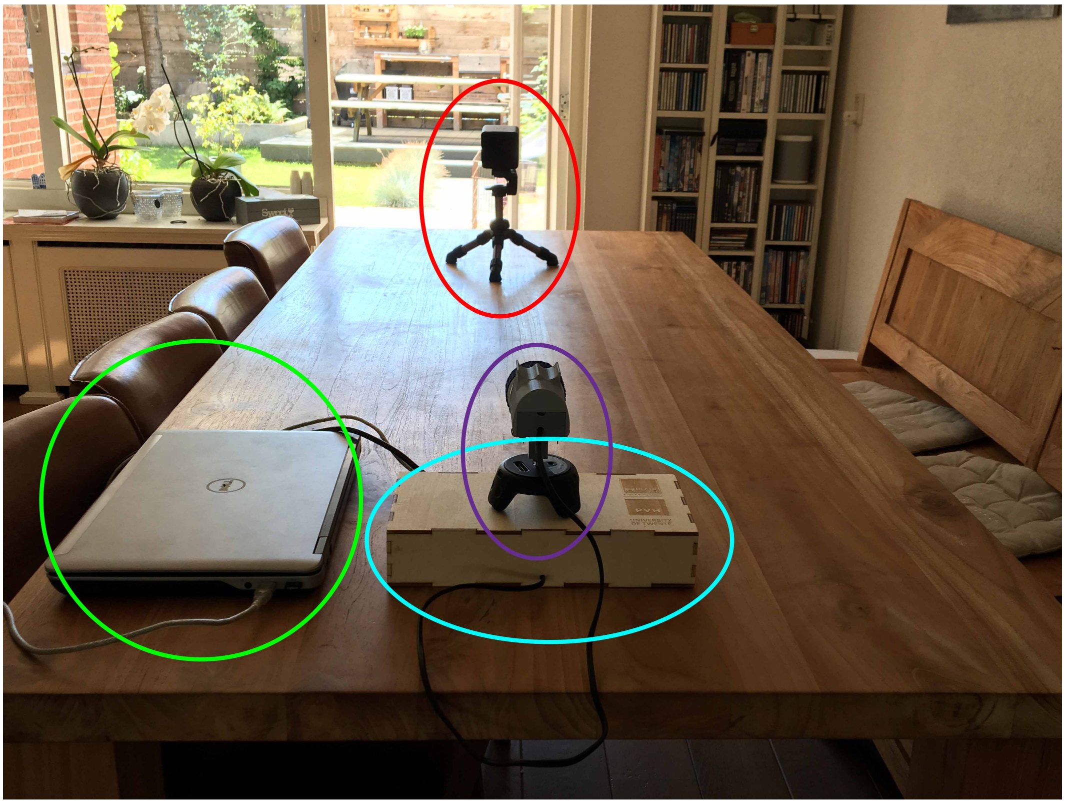

Figure 21 – Set-up of the prototype with the controller including a haptic wheel (inside purple circle), the box with electronics (inside blue circle), a laptop (inside green circle) and the HTC VIVE tracking system (inside red circle).

Electronics
The electronics are connected according to the schematic found in figure 22. This schematic holds the 12VDC motor, the 12V DC power supply, the H-Brdige module and an Arduino UNO.

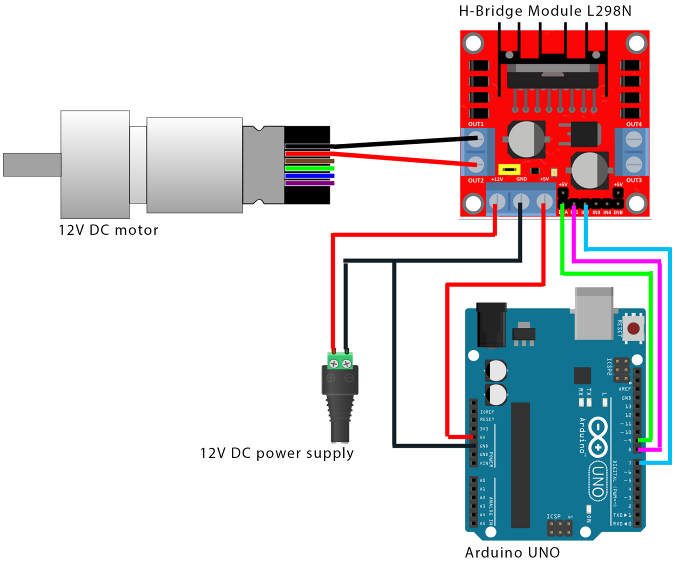

Figure 22 – Schematic of the prototype, with the 12V DC motor, 12V DC power supply, H-Bridge and an Arduino UNO.

Fabrics
The fabrics used for the prototype are listed below. These fabrics are chosen because of their characteristics, which differ a lot. Each fabric is listed and briefly some characteristics are stated. In figure 23 these fabrics placed on top of the haptic wheels are displayed. The fabrics are attached to the haptic wheels using glue. The characteristics of the fabrics are formulated by the developer, using the website of TextileSchool [52]. This website offers information on the topic of textile. The characteristics stated at each fabric should be taken as leading and not as being the unswerving truth.

- **Satin** - Smooth and soft, dry, glossy look, texture is too small to be noticed
- **Cotton** - Smooth and soft, dry, flat look and a distinguishable texture
- **Denim** - Rough, flat look, little rough, but small texture
- **Rib fabric** - Soft and bumpy, flat look and clear texture (big ribs), warm
- **Terry** - Soft in one direction, rough in the other direction, fluffy look, present texture
- **Leather** - Smooth, cool, glossy look, characteristic leather texture (with grooves)
- **Sackcloth** - Rough texture and a prickling surface, a bit fuzzy

Figure 23 – The seven haptic wheels, each with a different fabric attached on top. From left to right: Cotton, Satin, Denim, Rib fabric, Terry, Leather, Sackcloth.

5.4.2 Functionality

The data of the tracker is imported via the Python script (Appendix B), processed and outputted via the USB-cable to the Arduino UNO. The tracker sends the absolute position of the controller, based on the location of the controller with respect to the center of the base-stations. This location is compared to a previous location, divided by the time, which returns a speed (direction and velocity). The Arduino UNO processes the velocity and direction (script can be found in Appendix A), and sends signals to the H-Bridge module. Using digital signals the direction of the rotation is determined, using a PWM signal the amount of voltage provided to the motor is determined. This is done by sending these signals to the H-Bridge module, which regulates the power of the 12V DC power supply. This voltage is applied to the motor, which start to rotate. At the axis of the motor, the haptic wheel is attached with a fabric on top. The wheel rotates according to the movement of the user.

6 Evaluation

The evaluation phase is the fourth phase of the design method for Creative Technology. In this phase the hi-fi prototype is tested with potential users. This phase evaluates whether all the identified requirements in the ideation and specification phase are met [53].

First a functional test is conducted, this test treats all of the 'must-haves' of chapter 4, all of these requirements are met. After evaluating the functional requirements, the user test is stated. First an explanation of the tests is given, second the results are given and third, conclusions are drawn. After these user tests, the feedback of the client PVH is stated. Combining all the findings of the functional test, user test and the feedback of the client results in conclusions regarding the concept, and the hi-fi prototype. Using the conclusions, the system can be placed in the context of existing work.

6.1 Functional test

In order to evaluate whether or not the prototype meets all the functional requirements, a functional test is performed. The focus of the functional test is on the 'must-have' requirements of chapter 4, since these requirements decide whether or not the system succeeds. Each requirement is stated and treated separately.

6.1.1 Evaluation of the 'Must-haves'

The wheel must be able to spin at both low and high speed.

The motor is able to rotate at 80RPM when 12V is applied, less voltage means less speed. A brief calculation gives more insight in what this speed of the motor means. The highest speed is 80RPM, this means a PMW signal of 255 is send by the Arduino to the H-Bridge. The circumference of the haptic wheel with a diameter of 60mm is 188.4mm (found as following: $60mm*pi$). The total distance covered in one minute at 80RPM is 15072mm. This means a speed of 251.4mm/s, which seems to be sufficient when presenting fabrics for judgment.

The lowest possible speed found, is with a PWM signal of 50, this is a voltage of approx. 2.4V (found as following: $(12V/256)*51$). The speed meeting this voltage is 16RPM (found as following: $(80RPM/12V)*2.4V$). Using the circumference of the haptic wheel, 188.4mm, the total distance covered in one minute with a speed of 16RPM can be found, approx. 3014mm. This gives a speed of 50.2mm/s.

Both the highest and lowest speed of the haptic wheel seem to meet the requirement. The lowest speed could be lower in order to allow the user to experience the fabric at an even lower speed, but 50mm/s is sufficient. The highest speed is high enough, higher speeds are not useful when judging fabrics.

The wheel must be able to rotate at a speed matching the movement of the user.

Using the HTC VIVE tracker, the movement of the user is tracked. The mapping of the speed can be found in table 4 of the previous chapter. The speed is not linear, and especially at very slow movements of the user the rotation is equal for different speeds of the user's movement. However, when trying the device, the rotation not precisely matching the movement of the user is not experienced to be disturbing. The speed mapping leaves room for improvement, but is not the bottleneck and seems to work fine at the current mapping (as stated in table 4).

The wheel must be able to rotate in two direction and quickly switch from rotation direction.

Using a H-Bridge it is possible to let the motor rotate in two directions. Also, the motor can switch from direction when desired. This switching can be done almost instantly. A delay of less than a second is present, but this is not experienced as begin disturbing.

The system must have a speed limit to prevent the wheel from spinning too hard (which may cause burning wounds).

As stated before, the highest speed of the wheel is 80RPM, meaning approx. 25cm/s. Testing with the rough fabric sackcloth proves this does not cause burning wounds. This is tested by letting the wheel rotate at its highest speed, and touching the wheel with two fingers for 5minutes. Normal use would not let the motor rotate for this long at this high speed, so a speed limit is not required. Pressing very hard on the wheel could increase the chances of burning wounds, this is not recommended to do. Also the kind of fabric could influence whether or not the haptic wheel causes wounds, this should be examined.

The system must allow for a wide range of motion.

When standing 3m in front of the HTC base station, the system can track the movement of the user at least 2.5m to the left and 2.5m to the right. This implies a range of motion of at least 5m, this is big enough to freely experience the fabric. Normal use would most likely be in a range between 1.5m and 2.5m, since most users will just stand/sit on one place and move their arms, instead of start walking around.

The system must track the movement of the user with high precision.

The HTC VIVE tracker is able to track the movement of the user with an accuracy of 1mm, these movements are tracked and processed using Python. This results in a precision of at least 5mm, which is sufficient for a realistic experience.

The system must be designed in such a way, the user's fingers touch the wheel without effort.

As discussed in the chapter Realisation, the casing is designed in such a way that the fingers of the user lay on top of the haptic wheel without effort. In figure 16 of the realisation, chapter 5, it is shown how the height of the grooves is equal to the height of the wheel. The user doesn't need to press or bend his fingers in order to touch the wheel, so the haptic wheel can be touched without effort.

The device must, at least, allow for judgment by rotating in the x-direction.

One 12V DC motor is used, which can rotate over one axis. This means the system can rotate a haptic wheel in such a way, it allows for judgment of fabrics in the x-direction. Since the motor is able to rotate at both high and low speeds, with a piece of fabric on top, it allows for judgment of the fabric.

The tracker-system must be robust.

The HTC VIVE tracker is used, which is part of the HTC VIVE VR-set. This is a robust and stable system. When the base-station and the tracker are in each others field of view, the system will work. The tracker only stops working properly when the field of view is blocked, or when another HTC VIVE system is present in the room. Otherwise, when using in a closed room with no interference of another HTC VIVE or a block of the field of view, the tracker-system is stable and robust.

Wheel must rotate, even at little movements of the user (1cm/s for instance).

The mapping of the rotation speed, as stated in table 4, shows that at little movements (low velocity values) the motor gets a signal to rotate at its lowest speed possible. This means that even very little movements, the system still responds. This response is not linear, this does not seem to be a problem when testing the system.

6.2 User test

In order to get insight in how users experience the prototype, five user tests are performed. The user test are divided in the 'Haptic wheel test', and the 'Sheet of fabric test'. During the 'Haptic wheel test' test 1-4 are conducted, these tests include the haptic wheel. The 'Sheet of fabric test' consists out of test 5, and is conducted without the user of the haptic wheel, and using another group of participants than the group used during the 'Haptic wheel test'. The test 1-3 where performed whilst blocking the sight of the participant so the participant could not see the fabric being used on the wheel. During test 4 the participant was able to see his hand, the controller and the fabric on top of the wheel. During test 5 the sight of the participant is first blocked (to avoid the ability to see the fabric), but halfway he is again allowed to see everything. First the tests are explained, second the results are stated and third conclusions are drawn. The participants are both men and woman, for formulating reasons this chapter talks about 'he', but both 'he' and 'she' are applicable. Two groups of participants are asked to participate in the tests. For the 'Haptic wheel test' (test 1-4) group A is used, for the 'Sheet of fabric test' (test 5) group B is used. The test setup for test 1-5 was the same, with changes for test 4 and 5. In figure 24 the setup is displayed.

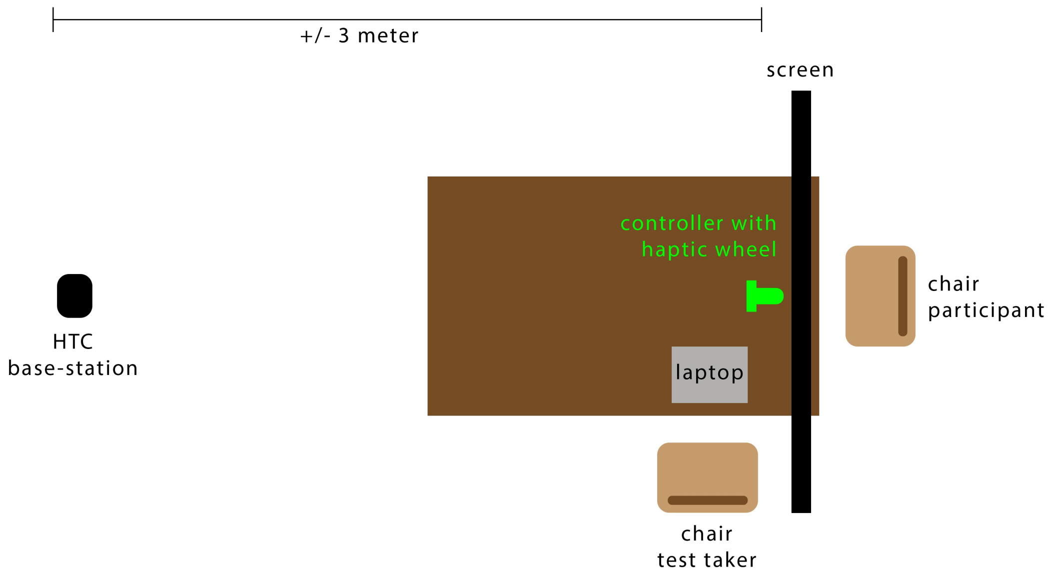

Figure 24 – Test setup for both the 'Haptic wheel' and the 'Sheet of fabric' test. During test 1-3, the setup includes a screen to block the sight of the participant. For test 4 the black screen was removed in order to allow the participant to see the controller and the fabrics. During test 5 the controller and HTC base station are removed, during the first half the screen is present, during the second half the screen is removed.

6.2.1 Haptic wheel test

The test setup for test 4 is equal to the setup of test 1-3, only the screen is removed in order to allow the participant to see everything he does. The participant is asked to sit on the chair watching in the direction of the base-station. In front of the participant is a table with the controller on top of it. The test taker sits on a chair next to the table and has the haptic wheels and pieces of fabric out of sight of the participant. The laptop is needed to both control the controller with the haptic wheel, and to register the answers given by the participants.
Before the tests are explained to the participant, he must sign a consent, describe how much experience he has with fabrics and a short introduction to the project is given by the test taker. The introduction is as following: *"The system looks as following - hand over the controller -. The system is a handheld device with two grooves. In this grooves you can lay your fingers. Underneath your fingertips a wheel will be attach to the controller. On top of this wheel is a fabric attached. When you start moving your hand (in which you hold the controller), the wheel will start to spin. This movements must be over the x-axis, so from left to right and vice versa."*

After this introduction a brief introduction to the tests is given. Before a test is performed, again an explanation of the test is given. This is done to ensure the participant understands what is expected of him, and knows clearly what he must do. All of the tests consist of different combinations of fabrics, these are pre-formulated in an excel-sheet. This is pre-formulated to avoid adaption to the knowledge of the participant, so to avoid biased results. All of the fabrics are given a number, and using a random number generator the numbers (fabrics) and the order of the numbers (fabrics) is chosen. All of the results are listed by the test taker in a pre-formed excel-sheet. During the tests the test taker writes down observations. These observations were shared and discussed with the participant after all the tests were finished.

Test 1
Blindfolded testing. Test if the participant is able to link the presented sheets of fabric to the correct wheel.

The participant sits on his chair with the screen in front of him. He sticks is hand through the screen and 3 pieces of fabric are presented. First satin, second cotton (95%) and at last denim. The participant is free to feel the fabric with both one or two hand, and can take as much time as he needs. After presenting the sheets of fabric, the test taker places a haptic wheel on the controller (which wheel is pre-formulated in the excel-sheet), and guides the hand of the participant to the controller. The participant can experience the fabric freely moving his hand over the x-axis. After a few seconds the test taker asks the participant if the wheel is either fabric 1, 2, 3 or another fabric. The answer is notated and the next wheel is added to the controller. The participant is allowed to feel the fabrics again between different wheels, but when a wheel is touched he must first answer which fabric he think it is, before feeling the pieces of fabric again. This test is performed three times. That means: the participant gets three haptic wheels presented. This wheels could include the same fabric, or be different fabrics.

Test 2
Blindfolded testing. Objective test, the participant must fill in the form for each fabric he feels.

The participant sits on his chair with the screen in front of him. He sticks is hand through the screen and a haptic wheel is placed on the controller. The participant picks up the controller and can experience the fabric. A list is given (Appendix C) with objective factors, based on the work of Guest et al. [54]. This factors including their characters can also be found in table 5. The participant is asked to mark the characteristics of the factors he thinks apply to the presented fabric on the haptic wheel. The order of the haptic wheels is pre-formulated in the excel-sheet. This test is performed three times. That means: the participant gets three haptic wheels presented. This wheels could include the same fabric, or be different fabrics.

Test 3
Blindfolded testing. Subjective test, the participant must name the fabric he feels.

The participant sits on his chair with the screen in front of him. He sticks is hand through the screen and a haptic wheel is placed on the controller. The participant picks up the controller and can experience the fabric. The participant is asked to say which fabric he thinks is presented. This is completely open, no suggestions are given. The participant must name the fabric based on prior knowledge. The order of the haptic wheels is pre-formulated in the excel-sheet. This test is performed three times. Again, this are three haptic wheels, with either the same of different fabrics.

Test 4
Allow the participant to see the fabrics whilst testing. Objective and subjective test, the participant must fill in form and name the fabric he feels.

The participant sits on his chair without the screen in front of him. A haptic wheel is placed on the controller. The participant picks up the controller and can experience the fabric. The participant is asked to fill in the form with factors (Appendix C), and asked to say which fabric he thinks is presented. Again, the order of the haptic wheels is pre-formulated in the excel-sheet. This test is performed three times. Also, three haptic wheels, which can either hold the same fabric, or a different fabric.

End
After the four tests are conducted, the participant is asked to fill in three questions (stated below). After answering the questions the test taker asks the participant to explain these answers to him. Also, the observations of the test taker are fed back to the participant and discussed. The questions are:

- *How was the experience in general?*
- *Did the ability to see add value to the experience?*
- *What do you think are points for improvements?*

6.2.2 Sheet of fabric test

Test 5
After conducting the first tests (test 1-4) it seemed necessary to conduct another test. During test 2 and 4 the participants are asked to fill in a form with percept factors for the fabrics they feel on top of the haptic wheel. The participants are presented three wheels while they are blindfolded, and three wheels while they are able to see everything. In order to make the results of this test relevant, another test must be performed without the wheels, this is test 5.

The aim of test 5 is to find data which can be compared to the found results during test 2 and 4. Instead of presenting fabrics on top of the haptic wheel, this test presents fabrics by handing over a sheet of fabric. During the begin of the test the sight of the participants is again blocked using a screen, the setup is the same as in test 1-4, so according to figure 24. The test taker hands over a piece of fabric, lists which fabric he gives, and asks the participant to fill in the form (which can be found in Appendix C). Also, the participant is asked to name the fabric, this is listed by the test taker. In total this blindfolded presenting is done three times. The test taker removes the screen and again hands over a piece of fabric, list the fabric, and the participant fills in the form. Again, the test taker asked the participant to name the fabric. This is also repeated three times. In total the participant has been presented six fabrics, three blind, three while being able to see.

6.2.3 Results

The results of both the tests can be found in Appendix E.

Group A, test 1-4
This group of participants consists of eight participants, four men and four woman, all in the age of 20-24. The participants were asked to give a number to their knowledge of fabric on a scale of 1 to 5, with 1 being no knowledge about fabrics, and 5 being a lot of knowledge. Three participants ranked their knowledge of fabrics with a 2, four participants ranked their knowledge with a 3, and one participant with a 5.

Group B, test 5
This group of participants also consists out of eight participants, again four men and four woman, and in the age of 20-24. In this group two participants ranked their knowledge of fabrics with a 2, five participants ranked their knowledge with a 3, and one participant with a 4.

Quantitative results test 1-4, group A
In test 1, 3 and 4 the participants of group A where asked to give either the name of the fabric, or to say whether or not the haptic wheel holds the fabric presented as pieces before. The outcomes of these tests are used to come up with these quantitative results.

Stating the fabric
There are two participants who had eight of the nine fabrics correct. These participants filled in a 3 and 5 on the scale of fabric-knowledge. Also the person who had seven correct filled in a 3 on the scale. So the highest scores of correct fabrics where from people with a fairly high number on the scale of knowledge about fabrics. Vice-versa this observation does not hold. Also the lowest score, four, was achieved by a person who filled in a 3 on the scale.

Test 1 used three pieces of fabrics which have somewhat similar characteristics: Satin, Cotton, and Denim. All of them feel smooth, dry, and have an average temperature (use of describing factors stated by Guest et al. [54]). Most participants made errors during this test. The participant with a 5 on the scale of knowledge had all three of them correct.

Also, when combining the results of all the tests, it can be seen that it is harder to distinguish fabrics which have a lot in common with other fabrics, compared to fabrics which differ a lot. The fabrics Satin, Cotton and Denim have a lot in common, and respectively 43%, 64% and 62% of the times this fabric was presented, the participants had it correct. Compared to the more distinguishable fabrics Terry, leather and Sackcloth, which were respectively 100%, 86% and 89% of the times correct. Rib fabric also has the characteristics to be quite distinguishable, however just 50% of the times it was presented it was correct. Participants said they recognized the fabric, but did not know the name, this could explain this low score. The results of the total of the tests 1, 3 and 4 can be found in figure 25. The blue bar represents the times the fabric was presented, the green bar represents the times the participants had this correct.

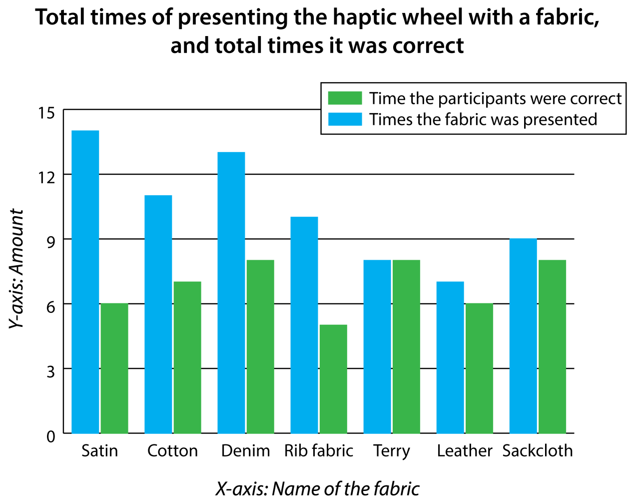

Figure 25 – The results of the total of the tests 1, 3 and 4. The blue bar represents the times the fabric was presented, the green bar represents the times the participants had this correct.

During test 1 all the participants were blindfolded presented three haptic wheels, this means a total of 24 wheels is presented. In total 13 times participants choose the correct fabric, this results in 54% of the fabrics which were guessed correct. The participants where given four options: one of the three fabrics, or a different fabric. This means the participant had a change of 25% to guess correctly the presented fabric.

During test 4 all the participants were presented three haptic wheels, this means a total of 24 wheels is presented as well. However, this time the participants were not blindfolded. In total 19 times participants choose the correct fabric, this means 79% of the fabrics were guessed correct. The participants where asked to name the fabric on the haptic wheel, without giving them any names or other ways to refer to a fabric. This means there was not a gambling factor, which was present during test 1.

Since test 1 involves a gambling factor, also a graph with results of test 3 and 4 is made, which can be used to compare results with test 5. The results of test 3 and 4 are stated in figure 26.

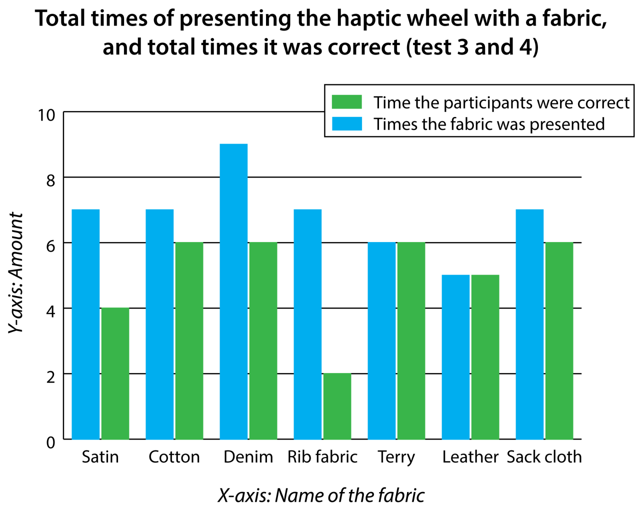

Figure 26 – The results of the total of the tests 3 and 4. The blue bar represents the times the fabric was presented, the green bar represents the times the participants had this correct.

Characteristics
During test 2 and test 4, the participants were asked to fill in a form with three factors, based on the describing factors stated by Guest et al. [54]. This form can be found in Appendix C, the factors and their characteristics can also be found in table 5. The participants were asked to check the characteristics of the three factors which applied to the presented fabric. The fabric of the haptic wheel was listed by the test taker. The three factors are roughness, pile and temperature. This tests aims to find which characteristics of a factor seem to be applicable for the presented fabrics, when using a haptic wheel. The characteristics Cold, Hot and Burning drop out immediately since they were never chosen.

Table 5 – Characteristics of three percept factors. *

Factor 1: Roughness	**Factor 2: Pile**	**Factor 3: Temperature**
Rough	Fuzzy	Cold
Smooth	Fluffy	Chilly
Bumpy	Dry	Cool
Prickly	Damp	Average
Soft		Warm
Gritty		Hot
Jagged		Burning

* Table is based on the describing factors stated by Guest et al. [54].

The characteristics which apply to a certain fabric, and which are found during the user tests are presented in table 6. These characteristics are determined as following. During the tests 2 and 4, all the participants got six haptic wheels presented in total. For each of these wheels they had to fill in the characteristics applicable to the fabric on top of the wheel. The found results are noted in an Excel-sheet. For each fabric, the amount of times a characteristic was mentioned is counted.

Sum of every time [characteristic] is chosen for [fabric]

This results in a table with the fabrics against the characteristics. So for each fabric, the times a characteristic occurs. For each characteristic the average of times this specific characteristic occurs is calculated.

(Sum of every time [characteristic] occurs) / (times this [characteristic] occurs)

Also the averages of the number of all characteristics counted for one specific fabric are calculated.

(Sum all occurrences of characteristics for [fabric]) / (number of characteristics which occur for [fabric]

The average of these two averages is taken as guiding per fabric, per characteristic. This value can be considered to be the threshold. When a characteristic of a fabric occurs more often than the found average times of occurrence for that specific characteristic for that fabric, it is marked as being typical for that fabric.

For example: The characteristic 'Rough' occurs two times for the fabric Satin. In total, Rough occurs 20 times. 20 times, divided by seven (for every fabric this characteristic has occurrence > 0) gives an average of 2.9. The sum of all the times characteristics occur for Satin is 21. Dividing 21 times, by seven (in total seven different characteristics are filled in for Satin) gives an average of 3.0. The average of this two averages (2.9 and 3.0) gives an average, a threshold, of 2.95. The characteristics 'Rough' occurred two times for the fabric Satin, this value is lower than the threshold of 2.95 and so 'Rough' is not considered to be typical for Satin.

Table 6 – Found characteristics of three factors, describing the used fabrics when presented to participants using the haptic wheel. *

Fabric	**(1) Roughness**	**(2) Pile**	**(3) Temperature**
Satin	Smooth	Dry	Average
Cotton	Smooth, Soft	Dry	
Denim	Rough	Dry	Average
Rib fabric	Bumpy, Soft	Fluffy	Warm
Terry	Rough, Soft	Fuzzy, Fluffy	Average, Warm
Leather	Smooth, Bumpy	Dry	Cool
Sackcloth	Rough, Prickly	Fuzzy, Dry	Average

* Table is composed using data found during user tests with 8 participants, test 1-4. The number between brackets stands for the number of the factor.

Quantitative results test 5, group B
In test 5 the participants of group B where asked to name the fabric, and to fill in a form about the presented fabric. The outcomes of these tests are used to come up with these quantitative results.

Stating the fabric
Out of the eight participants, one participant had all six fabrics correct, this is the person who said to have a knowledge of 4 about fabrics (on a scale from 1-5). Amount of times participants who filled in a 3 on the scale of knowledge guessed correctly out of six: three, four, four, five, and five. In average, people with a 3 scored a four. The participants with a 2 on the scale of knowledge guessed zero and four times correct, out of six.

The results of test 5 can be found in figure 27, located at the next page. Again the blue bar represents the times the fabric was presented, and the green bar represents how often this was guessed correctly. Out of group B most of the participants could describe the use of rib fabric and terry, but they were not able to recall the names of the fabrics, this could be an explanation for the low number of correct guesses. Fabrics which are fairly similar, satin, cotton, and denim, were mixed up quite often. Most of the times the participant guessed it incorrect in case of one of these fabrics, they called one of the other two remaining fabrics.

This test did not involve a gambling factor since no options were given, the participants had to call the name of the fabric themselves and were not presented with options. Results can be found in Appendix E.

During the first part of test 5 all the participants were blindfolded when three sheets of fabric were presented, this means a total of 24 sheets fabric are presented. During this part of the test, 58% of the participants had guessed the correct fabric.

During the second part of test 5 all the participants were again presented three sheets of fabric, again a total of 24 sheets of fabric were presented. However, this time the participants were not blindfolded. This resulted in 71% of the times a correct guess.

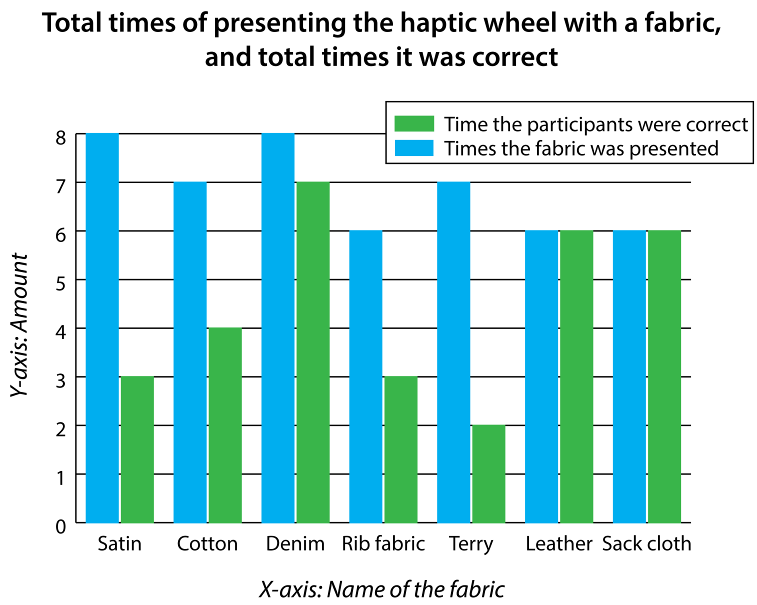

Figure 27 – The results of test 5. The blue bar represents the times the fabric was presented, the green bar represents the times the participants had this correct.

Characteristics

During test 5, the participants of group B were asked to fill in a form with three factors, based on the describing factors stated by Guest et al. [54]. This form can be found in Appendix C, the factors and their characteristics can also be found in table 5, these are the same as used for test 2 and 4. The participants were asked to check the characteristics of the three factors which applied to the presented fabric. The presented sheet of fabric was listed by the test taker.

The characteristics which apply to a certain fabric according to test 5 are stated in table 7. These characteristics are determined the same way as for test 2 and 4. The same calculations are used and the way of checking against averages is performed. The characteristics Jagged, Hot and Burning drop out immediately since they were never chosen.

Table 7 – Found characteristics of three factors during test 5, describing the presented sheets of fabric. *

Fabric	**(1) Roughness**	**(2) Pile**	**(3) Temperature**
Satin	Smooth	Dry	Cool, Average
Cotton	Smooth, Soft	Dry	Cool, Average
Denim	Rough	Dry	Average
Rib fabric	Bumpy, Soft		Warm
Terry	Soft, Gritty	Fluffy	Warm
Leather	Smooth	Damp	Cool
Sackcloth	Rough, Prickly	Fuzzy	

* Table is composed using data found during user tests with eight participants, test 5. The number between brackets stands for the number of the factor.

Quantitative results combined

During test 3, 4, and 5 the participants were asked to state which fabric they thought they were presented. The results of these tests can be found in figure 28. In this graph the orange bars represent the percentage of times the participant guessed the correct fabric, the purple represents this percentage for test 5. In total 96 fabrics are shown, 48 during test 3 and 4 combined, 48 during test 5. Test 3 was blindfolded (24 fabrics) and during test 4 the participants were able to see the fabrics (also 24 fabrics). The half of test 5 was blindfolded (24 fabrics), during the other half the participants were able to see (also 24 fabrics).

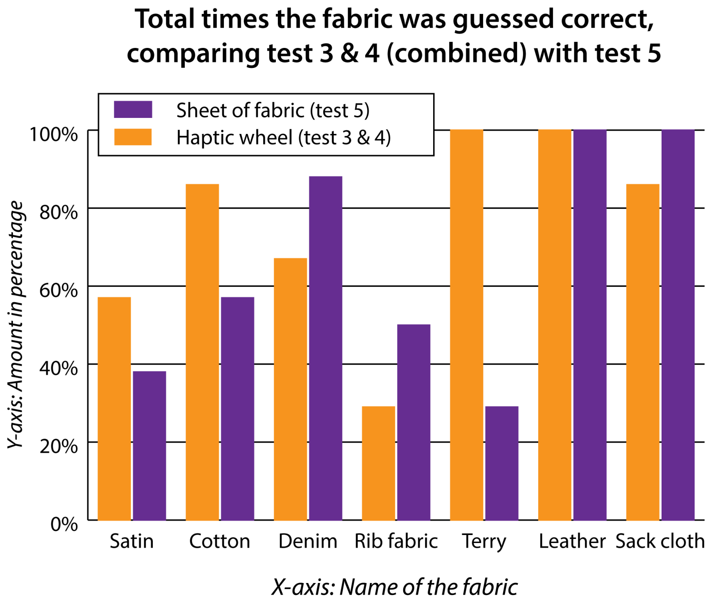

Figure 28 – The results of test 3 & 4, compared with the results of test 5. Percentages of how often the participants guessed the correct fabric are compared. 'Percentage' means the percentage of times it was correct with respect to how often the fabric was presented.

During test 2, 4 and 5, the participants are asked to check characteristics on a list (appendix C). Test 2 and the first half of test 5 were blindfolded, during test 4 and the second half of test 5 the participants were allowed to see the fabrics. Table 8 combines the found characteristics as presented in table 6 and table 7. The blue characteristics are the characteristics which occurred in both tables. Also, a lot of the blue characteristics match the characteristics formulated by the developer using TextileSchool [52] at chapter 5.

Table 8 – Found characteristics of 3 factors during test 2, 4 and, 5, describing the presented fabric (either on top of the haptic wheel or as a sheet of fabric). *

Fabric	**(1) Roughness**	**(2) Pile**	**(3) Temperature**
Satin	Smooth	Dry	Average, Cool
Cotton	Smooth, Soft	Dry	Average
Denim	Rough	Dry	Average
Rib fabric	Bumpy, Soft	Fluffy	Warm
Terry	Soft, Rough, Gritty	Fluffy, Fuzzy	Warm, Average
Leather	Smooth, Bumpy	Damp, Dry	Cool
Sackcloth	Rough, Prickly	Fuzzy, Dry	Average

* Table is composed using data found during test 2, 4, and 5. The blue characteristics are found during both test 2, 4, and test 5. This means that these characteristics are found both using the haptic wheel and using a sheet of fabric.

Qualitative results

During test 1-4 the participants were observed by the test taker. Also, remarks are asked to the participants, group A. The most relevant findings, and most often occurring feedback is stated in this part. A complete list with remarks and feedback is included in appendix D.

Most participants found the experience in general good and nice. The participants were all able to at least distinguish between different fabrics, and sometimes even to state the correct fabric. Most of the participants first had to get familiar with the system and the way of interacting before they could properly focus on the fabric at hand. Learning how to interact was obviously also obstructed by the disability to see what they were doing with their hands, and what they hold in their hands. After removing the screen, the participants started to move more freely and took a closer look to the controller and how it works. Almost unanimous the answer to the question 'if the ability to see added value to the experience' was yes. This is supported by the quantitative results, where a higher percentage of the guesses was correct when the participants were able to see.

According to the participants the system provides a fine experience in general, yet, leaves room for improvement. First of all it returned multiple times that the subsurface of the fabric was experienced as disturbing. The hard plastic of the haptic wheel, in combination with the tensioned, glued fabric, influences the experience of the fabric. Also, features like elasticity, and the ability to feel both sides of the fabric are lacking due to the wheel. Improvements can be made in the rotation of the wheel. Mainly the speed of rotation and the smoothness of rotating, but also the addition of an y-axis is preferable. Lastly, the wheel does not allow to feel the fabric between ones fingers, which is often a big indicator for the folding and elasticity of the fabric, this is lacking too according to participants.

6.2.4 Conclusions

Quantitative conclusions

Stating the fabric, test 1-4, group A

The participants who had most of the fabrics correct where people who filled in a high number on the scale of knowledge of fabrics. However, someone who filled in a 3 on the scale had the lowest score reached, four correct answers. It is debatable if people with a somewhat average knowledge about fabrics can use this controller to judge fabrics, since they can't even distinguish properly between fabrics. Most likely, people who already do have a lot of knowledge about fabrics, people who will fill in a 5 on the scale, can distinguish fabrics using this controller. This should be tested to a greater extend.

Distinguish between fabrics which feel similar to some extend, seems to be hard using the haptic wheel. This can be deduced by both the results of test 1 alone, but also by the results of test 1, 3 and 4 combined. At test 1, the participants who filled in a 2 or 3 at the scale of knowledge made a lot of errors, while the participant with a 5 on the scale had all of the fabrics correct. It can be said that distinguishing between similar fabrics is hard using the controller, yet possible for experts. The users of this concept are retailers and designers, people who have a lot of knowledge about fabrics, they can be called experts.

On a larger scale, it can be said that it is possible to distinguish between fabrics which differ a lot from each other. This applies for both the people who have little and big knowledge of fabrics (based on the scale used).

Seeing the fabrics adds a lot of value to the experience. When the participants tried to state the correct fabric while they were blindfolded, just 67% of the present fabrics were guessed correct. When the participants were allowed to look at the fabrics, they stated the correct fabric in 79% of the cases. Next to that, test 1 included a gambling factor, which was not present at test 4.

Stating the fabric, test 5, group B

Participants with a 3 or 4 or the scale of knowledge of fabrics had, with one exception, more than half of the presented fabrics correct. The fabrics Satin, and Terry were not guessed in over 50% of the cases. Rib fabric exactly 50%, and Cotton just above. Participants said to recognize Rib fabric and Terry, but were not able to recall the name of these fabrics, this can declare the low number of correct guesses. As stated before, Satin and Cotton are somewhat similar to each other, most participants who made errors with these two fabric indeed confused them with each other.

For experiencing the fabrics with or without the ability to see, the same applies as in the case of the haptic wheel: the ability to see the fabrics, adds value to the experience. When the participants were blindfolded 58% of the presented fabrics were guessed correct, compared to the 71% when the participants were able to see.

Stating the fabric, compare test 1-4 with test 5, group A and B
In figure 28 the two tests are compared with each other: testing with haptic wheel, and testing with a sheet of fabric. According to this figure it can't be said that experiencing the fabric using the haptic wheel is equal to experiencing the fabric in the form of a sheet of fabric. Leather and Sackcloth are guessed (almost) an equal amount of times correctly, but the other fabrics differ at least around 20%. However, when looking at the totals, this differences are put into more perspective. When the participants were blindfolded during test 3 (haptic wheels), they guessed 67% of the fabrics correct, during the blindfolded testing in test 5 (sheets of fabric), 54% of the times they guessed correct. When being able to see, 79% of the participants were able to guess the correct fabric during test 4 (haptic wheels). During test 5 (sheets of fabric), 71% of the participants guessed the correct fabric. So while being blindfolded the differences between the haptic wheel and the sheet of fabric is 15%, when not blindfolded this difference is just 8%. This is not a significant difference. In addition, the number of participants is fairly small, and a limited amount of tests is performed. This makes the results debatable, and one could argue if these results are useful. Based on the found results it can't be said whether or not the haptic wheel is better compared to judging using the actual fabric, since the differences are not significant and the amount of participants is too little. However, it can be said that the haptic wheel does allow for a proper experience since over 65% of the times, the participants were able to guess the fabric when using the haptic wheel. In order to make a relevant comparison between the haptic wheel and a sheet of fabric, more tests must be performed with a larger group of participants. In both cases (using the haptic wheel, and using a sheet of fabric) the ability to see the fabric adds value.

Characteristics, compare test 2 & 4 with test 5, group A and B
Most relevant with respect to the characteristics, is the table of combined results, table 8. This table combines the results of test 2, 4, and 5. The results of test 2 and 4 are combined since these are both performed using the haptic wheel, one half of the fabrics blindfolded and one half of the fabrics when being able to see. The same amount of fabrics are presented during test 5, now in the form of a sheet of fabric, again one half blindfolded and one half able to see. The found characteristics know many overlap. These test are called 'objective' earlier this chapter, since the participants have a list from which they can check what they feel. No prior knowledge, about names of the fabric for instance, is required.

In total seven different fabrics are presented to the participants. For four fabrics, each factor has an overlapping characteristic (a characteristic which is selected as being typical during both test 2, 4 and test 5). The other three fabrics have two factors which hold an overlapping characteristic. For the fabrics Cotton, Rib fabric and Sackcloth, even two characteristics overlap for factor 1: Roughness.

It can be said that using the haptic wheel there are not very big differences in perceptual describing a fabric, in comparison to using a sheet of fabric. This means that the haptic wheel allows for an objective describing of a fabric, and so, might allow for judgment of fabrics to some extend.

Qualitative conclusions
Most participants liked the controller including the haptic wheel, but improvements have to be made in order to make it possible to properly judge fabrics according to the qualitative results. Focus of this improvements has to be: the ability to experience the fabric in a way which meets the traditional way of experiencing the fabric. Participants found it disturbing how tight the fabric was attached around the haptic wheel, the fact that the wheel is of hard plastic and so offers a solid and static subsurface, the lack of movement in y-direction, and the absence of a way to experience the elasticity of the fabric. The participants liked the concept, but were not completely satisfied yet.

6.3 Feedback client

After building the prototype, the company of PVH in Amsterdam was visited, during this meeting eight employees of PVH were present. The goal of this meeting was to explain the findings on haptic feedback technology, present the prototype, and gain feedback on that prototype. Due to the limited time of the employees of PVH, the client, there was not enough time to conduct user tests. Since the findings of the literature research are discussed in more detail in chapter 2, no further notion is taken in this chapter. The client was sorry to hear that haptic feedback technology does not allow to render precise enough to be useful to judge fabrics. They would like it a lot to make the whole process digital in order to save time and money, so the need of using fabric is not preferred.

However, in general the client was very exited about the prototype and liked the concept. One by one, everybody present during the meeting, tried the controller with different wheels attached to it. The way they interacted with the system was as envisioned, they even said it was intuitive to interact correctly with the controller. The big remark was that the way of experiencing the fabric is completely different compared to actually feel a sheet of fabric. The system does not allow to feel the fabric between two fingers, to feel the bottom of the fabric, and the y-direction was missed. Also, feeling the weight of the fabric was desired, in order to be able to judge the fabric, next to seeing how the fabric folds and behaves when moving around with it. In general the experience was good, but there is still a lot of room for improvements.

After explaining in more detail how I, the developer, envisioned the use of the system, they started to think of other implementations. For instance to tension fabric between two wheels, in order to allow feeling the bottom of the fabric. Also ways of attaching the fabric to the wheel were discussed, for instance making more like a sleeve to put around the wheel in order to make the fabric feel more natural, instead of being tightly glued around the haptic wheel. Using the controller as an input device could allow designers to sculpt in a more tangible and natural way. Placing the fabric on top of the wheel would allow to even feel the fabric of the garment which is sculpted. In general, the client was satisfied an exited about the system, implementation however, is not of added value.

6.4 Conclusion

This chapter describes an evaluation of the build haptic wheel interface, a prototype. First a functional test is conducted, second an user test and lastly the client is visited in order to gain feedback. This section tends to draw conclusions based on the found results.

A functional test is conducted. During this test all the 'must-haves' of the specification are treated in order to gain inside to what extend the formulated functional requirements are met. All of the stated 'must-have' requirements are met, and so the specification is satisfied. The prototype fits the specification, room for improvement in present, but no lacks are found.

User tests are performed. This is done on two groups of eight people. The quantitative results of these tests show that the haptic wheel allows to distinguish fabrics to a certain extend, mainly the 'head categories' can be distinguished. Going into more detailed and complex fabrics should be examined to a greater extend, in order to conclude more on that topic. It can also be concluded that the haptic wheel allows people with prior knowledge about fabrics to experience fabrics in a new way, and offers the ability to distinguish between these fabrics. It does not allows people who already don't have prior knowledge, to experience fabrics in such a way they know more about these fabrics. So this device does not enhances ones knowledge. The ability to actually see the fabric is of added value when experiencing fabrics, this is the case for both the haptic wheel and an actual sheet of fabric.

Participants were not significant better in guessing the fabric when presented a sheet of fabric instead of the fabric on top of the wheel. The participants guessed even more fabrics correct when using the haptic wheel, compared to experiencing a sheet of fabric. This however, can not be treated as a solid statement, since the tests are not sufficient for such conclusions. More comments on the test later this section.

Using the haptic wheel and the sheet of fabric give a lot of overlapping characteristics. These characteristics play a role in judging the fabrics. So, if a lot of the characteristics stated by experiencing the sheet of fabric overlap with the characteristics found when using the haptic wheel, this might indicate the usability of the haptic wheel. To what extend these characteristics overlap via the different ways of experiencing the fabrics should be examined into more detail, but the first tests seem promising.

According to the performed user tests the haptic wheel seems to be useful to a certain extend. The ability to distinguish fabrics is present, and also the characteristics assigned to presented fabrics are similar to characteristics found using a sheet of fabric. To what extend the haptic wheel is useful should be examined into more detail.

The user test is useful to support thoughts, and also gave new insights. However, the results of the tests are not useful to found solid conclusions due to the shape and size of the tests. The number of participants is too small, and the number of tests is limited. Including equal gambling factors could also be of added value. In the current layout of the tests a lot of the results are biased by the knowledge of the participants. If they were not able to instantly think of the correct name, they instantly gave the incorrect answer. Presenting the participants possible fabrics could enhance their memory, and increase the number of correct answers. This would also meet the reality in another way, since the end-users do know the names of the fabrics, and use their associations with this fabric when judging. The user tests gave insights and support, but should not be considered as leading and solid support for conclusions. They give however, indications of abilities and using the feedback improvements can be made.

The general feedback of the client was very positive. They like the idea a lot, and were pleased to see the prototype. They had some doubts about the experience of the fabric since it did not meet the reality to the desired extend. They also aim to digitize the presentation of fabrics, so use no fabric at all, rather then reduce the amount of fabric needed. For this reason they liked the idea, but were not completely thrilled. It stimulates their ideas and creativity on the topic of haptic feedback with respect to the clothing industry, but the abilities of the controller do not meet the desired abilities. In general the client was satisfied and exited, actual implementations however is not intended.

The evaluation of the prototype learns that the functional requirements are met, and that the controller is able to present fabrics using the haptic wheel. People are able to distinguish fabrics using the system and the experienced perceptions meet the perceptions when experiencing a sheet of fabric. The design leaves room for improvement but offers sufficient basic functionalities. The client is satisfied to a certain extend, steps are taken in the process of presenting clothes in new ways to allow for judgment. The evaluation is positive, feedback can be used to improve the concept.

7 Conclusions and recommendations

7.1 Conclusions

This bachelor thesis describes the development of a controller with a haptic wheel attached to it. This system renders different fabrics in order to allow the user to judge the fabrics. This is done by placing a small piece of fabric on a haptic wheel, which starts to rotate when the user touches the fabric and moves his hand. This way, the user is able to experience a sheet of fabric, while only using a small piece of fabric. The controller is build and evaluated via a functional test, a user test, and a meeting with the client, PVH.

The research questions for this thesis were as following: '*How to develop a haptic wheel interface which allow both designers and retailers of a clothing company to judge fabrics?*' and '*To what extend does this haptic wheel interface allows for judgment of the fabrics?*'

The topic of this thesis is presented by Hecla Professional. PVH is a clothing company, and a client of Hecla Professional. PVH came with a desire of presenting clothes in a new way, this can be done digitally. The system is an addition to the recently developed digital showroom by Tommy Hilfiger (part of PVH) in which clothes can be presented.

After conducting an extensive context analysis, using a literature review and a state-of-the-art review, it was concluded that no technology currently exists which enables the rendering of fabrics in a satisfactory way. Different kinds of haptic feedback technology were researched: Force feedback, vibrotactile feedback, electrotactile feedback, ultrasound feedback, and thermal feedback. Different haptic feedback devices were examined too, the Haptic Revolver by Microsoft stood out. This device enables the user to explore a virtual world by providing tactile sensations. The principle of a rotating wheel of this device is leading in the thesis.

The Haptic Revolver by Microsoft is not available to test, in order to test with a system using a wheel, a variation on the Haptic Revolver is build by the researcher. The controller with a haptic wheel allows to render large sheets of fabric, with the use of a small piece of fabric. This system does not allow to render fabrics without the need of fabric, yet reduces the amount of required fabrics substantially.

The controller is build using an Arduino UNO, and a HTC VIVE tracker with base-stations. The casing is designed by the researcher and manufactured using a 3D-printer. Also the haptic wheels are custom designed and printed. The fabrics on top of the haptic wheels are selected based on their characteristics, which are diverse. After a few iterations a hi-fi prototype was developed.

The hi-fi prototype is evaluated via a functional test, a user test, and a meeting with the client, PVH. The following conclusions can be drawn based on the evaluation. In general the system works good, and people find it easy to interact with. The system meets all the defined functional requirements. The system is able to render the fabric and convey this to the user. The system allows a proper experience since people are able to guess the fabric on top of the rotating haptic wheel (both blindfolded, and while being able to see). Also, the characteristics people assign to fabrics when feeling a sheet of fabric comply with the characteristics people assign to the fabrics when experiencing it via the haptic wheel. However, to be able to actually judge the fabrics, this might not be sufficient. Participants of the test liked the experience of the controller, but missed some features of the fabrics. Mainly people missed the ability to feel the fabric between two finger, feel both sides of the fabric, the ability to feel the fabric in the y-axis too, and the interface does not allow to feel the elasticity of the fabric. To what extend these factors are necessary to judge fabrics should be investigated.

The client, PVH, was satisfied with the developed prototype. The client felt sorry for the fact that completely digitalizing the fabrics is not possible yet. The developed system however, allows the client to start formulating new ways of presenting fabrics since the idea differs a lot from traditional ways of presenting fabrics. This specific idea however, does not seem to be of added value to the current way of displaying clothes. In general the client was satisfied and excited, since this research triggers new ways of thinking and shows new possibilities, which was their intention of this research.

During this research also stakeholders were involved. The contact with the supervisor ('keep satisfied') and the critical observer ('monitor') of the University of Twente was satisfying. Weekly meeting with the supervisor are attended, and the given feedback is processed in the research. The two meetings with the critical observer were conducted, and a few different versions of the report are sent throughout the research. The contact with the company PVH was as envisioned, 'keep informed'. Two times the company is visited in order to present findings and prototypes. As stated, the actual designers and retailers were not involved in the process due to busy schedules. Via the contact person of PVH some insight about the retailers was gained, no insight about the designers is gained. This leaves room for improvement, in order to find their real needs and desires. The co-developer Juliette Hoedemakers is rather 'monitored' than 'keep informed', so this contact was slightly different than envisioned. However, this was expected, in the matrix she is located almost at the 'monitor'-side. Overall the contact with stakeholders was good, the people with the most power were highly involved, and well-informed. However, relevant stakeholders like the designers and the retailers are not contacted at all, this leaves room for improvement.

Currently, no device exists which is able to render fabrics in a satisfactory way to allow for judgment. Haptic feedback technology is not developed enough to render fabrics without the need of a piece of actual fabric. The developed system uses a small piece of fabric in order to render a large sheet of fabric, which can be experienced by the user. The concept of a haptic wheel is not new, but based on the Haptic Revolver by Microsoft. The implementation however, is new and progressive. Users of the system are able to distinguish fabrics, and the found characteristics of the fabrics using the haptic wheel correspond to the characteristics found using a sheet of fabric. If this is enough to judge fabrics must be investigated. Improvements can be made, these might enlarge the usability in order to judge fabrics. The controller is build successfully, and the wheel allows for distinguishing and describing fabrics, which is a start of judging.

7.2 Recommendations

This report describes the development of a system which tends to render fabrics, in order to allow the user to judge these fabrics. The research tries to be complete and to cover different aspects. This section states recommendations in order to improve the research, and in order to perform a follow-up study. The recommendations are divided into: the prototype, the test, general recommendations

The prototype

In order to create a more smooth and realistic rotation of the haptic wheel, the code for rotating can be improved. Currently this is done by trial-and-error due to limited time. Using the number of measurements, the time, and the displacement, a speed can be formulated which can be expressed in an unit. This can be used in order to give the motor a speed which matches the reality. Taken into account the circumference of the wheel, the motor might be able to rotate at such a speed, the distance covered on the wheel matches the distance covered in real-life.

Also, by implementing better hardware, the system can work more accurate and smooth. Stronger motors allow for rotation at low speeds, where the current motor just rotates at its lowest speed possible. This allows the user to feel an even more realistic rotation, fitting to his movement. Also, a smaller motor would allow for a smaller and more ergonomic controller. Adding components to make the device wireless allows the user to move more freely. Using an advanced accelerometer instead of the HTC VIVE tracker would allow for the system to work without the need of the base-stations, makes the systems limitations due to the HTC system disappear, and would allow for rendering without the need of a laptop. This makes the system more portable and user-friendly. Adding a servo to move the haptic wheel up and down offers possibilities regarding rendering of buttons and stitches. Participants of the user test state that an y-axis is desired, this could be implemented in an improved version.

The test
In order to make the user test more meaningful and meeting the reality to a greater extend, a bigger test group can be used. Instead of using two groups of eight people, a group of 50 people would allow to remove extremes and deviations. Also , by increasing the size of the user group, statistical analysis can be performed on the results. A t-test, for instance, can be performed in order to find significant differences. Using a bigger group of participants would allow for more meaningful results and better interpreting.

The testing could be done more elaborate. Asking a greater amount of wheels to participants gives more results, and by asking the same wheel for multiple times enables to remove biased or not matching results.

Perform tests which actually regard the quality of the fabric. Let participants for instance judge two fabrics by stating which is stronger. Afterwards perform a pull-test for instance, to find out which fabric actually is stronger. Check the results with the found judgments. Other ways of exploring the ability to judge a fabric using the haptic wheel can be formulated and tested.

Always have a control group when testing. When participants perform a test with the haptic wheel, always let participants perform the same test with a sheet of fabric. This allows to check the found results and compare them.

General
During the process, ensure to keep contact with retailers and designers. They are the actual envisioned users, check whether or not the system would work according to them. Until the system performs at a certain level, testing can be done using random participants. However, testing with the actual user is most relevant in evaluating the system.

System can be improved. Main point of interest formulated at the test are: allow ability to feel the thickness, to feel the elasticity, and to feel both sides of the fabric. Also rotating the wheel in the opposite direction can be investigated to a greater extend. It feels almost the same, use of this given, and testing of it should be done.

This research focuses only on the implementation of judging fabrics. However, other implementations can be found too. Further investigation should explore possible other implementations. For instance, when using the controller as an input device, it can be used to sculpt clothing in a VR-setting.

In order to render fabrics without the need of fabric, more research must be performed on the topic of haptic feedback technology. This is out of scope of this research, but is an interesting field of research with great potential.

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8 Appendices

Appendix A — Arduino coding

```
 /*
 Sketch to interpret the received values (of the HTC VIVE tracker)
 and control the 12V DC motor via an H-Brdige
 */

// Motor A
int enB = 9;  // speed of the motor [PWM]
int in3 = 8;  // either on or off, determines direction
int in4 = 7;  // either on or off, determines direction

int input;
char dir;

int counterRight, counterLeft;

boolean SmallCounter = true;
boolean Left = false;
boolean Right = false;

void setup() {
  Serial.begin(19200);
  pinMode(enB, OUTPUT);
  pinMode(in3, OUTPUT);
  pinMode(in4, OUTPUT);
}

void loop() {
  speed_function();

  if (Left) {
    direction_Left();
  } else if (Right) {
    direction_Right();
  }
}

void direction_Left() {   // let the motor rotate left
  digitalWrite(in3, LOW);
  digitalWrite(in4, HIGH);
}

void direction_Right() {  // let the motor rotate right
  digitalWrite(in3, HIGH);
  digitalWrite(in4, LOW);
}

// function which returns the speed of the wheel (in form
of a voltage)
void speed_function() {
```

```
  while (Serial.available() == 0)  {}
  input = Serial.parseInt();

  if (input < 5) {
    input = 0;
  } else if (input >= 5 && input < 50) {
    input = 50;
  } else if (input >= 50 && input <= 250) {
    input = map(input, 50, 250, 50, 255);
  } else if (input > 250 && input != 888 && input != 999) {
    input = 255;
  }

  if (input == 999) {                     // Right is true
    counterRight = counterRight + 1;
    counterLeft = 0;
    input = 0; // this value is not the speed, so make speed zero
    if (counterRight > 1) { // 2 or more times right, rotate right
      Right = true;
      Left = false;
    }
  }

  if (input == 888) {                     // Left is true
    counterLeft = counterLeft + 1;
    counterRight = 0;
    input = 0; // this value is not the speed, so make speed zero
    if (counterLeft > 1) { // 2 or more times left, rotate left
      Right = false;
      Left = true;
    }
  }

  analogWrite(enB, input);                //min is 50, max is 255

}
```

Appendix B — Python coding

```
import triad_openvr_graduationproject
import time
import sys
import serial
import math

previous_position = 0.0

v = triad_openvr_graduationproject.triad_openvr()
v.print_discovered_objects()
ser = serial.Serial('COMX',19200) #replace 'X' with the actual port



# get the position
def get_position():
    avarage = 0
    for x in range (0,50): # measure 50 times and take avarage
        # function to obtain position
        for each in v.devices["tracker_1"].get_pose_euler():
            value = 1 + float(each) # 1 + avoids negative values
        avarage = avarage + value
    avarage = (avarage / 50)
    return float("%.4f" % avarage) # return the found value

# function to convert position to velocity
# use previous position and current position to calculate the speed
def get_velocity(prev_pos, pos):
    value = 1000 * (pos - prev_pos)

    if value <= 0.1 and value >= -0.1: # filter small values
        value = 0

    value = value * 10 # to enlarge different values
    return int(value) # return the speed

interval = 1/60

if interval:
    while(True):
        start = time.time()
        position = get_position()

        # get velocity by stating prev. pos. and current pos.
        velocity = get_velocity(previous_position, position)
        print(velocity)

                # current pos. is stored as prev. pos.
        previous_position = position

        sleep_time = interval-(time.time()- start)
```

```
        if sleep_time>0:
            time.sleep(sleep_time)

        num = velocity

        # negative velocities implies moving to the right
        if num < 0:
            ser.write(b'999')
            ser.write(b'"')
            #print('R')
        # positive velocities implies moving to the left
        if num > 0:
            ser.write(b'888')
            ser.write(b'"')
            #print('L')

        # make the velocity absolute, no negative values can be
        # transported via serial com
        num = math.fabs(num)

        if num == 0: # if the value is '0' send a '0'
            ser.write(b'%d' % 0)

        elif num > 0:
            i = math.ceil(math.log(num,10))
            for x in range (i):
                val = (num//math.pow(10,i-1))
                val = int(val)
                ser.write(b'%d' % val) # covert to bytes
                num = (num - val*math.pow(10,i-1))
                i = i-1



        ser.write(b'"')
```

Appendix C — Form with percept factors

Form with percept factors

With use of: https://link.springer.com/content/pdf/10.3758%2Fs13414-010-0037-y.pdf

For each factor check the boxes which apply to the fabric.

- English (*Dutch*)

Factor 1: Roughness (*Ruwheid*)

- Rough (*Ruw*)
- Smooth (*Glad*)
- Bumpy (*Hobbelig*)
- Prickly (*Stekelig*)
- Soft (*Zacht*)
- Gritty (*Zanderig*)
- Jagged (*Getand/gepunt*)

Factor 2: Pile (Vacht)

- Fuzzy (*Groezelig*)
- Fluffy (*Pluizig*)
- Dry (*Droog*)
- Damp (*Vochtig*)

Factor 3: Temperature (*Temperatuur*)

- Cold (*Koud*)
- Chilly (*Fris*)
- Cool (*Koel*)
- Avarage (*Gemiddeld*)
- Warm (*Warm*)
- Hot (*Heet*)
- Burning (*Gloeiend*)

Figure 29 – Form with percept factors used in test 2, 4, and 5.

Appendix D — Feedback test 1-4

Asked question: ”How was the experience in general?”

- By feeling the fabrics blindfolded, other senses are tickled compared to feeling when being able to see
- Funny to experience fabrics in this way, and also partly without the ability to see the fabrics
- Good, realistic, fun to try and recognize the fabrics
- Good, easy to use
- Nice, pleasant and a bit odd experience, especially blindfolded
- Good, it works smooth and nice
- Interesting and nice
- Cool experience

Asked question: ”Did the ability to see the fabric add value to the experience?”

- Yes, you use associations based on what you see
- Yes
- No, not really, the fabric felt the same/similar
- Yes, you often already know the fabric, so it is easier to figure out which fabric is presented
- Yes, a lot actually, especially the ability to see the fibers and the weaving pattern
- Yes, you can get more grip on your thoughts and the experience
- Yes, the ability to see the fabric actually adds surprisingly much to the experience, big influence on what you feel
- Yes, I immediately started to associate when I was able to see, this helped in figuring out which fabric I touched

Asked question: ”What do you think are points for improvement?”

- The haptic wheel is hard from itself, due to this I’m not able to experience how soft the fabric is, the elasticity is also lacking due to this
- I missed the ability to feel the fabrics from both sides. I also experienced some disturbance due to the hard wheel
- The possibility to move over the y-axis as well would make the experience more realistic
- A bit smaller device would be easier to hold, right now the controller is fairly big. Make the wheel rotate smoother
- Feel how the fabric behaves when stretching it
- A wider wheel to prevent the possibility to feel the edges, and to have more surface to feel
- When feeling a sheet of fabric you mostly feel the fabric between your fingers, this wheels only allow you to touch it with the tops of your fingers
- The wheel rotated not at the right speeds, maybe this could be improved to get a more realistic experience. Also the Y-axis was lacking

Appendix E — Results test 1-5

Results test 1-4

		test 1 gegeven	test 1 goed of fout?	test 1 namelijk	test 2 gegeven	test 3 gegeven	test 3 goed of fout?	test 3 namelijk	test 4 gegeven	test 4 goed of fout?	test 4 namelijk
persoon 1	wiel 1	5	1	ander	3	3	0	katoen	7	1	
	wiel 2	1	1		6	6	1		3	1	
	wiel 3	3	1		4	4	0	wol-achtig	2	0	nylon
persoon 2	wiel 1	2	1		7	4	0	fleece velorr	1	1	
	wiel 2	4	1	ander	6	3	1	katoen	5	1	
	wiel 3	1	1		4	2	1		3	1	
persoon 3	wiel 1	3	1		3	1	1		2	1	
	wiel 2	7	1	ander	6	4	1	corduroy	3	1	
	wiel 3	3	0	2	5	7	1		5	1	
persoon 4	wiel 1	1	0	2	4	2	1		5	1	
	wiel 2	2	0	3	5	7	1		4	0	geen idee
	wiel 3	4	1	ander	6	3	1	katoen	1	1	
persoon 5	wiel 1	7	1		3	4	0	katoen	3	1	
	wiel 2	1	0	ander	2	6	1		5	1	katoenachtig
	wiel 3	6	0	3	5	1	0	suede	7	1	
persoon 6	wiel 1	2	0	1	5	7	1		3	1	
	wiel 2	1	0	ander	1	2	1		1	0	zijde
	wiel 3	3	0	ander	4	3	0	zijde	5	1	
persoon 7	wiel 1	1	0	2	6	4	0	zacht, textuur, vorm	2	1	t-shirt
	wiel 2	4	1	ander	5	2	1	hele zachte spijkerstof'	6	1	
	wiel 3	1	0	3	2	7	1		1	1	fluweelachtig, linnen
persoon 8	wiel 1	5	1		4	5	1		7	1	
	wiel 2	6	1		2	1	0	denim	4	1	
	wiel 3	2	0	3	6	6	1		6	1	

Figure 30 – Results of test 1-4. Per test the presented fabric is stated, and when applicable: whether or not this was guessed correctly.

Results test 2 & 4 characteristics

	participant 1						participant 2						participant 3						participant 4					
	test 2			test 4			test 2			test 4			test 2			test 4			test 2			test 4		
	3	6	4	7	3	2	7	6	4	1	5	3	3	6	5	2	3	5	4	5	6	5	4	1
Rough		1			1		1						1		1		1		1	1		1		
Smooth						1		1		1		1	1	1		1	1				1		1	1
Bumpy	1		1				1		1										1				1	
Prickly							1																	
Soft									1		1					1							1	
Gritty				1																1				
Jagged																		1						
Fuzzy		1		1							1		1		1					1		1		
Fluffy			1			1					1							1	1				1	1
Dry	1				1		1		1	1		1	1	1		1	1				1			
Damp								1																
Cold																								
Chilly						1																		
Cool		1						1						1							1			
Average	1				1		1			1	1	1	1	1	1	1	1	1	1	1		1	1	1
Warm			1	1					1						1			1						
Hot																								
Burning																								

	participant 5						participant 6						participant 7						participant 8					
	test 2			test 4			test 2			test 4			test 2			test 4			test 2			test 4		
	7	1	6	3	5	7	5	1	4	3	1	5	6	5	2	2	6	1	4	2	6	7	4	6
Rough				1		1			1	1	1	1			1	1		1	1			1		
Smooth	1	1			1			1			1		1				1			1	1			1
Bumpy			1				1		1				1				1				1			
Prickly						1																1		
Soft	1	1	1		1		1							1	1	1		1	1	1			1	
Gritty				1										1										
Jagged																								
Fuzzy							1		1						1							1		
Fluffy		1	1		1		1					1		1					1				1	
Dry	1		1	1		1		1		1	1		1	1	1	1		1	1	1	1	1	1	1
Damp																	1							
Cold																								
Chilly																								
Cool				1		1		1			1						1				1			1
Average	1	1								1			1					1		1		1	1	
Warm			1		1		1		1			1		1	1	1			1					
Hot																								
Burning																								

Figure 31 – Found characteristics during test 2 and 4. Green indicates overlapping characteristics for one participant for the same fabric. Orange indicates a deviant characteristic for one participant for the same fabric.

Results test 5

persoon 1
knowledge: 3

test 5 blind				test 5 zicht			
	gegeven	goed of fout?	namelijk		gegeven	goed of fout?	namelijk
wiel 1	5	1		wiel 1	1	1	
wiel 2	3	0	katoen, géén denim	wiel 2	6	1	
wiel 3	7	1		wiel 3	4	1	

persoon 2
knowledge: 3

test 5 blind				test 5 zicht			
	gegeven	goed of fout?	namelijk		gegeven	goed of fout?	namelijk
wiel 1	4	0	katoen	wiel 1	2	1	
wiel 2	2	0	satijn	wiel 2	6	1	
wiel 3	7	1		wiel 3	5	0	

persoon 3
knowledge: 3

test 5 blind				test 5 zicht			
	gegeven	goed of fout?	namelijk		gegeven	goed of fout?	namelijk
wiel 1	3	1	katoen	wiel 1	2	1	stretch katoen
wiel 2	1	0	silk	wiel 2	6	1	
wiel 3	4	0	geen idee	wiel 3	3	1	

persoon 4
knowledge: 2

test 5 blind				test 5 zicht			
	gegeven	goed of fout?	namelijk		gegeven	goed of fout?	namelijk
wiel 1	2	1		wiel 1	3	1	
wiel 2	3	1	dunne spijker	wiel 2	1	0	katoen
wiel 3	6	1		wiel 3	5	0	dweil

persoon 5
knowledge: 3

test 5 blind				test 5 zicht			
	gegeven	goed of fout?	namelijk		gegeven	goed of fout?	namelijk
wiel 1	7	1		wiel 1	5	0	nylon
wiel 2	1	0	zijde	wiel 2	4	1	ribbelbroek'
wiel 3	3	1	katoen, spijkerstof	wiel 3	7	1	

persoon 6
knowledge: 2

test 5 blind				test 5 zicht			
	gegeven	goed of fout?	namelijk		gegeven	goed of fout?	namelijk
wiel 1	5	0	wol	wiel 1	4	0	bad
wiel 2	2	0	silk, zijde	wiel 2	1	0	zijde
wiel 3	1	0	zijde	wiel 3	5	0	

persoon 7
knowledge: 3

test 5 blind				test 5 zicht			
	gegeven	goed of fout?	namelijk		gegeven	goed of fout?	namelijk
wiel 1	6	1		wiel 1	3	1	
wiel 2	2	0	satijn	wiel 2	1	1	
wiel 3	5	1		wiel 3	7	1	

persoon 8
knowledge: 4

test 5 blind				test 5 zicht			
	gegeven	goed of fout?	namelijk		gegeven	goed of fout?	namelijk
wiel 1	7	1		wiel 1	6	1	
wiel 2	3	1		wiel 2	2	1	
wiel 3	4	1		wiel 3	1	1	

Figure 32 – Results of test 5. Per test the presented fabric is stated, and when applicable: whether or not this was guessed correctly.

Results test 5 characteristics

	participant 1						participant 2						participant 3						participant 4					
	blind			zicht			blind			zicht			blind			zicht			blind			zicht		
	5	3	7	1	6	4	4	2	7	2	6	5	3	1	4	2	6	3	2	3	6	3	1	5
Rough		1	1								1						1			1				
Smooth					1			1						1					1		1		1	1
Bumpy						1	1						1		1							1		
Prickly									1									1						
Soft				1						1									1					1
Gritty	1											1				1								
Jagged																								
Fuzzy			1			1			1															
Fluffy	1											1							1		1		1	1
Dry		1		1	1		1	1		1			1	1	1	1	1	1		1		1		
Damp											1													
Cold																					1			
Chilly								1				1												
Cool				1	1			1				1		1			1							
Average		1	1						1	1			1			1		1	1	1		1		
Warm	1					1	1				1				1								1	1
Hot																								
Burning																								

	participant 5						participant 6						participant 7						participant 8					
	blind			zicht			blind			zicht			blind			zicht			blind			zicht		
	7	1	3	5	4	7	5	2	1	4	1	5	6	2	5	3	1	7	7	3	4	6	2	1
Rough	1		1	1		1	1		1		1					1		1	1		1			
Smooth		1						1	1		1		1				1				1	1	1	1
Bumpy	1			1	1					1												1		
Prickly	1					1													1					
Soft		1	1		1		1			1				1	1					1	1		1	
Gritty	1											1							1	1			1	1
Jagged																								
Fuzzy	1		1			1	1								1			1	1					1
Fluffy	1			1						1		1									1			
Dry		1	1		1			1	1		1		1	1		1	1		1	1			1	
Damp																					1	1		
Cold																								
Chilly																						1		
Cool		1				1							1									1		
Average	1			1				1	1		1			1			1			1			1	1
Warm			1		1		1			1		1			1	1		1	1		1			
Hot																								
Burning																								

Figure 33 – Found characteristics during test 5. Green indicates overlapping characteristics for one participant for the same fabric. Orange indicates a deviant characteristic for one participant for the same fabric.