Haptic sense- Evaluating the reliability and perception of vibration motor arrays on the human body

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Media Computing Group
Prof. Dr. Jan Borchers
Computer Science Department
RWTH Aachen University

by
Max Jodl

Thesis advisor:
Prof. Dr. Jan Borchers

Second examiner:
Prof. Dr. Ulrik Schroeder

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Abstract

The nowadays most used feedback variants address the visual (writing, lights, images) and the auditory (alarm, sounds) senses. What if the visual sense is not usable and the auditory sense is busy with other everyday actions? Visually impaired people need to depend on other feedback methods, like the underestimated haptic sense to compensate the missing input.
Modern human computer interaction methods provide us to send precise information with haptic feedback. So far it is used in mobile phones as a vibrational alert, although there are more complex applications possible. The HaptiVision is a haptic feedback navigation vest, which allows visually impaired, to navigate securely through everyday life struggle, using vibrations to signal obstacles in the users way. This navigation aid enables the user to avoid obstacles, just using simple vibrations to signal the distance to the objects. That could replace white canes and guide dogs in the future.
It is not completely investigated what the human body is able to notice and to interpret by using haptic feedback. Simple directions and instructions are dependably interpreted, but complex pattern or instructions are recognized barely or not at all. Every body part has different sensitivities while processing haptic feedback, thus individual solutions are necessary. The forearm offers in longitudinal direction significantly worse results than in transverse direction. Not only the various directions are crucial for haptic feedback, the intensities of vibration are too. The whole range of the intensities is not usable, as the recognition rate decreases significantly, by reaching a certain amount.

Überblick

Die heutzutage am meisten genutzten Feedback Methoden addressieren die Sinne des Sehens (Schrift, Lichter, Bilder) und des Hörens (Alarm, Töne). Doch was, wenn der visuelle Sinn beim Nutzer nicht zur Verfügung steht und der auditive schon durch normale Aktionen ausgelastet ist? Blinde oder Sehbehinderte Menschen sind auf andere Feedback Methoden angewiesen, wie zum Beispiel auf den wenig berücksichtigten Sinn des Fühlens, um den fehlenden Input zu kompensieren.
Moderne Mensch Computer Interaktionstechniken ermöglichen präzise Informationsübermittlungsverfahren, mittels haptischem Feedback. Teilweise wird es schon angewendet, wie bei Vibrationsalarmen in Mobiltelefonen, wobei das Spektrum der Möglichkeiten wesentlich größer ist. Dies nutzt die VibroVision, eine haptische Feedback Weste, um Blinde Personen sicher durch den Alltag zu navigieren, indem dem Nutzer mittels Vibrationen Objekte signalisiert werden. Blinde können so Hindernissen ausweichen und Hilfsmittel wie Blindenstöcke oder Blindenhunde, könnten so in Zukunft abgelöst werden.
Es ist noch nicht vollständig erforscht, was der Mensch an haptischem Feedback wahrnehmen und interpretieren kann. Einfache Richtungen und Instruktionen werden zuverlässig interpretiert, während komplexe Muster oder Anweisungen schlecht bis gar nicht erkannt werden. Jedes Körperteil des Menschen hat eine unterschiedliche Sensitivität in Bezug auf haptisches Feedback, was individuelle Lösungen fordert. Beispielsweise hat der Unterarm in Längsrichtung eine signifikant schlechtere Erkennungsrate, als in Querrichtung. Nicht nur die unterschiedlichen Richtungen sind entscheidend, sondern auch die Vibrationsstärken. Es kann nicht das komplette Spektrum der Vibrationsintensitäten genutzt werden, da ab einer gewissen Höhe, die Erkennungsraten des Menschen signifikant schlechter werden.

Acknowledgements

First of all, I would like to thank Dipl. Ing. Jan Thar for supervising this thesis, the expertise he offered while facing several hardware problems and the useful feedback he contributed. Secondly, I want to thank Prof. Dr. Jan Borchers, for giving me the opportunity to be part of this interesting project at the Media Computing Group.

Last I want to thank my friends for respecting my tight time schedule and for their support while writing this thesis, especially Annkristin for always lending me a sympathetic ear while facing several issues; you were facilitating my work.

Conventions

Throughout this thesis we use the following conventions.

Text conventions

Definitions of technical terms or short excursus are set off in coloured boxes.

EXCURSUS:
Excursus are detailed discussions of a particular point in a book, usually in an appendix, or digressions in a written text.

Definition: *Excursus*

Source code and implementation symbols are written in typewriter-style text.

`myClass`

The whole thesis is written in Canadian English.

Download links are set off in coloured boxes.

File: myFile[a]

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Chapter 1

Introduction

Vision is the most used sense people use, to go through daily life. It starts with waking up in the morning and the first thing a person does, is to open his eyes and ends with going to sleep and closing his eyes.
In between of that, people decide what to wear, depending on what the weather is like, by looking out of the window. Finding a matching pair of socks, having conversations and looking each other into the eyes, driving to work with the car, choosing a tasty food in the bakery are a few examples on how much people rely on their visual sense, in everyday life. Without vision, all of these daily routines are more difficult.

People trust more in what they see, than in all the other senses combined. 80% of the information we obtain, is delivered by the visual sense. To make this possible, one quarter of our brain is occupied [See].
Even though, not every person is able to rely on their visual sense, some suffer from visual impairment and need assistance to compensate the missing information, others get from seeing. According to WHO, about 285 million people worldwide suffer from visual impairment [Organization et al., 2012].

According to WHO about 285 million people are visually impaired

Visually impaired people usually use navigation aids to compensate some aspects of the missing visual input. The most common ones are the white cane and the guide dog. But these devices have their limitations and are expensive to acquire. Most of the visually impaired people live in low income settings, so they can not afford them.

Figure 1.1: Person with a white cane [timeanddate]

One approach to develop an alternative navigation aid for supporting visually impaired, is the HaptiVision, made by Sánchez [2015]. He accomplished a remarkable piece of work by developing a completely different tool, using the possibilities of modern human computer interaction techniques.
The HaptiVision is a navigation vest for visually impaired people, that helps them to navigate around obstacles, without occupying their hands.

The HaptiVision scans the environment, using a camera with integrated depth sensor, mounted on the chest of the user and computes the distances to nearby obstacles. The received picture is scaled down from $640x480$ to $16x8$ pixel and each pixel is mapped to a single vibration motor, which is built into the chest of the vest. To signal the different distances to the obstacles, the intensity of each vibration motor is regulated via pulse width modulation. This haptic feedback allows visually impaired people to navigate securely through everyday life. The HaptiVision is built with low cost material with no commercial purposes and every single result is available publicly, in order to provide it to as many people as possible.

about 90 % of visually impaired live in low income settings

Figure 1.2: HaptiVision [Sánchez, 2015]

Even though the HaptiVision is a great work, there is potential to improve some aspects of it. The main interest of this thesis, is to analyse the basic hardware requirements, with focus on the vibration motors and the haptic feedback.

Sánchez [2015] used a kind of vibration motors, that offer a good functionality, but also includes some disadvantages. He chose ERM pager vibration motors with an external eccentric mass 3.1.3 "ERM Vibration Motors".
To ensure a smooth operation, it needs to be encapsulated, which he did by building a 3D printed case for each of it. This causes the sound pressure level to be very high. The auditory sense is the most important to visually impaired, so the high sound pressure level is quite a problem, their hearing sense is the one, they get the most input from.

The auditory sense is the most important to visually impaired

The HaptiVision offers the same range as the white cane, which is today's most used navigation aid. However white canes are not able to spot overhead obstacles and while operating it, one hand of the user is always occupied. In an analogous manner the guide dog has its limits. Also the guide dog is not able to detect overhead obstacles on a reliable basis. Most of the visually impaired can not achieve one, because 90% of them live in low income settings.

The HaptiVision has the same range as a white cane

The other key aspect of this thesis is to analyse the haptic feedback the human body is able to recognize and the kind of signals the human is able to understand and to differentiate from each other.
Haptic feedback offers a huge amount of usefulness.
In mobile phones it is used for years, in gaming controllers, in car seats as feedback for the driver and even in helicopters as feedback for pilots are just a few examples. The huge advantage of haptic feedback is its hands and eyes free usage.
The other feedback possibilities address the visual (lights, letters) and the auditory (sound, alarm) senses. Haptic feedback uses the sense of feeling, which is used to a lesser extent in comparison to the other senses. Vision and auditory are the most used senses for feedback and for daily navigation or activities and therefore it is likely to miss one or to be distracted by this kind of feedback.

The common feedback methods addresses the visual and the auditory senses

As for visually impaired, the sense of vision is not a possibility and the auditory sense is used for their daily life, while the haptic feedback offers a hands free navigation aid, which reduces the limitations of visually impaired people.

1.1 Thesis Overview

- **Chapter 2- Related work** Summarizes the work, that is done related to haptic feedback researches over the past decades and explains how the human body processes haptic feedback.

- **Chapter 3- Own work** Presents the advantages and disadvantages of the different hardware designs and the user studies that are developed, implemented and performed, to analyse the haptic feedback.
- **Chapter 4- Evaluation** Presents the results, that are evaluated regarding the hardware and the performed user studies.
- **Chapter 5- Summary and future work** Summarizes every important aspect of this thesis and briefly explains what work should be done in the future and how it should be done.

Chapter 2

Related work

This thesis is based on the work of Sánchez [2015]. The HaptiVision he created, is a navigation vest, that signals nearby obstacles via haptic feedback.
Haptic feedback was evaluated for over hundred years, with sometimes contradicting results, caused by the technical changes and the different experimental setups.

2.1 Receptors

The human body recognizes haptic feedback via sensory receptors. The most important receptors for vibration are the mechanoreceptors and the hair follicles of the skin, which are actuated by mechanical pressure and distortion. Together they produce the haptic feedback, which is relevant for recognizing a touch or a movement.
Studies showed, that the detection accuracy of body parts with hairy skin is higher than on body parts with glabrous skin [Kandel et al., 2000]. This is caused by the hair follicles, that react on every simple and slightest movement they are in contact with.

Hair improves the ability to recognize haptic feedback

To differentiate two stimuli from each other, the stimuli need to activate receptors connected with different nerve fibres. If the receptors are connected with the same nerve fibre, the stimuli appear as just one stimulus and are not

Two point discrimination threshold

differentiable. This is called the two point limen or two point discrimination threshold. It depends on the density of mechanoreceptors in the skin. The more mechanoreceptors and nerve fibres, the lower the two point discrimination threshold, the better the detection rate of this particular body part.

2.2 Haptic Feedback

One of the first who investigated the sense of touch and common sensibility of the human, was Ernst Heinrich Weber (1795-1878). He accomplished remarkable results and placed the foundation for all subsequent researches, by introducing the point localization test with the two point limen and the localization error [Weber, 1834]. Later it was formulated as Weber's Law, by one of his students.

$$k = \frac{\Delta S}{S}$$

Weber's Law

The law states, that the *Just Noticeable Difference* for a touching stimulus ΔS, to the previous stimulus S, which is recognized by the human, always is proportional to k. [Fechner, 1860]

Frequencies between $200 - 250Hz$ are felt best

Several studies show that the human is most sensitive to frequencies of vibration between $200 - 250$Hz. Frequencies below and above this range are felt, if the amplitude of vibration is proportunately increased [Kandel et al., 2000]. Changes in the frequency of vibration have little effect on the size of the threshold, evaluated on many occasions[Knudsen, 1928] [Sherrick, 1950] [Schiller, 1953]. Thus, for this thesis a frequency of 200Hz is chosen.

Interval of uncertainty

Parsons and Griffin [1988] established the term, *interval of uncertainty*, that occurs while testing with participants. There is a high possibility the subjects are guessing, if they are not sure what they felt or if they miss a feedback. This needs to be considered for all user studies.

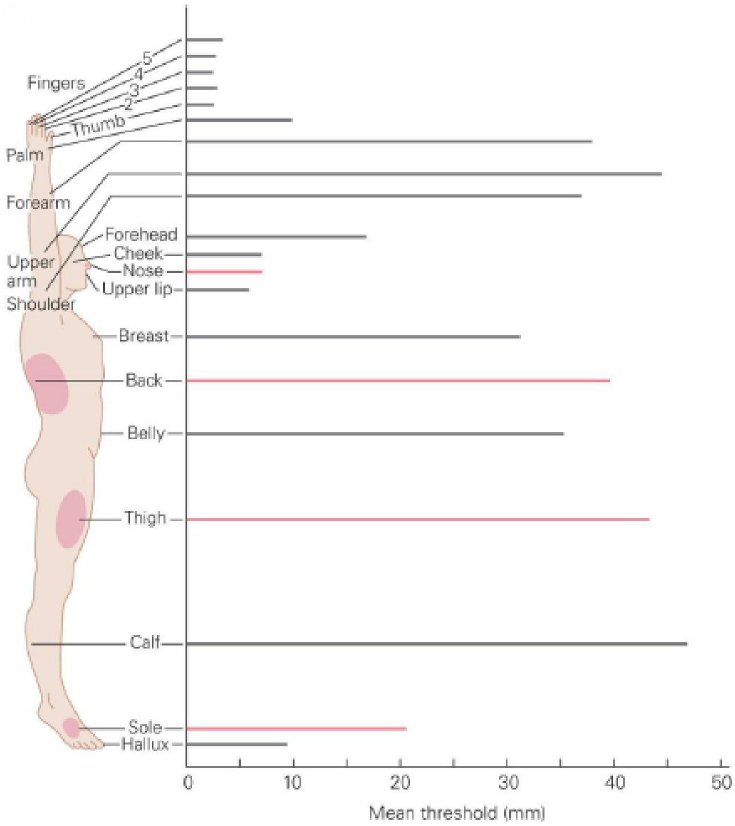


Figure 2.1: Two point discrimination threshold of the different body parts [Kandel et al., 2000]

Jones and Ray [2008] evaluated navigational commands, presented with haptic feedback on the human body. They performed their studies at the waist and the back, with fixed frequencies and got quite great results. The participants were able to interpret simple navigational and instructional commands on the torso. The accuracy of correct answers are located at 95% and 99% for the waist and the back, respectively.

Navigational commands are recognizable

Similar results were found, according to recognize directions via haptic feedback [Jones et al., 2009]. These experiments were conducted on the forearm, with good results with recognition rates of 98%, using a $3x3$ pattern of vibration motors.

The effects of vibrotactile stimuli are tested in many different ways and with many different aspects. A multitude of studies evaluated the stimuli on the fingertips, the back, the belly and some the effects on the forearm. The forearm is the least analysed part of the body, that is relevant for the HaptiVision. That is the reason why it was chosen to perform different user studies to verify or even to disprove the current findings. However it was analysed in a lesser amount, it showed good results with plenty possibilities.

The forearm offers various advantages and disadvantages for using it as an area for haptic feedback. The user has his hands free and does not suffer any restrictions while using it, like it would be with haptic feedback on the fingertips. The device is always accessible for the user and he is even able to adjust it while using it. Possible is a control unit to adjust the intensities of the vibration motors of the HaptiVision, to turn it on or off, to start navigation and many other potentials.
The forearm is not the most sensitive part of the body and the haptic feedback is limited in its complexness. Figure 2.1 stated a uniform two point discrimination threshold of 3.5 to $4cm$ for the forearm. It is roughly the same threshold like it was evaluated for the back and the belly, but on a much smaller body part with lesser area, which can be used [Van Erp, 2005b] [Kandel et al., 2000].
Nevertheless the possibilities of haptic feedback on the forearm are not utilised yet.

Chapter 3

Own work

The main focus of this thesis was to establish and evaluate the basic hardware requirements of the HaptiVision and analyse the haptic feedback, by designing and performing user studies.
First, this chapter is going to illustrate, which hardware should be used and which not.
Second, the user studies are going to be presented.

3.1 Hardware

In this section, the hardware that is the most suitable to use for future devices, is going to be analysed, regarding several requirements, that need to be fulfilled.. Those are

- Functionality
- Life period / Ability to work under pressure
- Maintainability
- Cost
- Wearing comfort

3.1.1 Control Devices

An Arduino Uno[1] microcontroller was used to control the vibration motors. It was connected to an I^2C board with integrated pulse width modulation driver and voltage regulation. The board offers space for 16 different vibration motors, which were directly connected to it.
Six address pins offer the opportunity to use 62 of these boards at one I^2C bus. For the following user studies, the

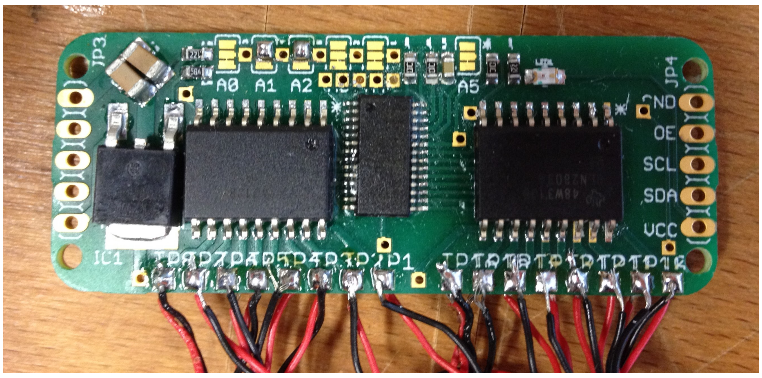


Figure 3.1: I^2C PWM driver

program processing[2] was used in addition to create an user interface 3.8 and to regulate the studies 3.2 "User Studies".

3.1.2 Material

The vibration motors are going to be embedded into some kind of material. The type of this material was important, because different types transfer the vibrations in different ways to the user. This could influence the haptic feedback in a positive or negative way.

Two kinds of materials were tested; on the one hand a very thin textile and on the other hand foam rubber. The textile is a very flexible material, that offers an almost not recognizable absorbing effect of the vibration, but it is that flexible, that the vibration motors were able to move

[1]https://www.arduino.cc/
[2]https://processing.org/

along with it. The foam rubber is not that flexible that the vibration motors were able to move it, but absorbed the vibration in a way. Both materials were comfortable to wear.

3.1.3 ERM Vibration Motors

Two different kinds of vibration motors were tested, to check for the requirements mentioned before 3.1. As a comparison the motor Sánchez [2015] used for his work, is considered at some points, too.

Every motor was purchased via www.aliexpress.com

- Pancake or Coin Type Vibration Motor [3]
- Encapsulated Vibration Motor[4]
- Pager Motor[5]

EXCURSUS:ECCENTRIC ROTATING MASS VIBRATION MOTOR:
The Eccentric Rotating Mass (ERM) vibration motor is a DC motor with an unbalanced mass attached to its shaft. The rotation of this unbalanced mass causes a constant displacement of the motor, which creates vibration effects.

Definition: *Excursus:Eccentric Rotating Mass Vibration Motor*

Due to its external eccentric mass, each pager motor needed to be encapsulated, which Sánchez [2015] realized with a 3D printed hull. The HaptiVision was built with 128 vibration motors and a 3D printed case for each of it, what increases the costs. Furthermore the sound pressure level increased to a point, that is not advisable to use, without risking hearing damage 4.1.2 "Sound Pressure Level".

The HaptiVision produced a dangerous sound pressure level

[3]https://de.aliexpress.com/item/100pcs-lot-10-2-7-MM-Ultra-Micro-Button-Type-Vibration-Motor-3-4-5V-0/32519124357.html?spm=2114.13010608.0.0.Dnm0HK

[4]https://de.aliexpress.com/item/100PCS-Exquisite-Built-In-Vibration-5MM-Coreless-Motor-Micro-Precision-Vibration-Motor/32741914893.html

[5]https://de.aliexpress.com/item/100pcs-lot-4-8-4-8MM-Super-Miniature-Vibration-Motor-Vibrator-1-5-V-3-V/32637772166.html?isOrigTitle=true

The pancake motor and the encapsulated motor do not need an extra hull, hence they offer a cheaper access to build a haptic feedback device and produce a significant lower sound pressure level.

It was hard to find datasheets for those products, manufactured in China, but the cheaper prices, compared to known brands, offer new possibilities, especially by the means of keeping the device cheap and affordable to everyone.

The figure 3.2 shows the pancake motor on the left

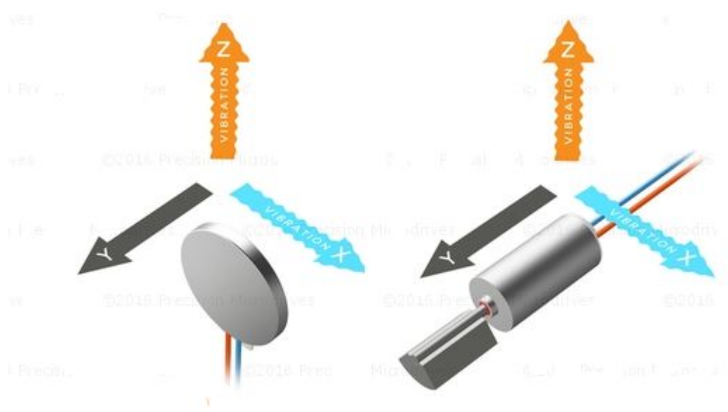


Figure 3.2: Vibration Directions of ERM Motors [Pre]

hand side and the pager motor on the right hand side. The encapsulated motor is a variant of the pager motor, encapsulated with plastic. Along with the motors, the directions the motors vibrate in, are illustrated.
Contrary to Sánchez [2015], who excluded the pancake motor because of its vibration axis, it is considered in this thesis. First tests showed good results and it seems to be an useful option.

3.1.4 Sleeve for the Forearm

This thesis focuses on building a sleeve for the forearm of the human, because it is the smallest part to built and therefore a logical consequence to start analysing the hardware requirements for. They can be transferred to building the bigger devices.

Throughout analysing and testing, several different versions were built and are going to be presented. For every version, a long term and stability test was performed. 3.2.3 "Long Term / Stability Test"

Every version had to pass a stability test

Version 1.0

The very first version consisted out of very thin textile and was built with pancake motors. To ensure a safe attachment, blanks were placed inside of the textile and the pancake motors were glued inside of it. Additionally,

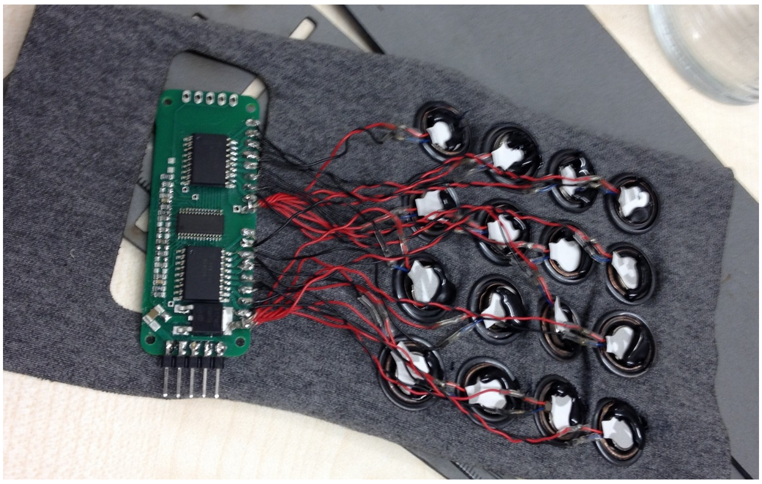


Figure 3.3: Textile Sleeve with blanks and pancake motors

the blanks offered a good transfer of the vibration to the forearm, because they increased the contactor area and were able to move as a single unit. The motors were soldered to the I^2C board, using $0.5mm$ litze wires with a covering heat shrinkable tube. The device consisted out of 16 vibration motors in a $4x4$ pattern with a spacing of $10mm$ between each motor in vertical and horizontal direction.

10mm spacing between each motor

The textile had a good single point transfer of the vibration and because of its flexibility and movement during the vibration, the soldered contacts broke on a regularly basis.

Version 2.0

This time foam rubber was used with the same pattern of 16 pancake motors. Again the motors were glued onto the material to ensure a safe attachment. Because of the

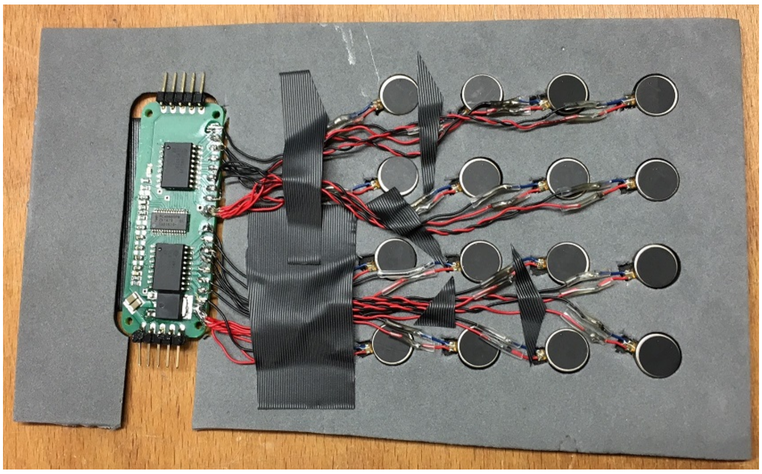


Figure 3.4: Foam Rubber with pancake motors

The tape reduced the movement of the wires

stiff material, parts of the vibration were transferred by the wires, which caused them to vibrate and apply pressure to the soldered contacts and eventually to break them. First feedback from testers showed, that the foam rubber tended to vibrate as a whole unit, which made it difficult to differentiate single motors from each other.

59% fault rate with 24 hour tests

For both versions a stability test was performed and for both versions a fault rate of about 59% of the motors was revealed. After random inspections of the motors, the soldered contacts were determined as the source of the failure. The flexible textile and also the stiff foam rubber put too much pressure to the soldered parts while vibrating, what caused them to break after a certain time.

Version 2.1

This version is alike version 2.0, with the exception, that the wires were not soldered onto the pancake vibration motors, instead they were crimped. It reduced the amount of soldered contacts by half.
The crimped contacts improved the performance to a fault

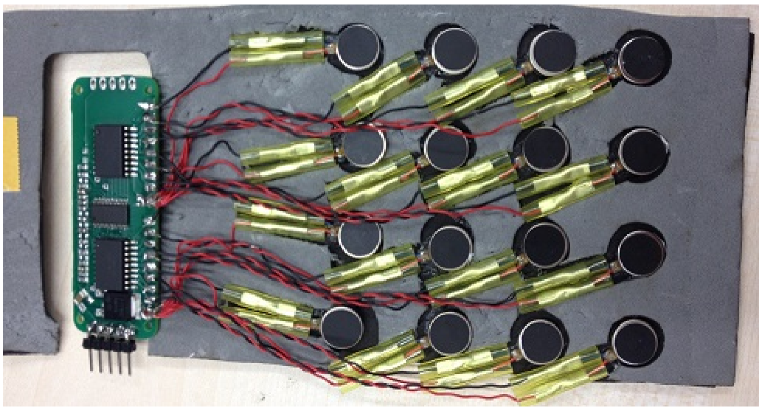


Figure 3.5: Foam Rubber with crimped contacts and pancake motors

rate of about 37% after running the stability test. This was a good improvement, but still not recommendable for the use of future devices.

Due to the fact that the soldered contacts were reduced by half and just some of the remaining contacts broke, a full inspection of every vibration motor, that has been used so far, was conducted, to fathom the still high fault rate. As a result, the pancake vibration motors turned out to be the problem. The previous faults were mistaken to be caused just by the soldered contacts. The pancake motors did not have a high long term stability. The life period and the ability to work under pressure is one of the most important requirements for the devices and as a result the motors were replaced with the following devices.

Pancake motors had a bad long term stability

Version 3.0

The pancake motor was replaced by the encapsulated vibration motor to validate its qualification for future usage. This version consisted out of a textile sleeve, where the motors were glued inside the blanks.
The textile material was preferred over the foam rubber, because of its better transfer of the vibration. The crimped contacts were not applicable to this kind of motors, so soldering was used again. After soldering the wires to the contacts of the motor, a heat shrinkable tube was used to cover the contacts, in order to increase the stability.

Crimping the contacts was not applicable to the encapsulated motors

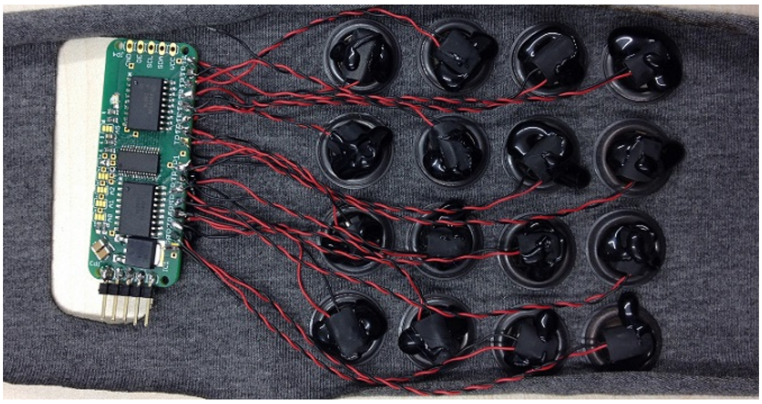


Figure 3.6: Encapsulated Motors in textile, glued in blanks

Encapsulated motors had a much better long term stability

Most important was, to check its long term stability at this point. The encapsulated vibration motors had a fault rate of about 10 %. This was a big improvement compared to the previous versions. The breakdowns were caused by the soldered contacts, based on a systematic inspection. The vibration was detaching the parts from each other.

Encapsulated motors offered a better maintainability

While building this version the vulnerability of the soldered contacts emerged negatively. Frequent reparations needed to be conducted. Based on the reparations that has been executed for this version, a higher maintainability was noticed, compared to the pancake vibration motors.

Version 3.1

The soldered contacts generated a lot of problems for the versions before. By the means of reducing those problems, two $8x2$ male pin headers were attached to the I^2C board. Furthermore, the diameter of the litze wires was increased to $1.25mm$. The long term test was passed without any faults.
Thus, this was the version, the following user studies were performed with. It offered the highest stability, due to the minimized amount of soldered contacts.

Fault rate of 0%

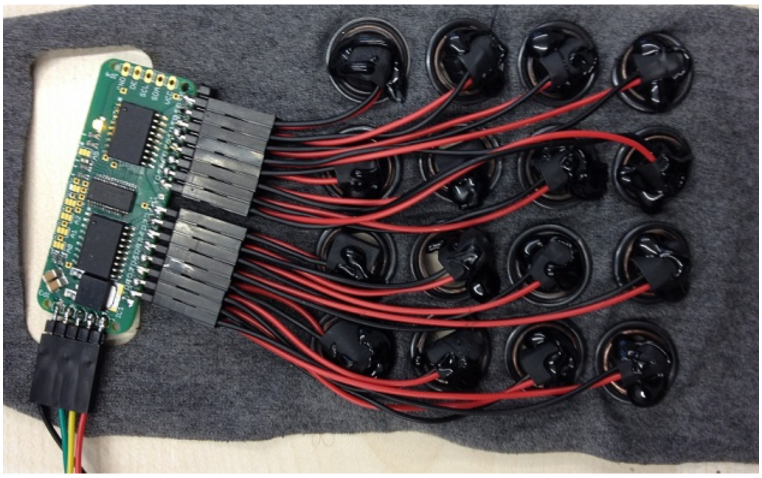


Figure 3.7: Textile sleeve with Encapsulated Motors, outside diameter of $1.25mm$ litze wire , pin headers

3.2 User Studies

Two main types of studies were performed. On the one hand the Differentiation study. There the participant had to differentiate between two different patterns, motors or intensities. For example a reference motor was turned on for a short time and in the following another motor was shortly turned on. The participant needed to say if it is the same motor or a different one. There were just simple answers to give, like *yes* or *no*.
The goal was, to check the distances the motors should have from each other, the intensities that were recognizable

by the human body and which kind of messages could be send via the haptic feedback.

On the other hand, there was the Identification study. The participant did not have an easy way to answer like yes or no, instead he needed to recognize a symbol or a pattern and had to describe it as good as he can. This was done to check the complexity of messages that can be send.

3.2.1 Identification Studies

In this kind of study the participant had to describe several patterns as good as he could. These patterns ranged from single motors to known (*e.g. letters*) and even unknown (*e.g. symbols*) ones. Those patterns also varied between very simple ones and complex ones. These studies showed the sensibility of the participants and the ability to recognize known and unknown symbols, in order to evaluate, whether it was possible to send concrete and complex messages via the haptic feedback or not. Those messages

The participant saw a pattern of 16 red coloured motors and had to choose the played motors by clicking on them

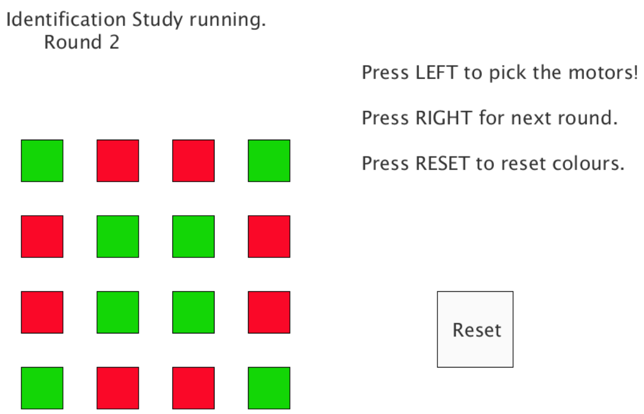


Figure 3.8: Example of a recreated pattern via processing interface

could be useful for navigation of the visually impaired. For example a cross could be played with the message of: *immediately stop walking!*. But more important, it tested the

ability to locate where the vibration came from, which is an essential task to be solved by the user.
Another useful task could be a caller ID feedback, if the HaptiVision interacts with your smartphone, assuming the letters are recognizable.

Pattern Recognition Study

In this study the participant had to describe a pattern that was shown for 2 seconds. In order to do that, a $4x4$ pattern was shown on the computer monitor, via the program processing, and the participant had to choose the vibration motors, that were played, as accurate as he could.

Pattern Recognition Study in a Nutshell

- A pattern was shown for 2 seconds
- Participant had to recreate the pattern via a given User Interface 3.8
- Participant had as much time as needed
- No feedback was given

3.2.2 Differentiation Studies

For the Differentiation studies the participant had to differ between two motors /pattern /intensities, whether it was the same location /intensity or not. The participant had easy two paired answer options at his disposal, like *Left* / *Right*, *Yes* / *No* or *Same* / *Different*.

Top or Down and Left or Right Study

Both motors were played the exact same time and intensity

The participant was shown a single reference motor, for a short time and then another motor, which was located top or down (left or right), from the reference motor. The only thing the participant had to do, was to locate whether the second motor was located top or down (left or right) from the reference motor. To realize that, a computer mouse was placed in front of the right hand of the participant. The left button correlated to the answer *left* and the right button to the answer *right*. For the top or down study, the left forearm was bent in a square angle, so from the participants point of view, it was the same as the first study, except the forearm changed its position. The left button correlated to the answer *down* and the right button to the answer *top*.

Memory Study

Both patterns were displayed the exact same time and intensity

This study in general worked the same as the ones before. The only thing that changed, the participant was shown a pattern from 1 to 16 motors used. The participant had to differentiate whether the second pattern equals the first pattern or not. The left button correlated with the answer *same pattern* and the right button with the answer *different pattern*. Each pattern was shown for exactly two seconds and with a break of two seconds in between.

Intensity Study

In this study just one motor was used instead of several different ones, but the intensity of the motor was changed. The participant had to differentiate whether the intensity had changed or not. Again the differentiation was realized in the same way as in the studies before using a computer mouse. The left button correlated with the answer *yes* and the right button with *no*.

Differentiation Studies in a Nutshell

- a reference Motor/ Pattern/ Intensity is played
- after a short pause another Motor / Pattern / Intensity is played

- Participant has to differentiate whether the second Motor/ Pattern/ Intensity is **located left-/right** or **top/down** or **differs/equals** the reference
- answers are given via left and right computer mouse buttons
- Participant has as much time as needed
- no feedback is given

3.2.3 Long Term / Stability Test

For every single version built, a long-term-test was performed to verify whether it was suitable for the future usage or not. The vibration motors were tested with maximum intensity for 24 hours straight, placed in a location with no interferences.

3.2.4 Setup of the user studies

Participants

Three females participated voluntarily in the studies. They were all between 26 and 28 years old. No neurological or dermatological conditions were known. They were all students and not familiar with the studies.
As McKay [1972] and Parsons and Griffin [1988] stated, there are only small gender effects, therefore the results were not affected by just female participants.

Structure

Every participant was placed in a silent room without any distraction by people or other influences and was seated on a chair in front of a desk with a laptop on it. The participant had to put his left arm on the desk, after the sleeve was put on the forearm. In order to minimize the distraction and the ability to distinguish motors by noise, every participant had to wear a hearing protection. Due to the fact, that there is a user input needed, they were not blindfolded, but were advised to close the eyes to focus on the motors. Additionally a scarf was placed above the sleeve, to ensure they are not able to see the different motors.

Before every testing the participants had a few minutes to get to know the vibration motors by turning them on and off several times and in different orders.

They had as much time as they need to submit their answers

The input and answers were realized by a computer mouse, where the participant had to click either the left or the right button to submit the answer.
None of the participants got any feedback of how they were performing. For every answer they had to give, they had as much time as needed.
Before the next round started, there was a pause of a few seconds, to minimize the effect of the skin, to memorize the vibrations from before and to prevent the skin memory from masking the following vibrations, like Craig and Evans [1987] found out in their studies.

3.2.5 Observations

While building the different versions and running the studies, several problems were revealed and observations were made.

If all motors were turned on, the very first motor always had a much lower intensity than the other 15 motors. It was not a software flaw and it occurred with every kind of motor that was used.

After a certain amount of time of stress testing, the I^2C board got quite hot. This should be inspected a little further, especially when there is no air circulation inside the vest.

Chapter 4

Evaluation

In this chapter, the different hardware set ups are evaluated by the means of performance and usability. Therefore every version that was built, is analysed and compared to each other.
Additionally the performed user studies are evaluated, to check the impact of the haptic feedback on the human body.

4.1 Hardware

The hardware requirements, set for building haptic feedback devices, are evaluated for every version, that was built for this thesis.

4.1.1 Material

Two different kinds of material were reviewed. On the one hand the thin textile and on the other hand the foam rubber. The textile is a very flexible material, which is very comfortable to wear, because it is assimilating to movements of the user. However its flexibility brings out a problem with executed pressure to soldered contacts. The vibration motors are able to move the textile and therefore they put pressure to those contacts and cause them to break.

	foam rubber	textile
transfer of vibration	high absorption, vibrates as a whole unit	good single point transfer
characteristics	stiff	flexible
wearing comfort	does not assimilate to movements and can get an obstacle itself	assimilates to the forearm

Table 4.1: Material Characteristics

Both materials have problems with the soldered contacts

The foam rubber is very stiff and hinders the vibration motors on moving it, but thereby the wires are transferring parts of the vibration and therefore put pressure on the soldered contacts.
Its stiff characteristic hinders the user to move freely with the device applied to the forearm. The arm is one of the most used body parts and the device should not impair them. Furthermore the foam rubber kind of absorbs the vibration and vibrates as a whole unit, what makes it difficult to identify single motors or directions.
In contrast, the textile offers a good single point transfer of the vibration, with an increased contactor area, throughout the integrated blanks. The flexible characteristic of the textile provides a comfortable wearing experience. All in all the textile has more advantages than the foam rubber, but the most important point, is the transfer of vibration. The foam rubbers dampening effect makes it not advisable for future usage. Therefore the textile material is advised. 4.1

The foam rubbers huge disadvantage is its dampening effect

4.1.2 Sound Pressure Level

EXCURSUS: SOUND PRESSURE LEVEL:
Sound pressure level is a logarithmic measure to describe the pressure of an acoustic event, relative to a reference value and is denoted in dB.

$$L_\rho = \ln\left(\frac{\rho}{\rho_0}\right) N_p = 2\log_{10}\left(\frac{\rho}{\rho_0}\right) B = 20\log_{10}\left(\frac{\rho}{\rho_0}\right) dB$$

The most commonly used sound pressure reference is $p_0 = 20\mu Pa$ and is the minimum sound level an average human ear can hear. It correlates with $0dB$ sound pressure level. [Winer, 2012]
As an example, an acoustic source produces a sound pressure level of $50dB$. If there is an incoherent second acoustic source with $50dB$, the addition of this sound pressure level is $53dB$. That means, to express a doubled sound pressure level with incoherent sources, it is denoted by a rise of $3dB$.

Definition: *Excursus: Sound Pressure Level*

The HaptiVision produces a sound pressure level of about $86dB$ with a distance of $10cm$ to the sound level meter and with the maximum intensity.
On common scales it is comparable to traffic on a busy roadway with a $10m$ distance to the source and to a loud factory building. Hearing damage is almost sure, with a constant exposure. Therefore the pager motors Sánchez [2015] used, were not considered any longer. 3.1.3 "ERM Vibration Motors"

The HaptiVision can cause hearing damage

Version 3.1 produces a sound pressure level of about $69dB$ with the maximum intensity. Projecting it to the same amount of vibration motors, the HaptiVision consists of, it would add up to about $78dB$. That means, it is more than 4 times lower than the HaptiVision.

Using the encapsulated motors, reduces the sound pressure level significantly

$$L_\Sigma = 10 * \log_{10}\left(10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}} + ... + 10^{\frac{L_n}{10}}\right) dB$$

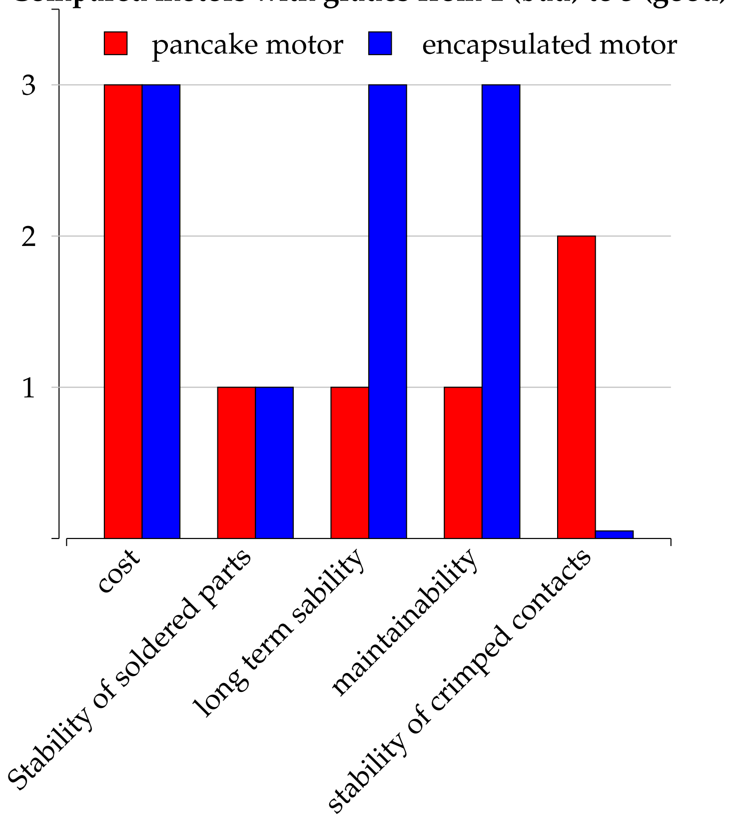
formula to add incoherent sources

With decreasing intensity of the vibration motors, the sound pressure level decreases as well. As the motors should not be used with the maximum intensity 4.2.1, the sound pressure level reaches an even more acceptable level. With 85% intensity, version 3.1 produces about $67dB$.

4.1.3 Vibration Motors

Three different kinds of motors were tested.
The pancake vibration motor disqualifies, due to its bad long term stability completely from future usage.

Compared motors with grades from 1 (bad) to 3 (good)



The pager motor needs to be encapsulated into a hull. Sánchez [2015] built a $3D$ printed hull for each motor, which is cost-intensive and additionally the result produces a sound pressure level, that is too high. 4.1.2.

The encapsulated motor is not in need of an extra hull, has a good long term stability and produces a significantly lower sound pressure level, thus this motor is advised.

The encapsulated motor is the best choice

4.1.4 Versions

The advantages, disadvantages and problems of every version were described in 3 "Own work".

Figure 4.1 sums up the results of how the different versions perform, by the means of the hardware requirements 3.1. Additionally the HaptiVision is considered, too.

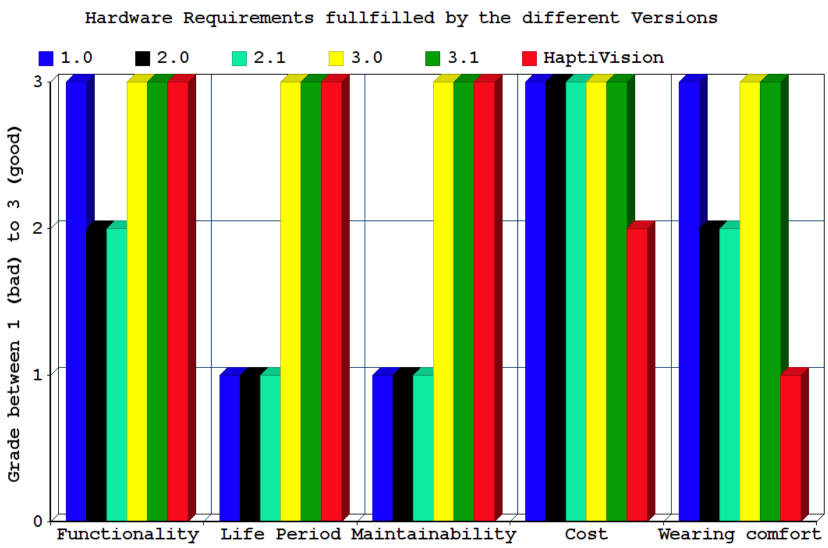


Figure 4.1: How every version fullfills the Hardware Requirements3.1. Graded from 1 (bad) over 2(moderate) to 3 (good)

As one can see, the HaptiVision has good results, except for the wearing comfort requirement. This is caused by the extremely high sound pressure level, mentioned before 4.1.2. One can not take the sense of hearing from the visually impaired, as it is their most valuable sense for daily life struggle.

The high sound pressure level is produced by the $3D$ printed hull and secondary the hull increases the costs of the device, what explains the moderate grade for the cost requirement.

Version3.1 has better results than the HaptiVision

Compared to the HaptiVision, version3.1 has overall good results. It is no hull needed and therefore the costs are lesser and co-occurring the sound pressure level is significantly lower.

4.2 User Studies

Some of the results, that are maintained by performing the studies are just tendencies and need to be confirmed with more testing. Because of time constraints set for this thesis, there was not enough time to perform the studies in a wider spectrum and with enough participants to get more representative results.
Furthermore, some of the studies that are performed, are just excerpts chosen, to get tendencies, which sections need to be investigated with more testing. It was not possible to tap the full potential out of the studies.

4.2.1 Left or Right and Top or Down study

As a first result the top or down and left or right study showed, that the sensation on the forearm, is not that accurate in longitudinal direction, like it is in transverse. The accuracy in longitudinal direction reaches from 60% correct answers to 93%, with a mean of 80.7%. Transverse the accuracy of correct answers reaches from 87% up to 100%, with a mean of 96.6% 4.3. Similar results were evaluated by Jones et al. [2009], during their navigational directions experiments.

This is probably caused by the bone, where the human body is not that sensitive, compared to the other parts. The amount of mechanoreceptors and nerve fibres is not that

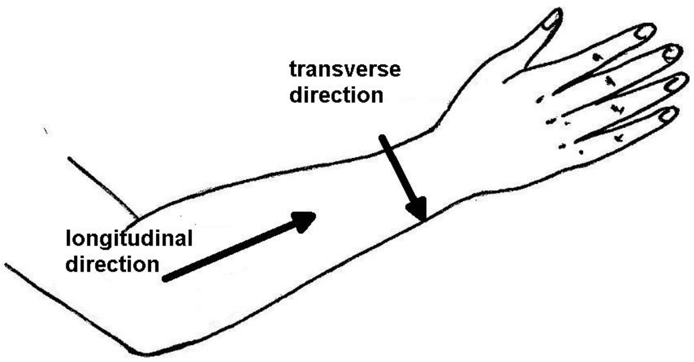


Figure 4.2: Forearm with explanation of the directions

high along the bone, like it is next to it.
As a result, the distances in longitudinal direction need to be increased, as [Kandel et al., 2000] stated, the two point discrimination threshold is about 3.5 to $4cm$ for the whole forearm. But this is only correct in longitudinal direction, in transverse direction the threshold is much lower than he stated. In transverse direction, the two point discrimination threshold is about $1cm$. [Kandel et al., 2000] did not differentiate between those two directions on the forearm, which lead to an imprecise result.

Two point discrimination threshold can not be generalized for the forearm

The human can identify different motors in the various directions by a different correctness. As a result, the distance of the motors for the sleeve was increased, in longitudinal direction to 1.5cm. This was done to check, whether the results are contradicting the two point discrimination threshold of 3.5 to $4cm$. However with no varying results, the longitudinal threshold seem to be correct.

Another interesting result is, that the accuracy of correct answers decreases, after the intensity has reached a certain point. That means, that the maximum intensity is not advisable for regular and daily usage of the device.

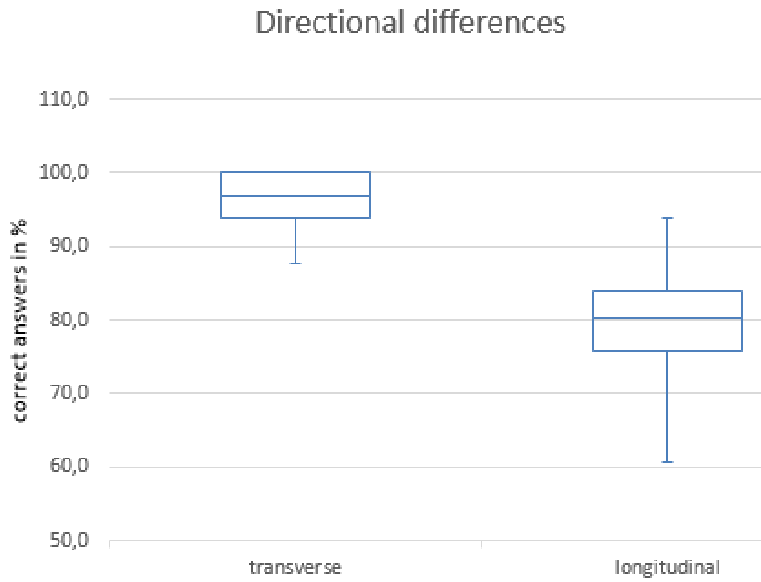


Figure 4.3: Different results for the directions on the forearm (with standard errors of the mean)

Higher intensity does not imply better performance

Top or down study revealed, with an intensity of 100%, the accuracy has a mean of 70.7% of correct answers, with 61% a mean of 84.8 %, with 85% a mean of 81.8%, with 75% a mean of 81.8% 4.4. This shows, that it is advisable to use intensities just up to 90% for the normal usage of the haptic feedback devices. Above this upper bound, the accuracy decreases by nearly the same amount, the intensity increases.
To give a lower bound for the intensity usage, further studies need to be done, so far there were no significant results.

Intensities above the upper bound could be used as special signals

Although the accuracy decreases, it does not mean that higher intensities are not usable at all. Intensities above that upper bound could be used for warning signals, but should not be used for the standard everyday usage for signalling obstacles. This would also be useful for the battery usage of the device.

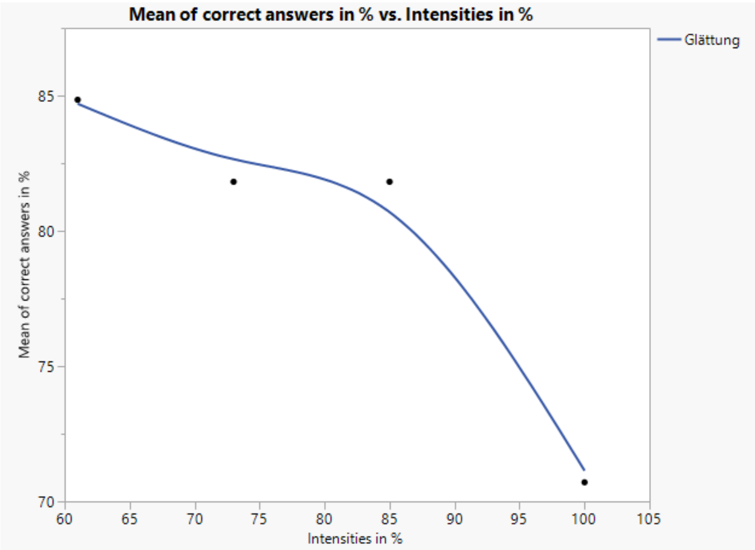


Figure 4.4: Intensities of vibration and correct answers

4.2.2 Memory Study

The memory study supports the results evaluated before. The participants recognize a change of the motors in the longitudinal direction just with an accuracy of 16.66%. In contrast they recognize a change of the motors in transverse direction with an accuracy of 79.165%. In most cases, changes were only recognized, if the outer most motors were used. This supports the different discrimination thresholds for the two directions of the forearm. With those significant results, the directions need to be looked at separately to give properly thresholds for the forearm.

The more motors were used, the harder to recognize changes in the pattern. Because of that, there is no gain in using that high amount of motors, it should be reduced.

4.2.3 Intensity Study

The results show, that it is nearly impossible to recognize small amounts of intensity changes. The changes, that are evaluated range from about 2 % to 25 % in relation to the maximum intensity. For changes of 2 % to about 7.5 %, the results are quite stable with an accuracy of 21 % up to 30 % of correct answers. That is a very bad detection rate and it does not matter, whether the intensity is in the low, middle or high sector of its range. A small improvement is noticeable at about 12.5 %, with an accuracy of 47.65 %. A good accuracy is achieved with about 25 %. There, the participants answered with a correctness of 71.43 %.

Detection of intensity changes is in the low sector as bad as in the high sector

Identifying the same intensity is not as good as expected. The participants answered correctly with an accuracy of 70.329%, again with no significant differences for the whole sector of intensities.

Higher intensities do not improve the ability of identifying the same intensity

This needs to be investigated further and with varying setups, because the results may change, if the test is performed with all 16 motors instead of just one, or if the motors, that are compared with each other, are played at the same time not successively. This offers a more directly comparison of different intensities 5.2 "Future work".

4.2.4 Identification Study

This study showed quite unexpected results. The participants were not able to recreate almost every single pattern. The patterns range from single motors up to all 16 motors used. Complex pattern, including more than four motors, were recreated with a correctness of 0%. The participants were not even close to recreate them.

Not a single pattern with more than four motors was recognized correctly

Even the single motors were not recognized appropriately, just 23.5% of the single motors were recreated with the correct position. The previous studies showed a better sensitivity in transversal direction than in longitudinal direction. In consideration of that, another 23.5% of the answers had the correct quantity of motors, but were mistaken by one motor in longitudinal direction, and 10% were mistaken in transversal direction. Thus, the insecurity in longitudinal direction is higher, than in transverse direction, as stated many times before.

All in all, the participants answered with a correctness of 10.4%.

It is suggested not to put as much effort into this study, like into the others. The messages, that can be send are not complex enough to be worth testing it in a more intensive way.

Chapter 5

Summary and future work

This chapter summarizes the work that is done and the possibilities the work offers and explains, how future haptic feedback devices should be constructed and could be improved.
Then it is explained, how the studies need to be enlarged, to get the most out of it and all the possibilities, that exist to improve haptic devices.

5.1 Summary and contributions

The encapsulated motor works without flaws

The encapsulated motor turned out to be the most reliable vibration motor, regarding the long term stability, the maintainability, the cost, the wearing comfort and the functionality.
Neither the pancake motor can be used, due to its bad long term stability, nor the pager motor, due to its hearing damage causing sound pressure level.

Textile showed better results

From the two different kinds of material, the thin textile is the best choice, because it transfers the vibration in good manner to the user, and does not disturb the user in movements, like the foam rubber.

Combining the results by considering the material and the vibration motors, 3.1.4 "Version 3.1" was constructed. The performed studies proved its adequacy for future usage.
The problem of the HaptiVision, is its high sound pressure level. Changing the hardware, the way this thesis advises, the level reduces significantly and the user will not suffer hearing damage.

Maximum intensity of the motors is not advisable

The haptic feedback devices should not be used with the maximum intensity of the vibration motors, as the accuracy of correct answers decreases.
Along with that result, there are several advantages to acknowledge.
First, the energy consumption is lesser than with the maximum usage.
Second, the sound pressure level decreases and therefore the chance of causing limitations and hearing damage while using it.
Third, there is a spectrum of intensities, that is not used for daily or usual usage to send special messages.

One can not state a uniform two point discrimination threshold for the forearm

Contrary to some results, evaluated in several experiments in the past, the forearm does not have a uniform two point discrimination threshold. The two different directions have significantly different detection rates for stimuli. In transverse direction, the accuracy is about 16% better than in longitudinal direction.

The ability of the human, to detect complex messages via haptic feedback is not as good as expected. The participants were not able to recognize and reconstruct a single pattern, involving more than four motors4.2.4 "Identification Study". Thus, the possibilities of sending complex messages are limited.

5.2 Future work

The wide field of possibilities this work offers, are presented and briefly explained, divided into a hardware section and a haptic feedback/ user study section.

5.2.1 Hardware

As evaluated before, the vibration motors should not be used with the maximum intensity, thus there is a spectrum of intensities that could be used for special messages or warning signals. It offers a wide field of possibilities, like signalling a low battery level or sending alarms. As long as those high intensity signals are used with a short exposure time, they will not cause hearing damage.

Using the sleeve as a control unit for the HaptiVision

The sleeve can be used as a control device for the HaptiVision, like turning it on or off, or pause it, while having a conversation. With its position, it offers an unlimited access to the user.
It is possible to use it as a regulator for the intensities, the vest works with. One could classify it in maybe 3 different stages of intensities, like "home use", "outside use" and "crowded / busy outside use". At home, it is not necessary to use the same intensity as outside, as there are fewer distractions for the user.

Presenting directions via haptic feedback

Another interesting possibility, is an integrated navigation system. As Van Erp [2005a] showed, directions are recognizable via haptic feedback. One could use the vest as an obstacle detection device and present navigational directions via the sleeve on the forearm. Jones et al. [2009] were performing those experiments on the forearm and achieved recognition rates of 98% with interpreting the right directions.

5.2.2 Studies

Due to the time constraints, set for this thesis, it was not possible to tap the full potential out of the studies. This section explains, how the single studies have to be performed in a wider spectrum to analyse the haptic feedback in a more appropriate way.

Setup

More participants, and hopefully get visually impaired for tests

More participants will help to improve the results and the accuracy of the results that are maintained. Especially, visually impaired people should take part in it, because they probably have a much more sensitive experience than other people, as they rely on their feeling sense in daily life.

Training with the devices

Another point is to have the participants train with the haptic feedback devices to get them used to how it feels, before obtaining the data. Training sequences of several hours, spread over several days, should be done.
As studies showed, trained participants are able to receive haptic information much better and faster than untrained participants. [Hao et al., 2013] experiments showed, that the detection rate increases by about 10% for trained subjects and the time interval needed to recognize haptic information, decreases by about 1.5 seconds.

Obtain data in a more realistic environment

The performed studies took place in a silent room, without any distractions for the participants. However, the actual user of the haptic feedback devices will have distractions in his daily routine, because of that, the studies should also be done with some kind of distraction, to simulate the actual using environment.

Differentiation Studies

The concrete lower and upper bounds of the intensities need to be investigated further. This thesis did not have enough data at its disposal to give concrete values, especially for the lower bound.

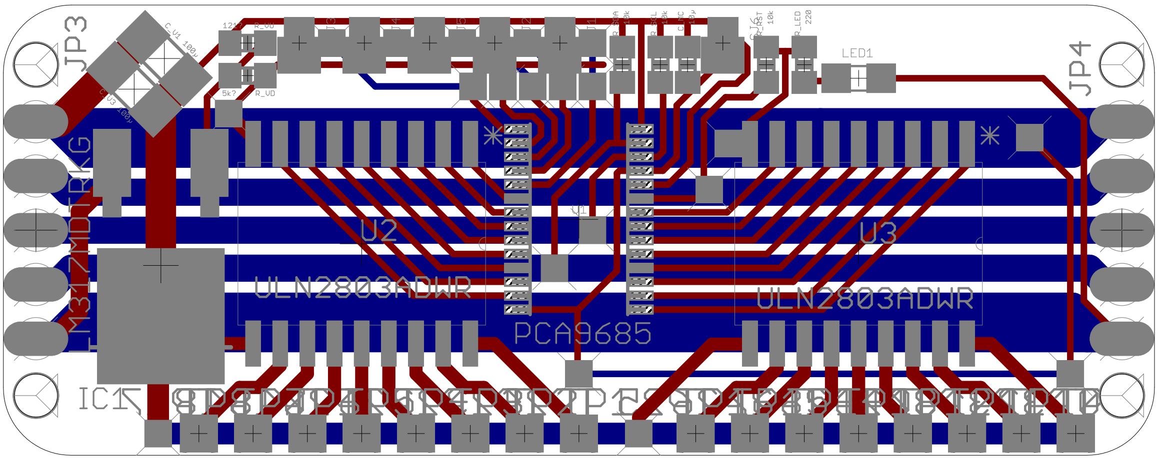
Identification Study

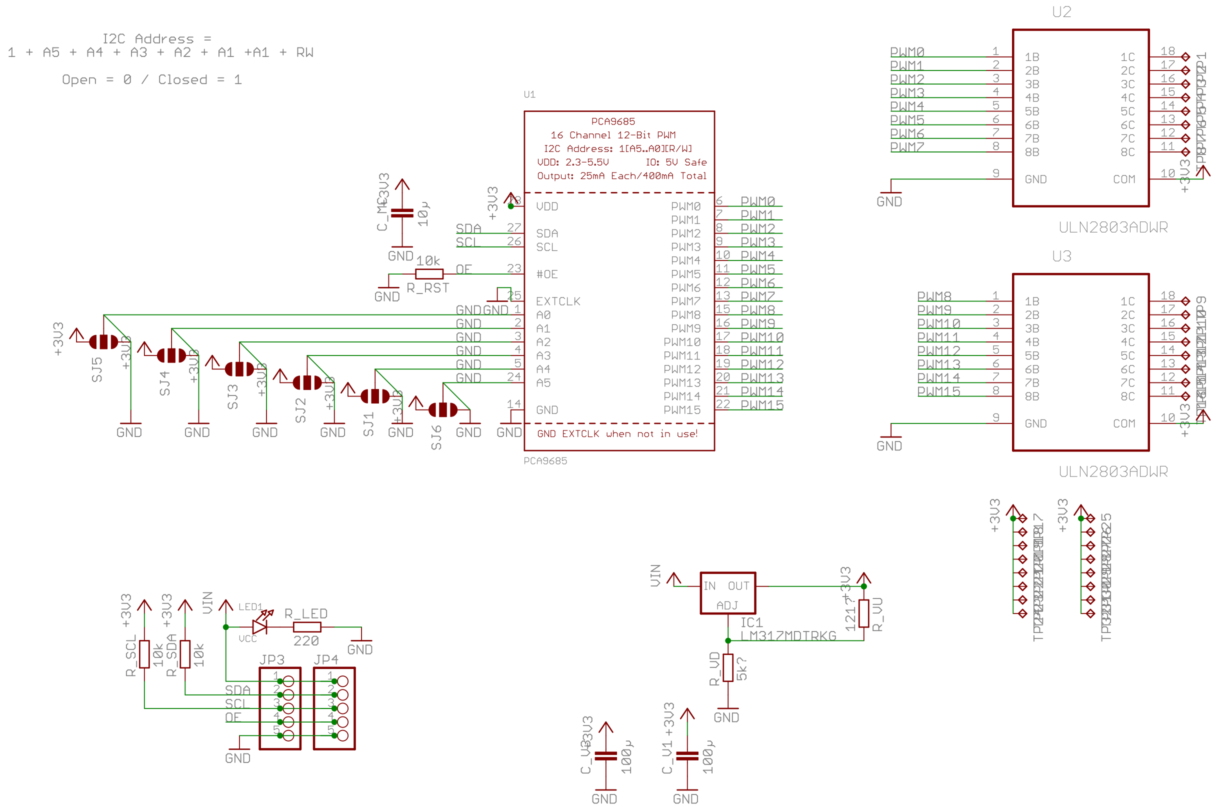
As evaluated before, the identification study provided quite disillusioning results. On the forearm, the human is not able to recognize complex pattern. Nevertheless, it should be conducted for the belly and the back as well. There are much more motors available to create different kinds of patterns and messages.

A certain part of the bad results could be caused due to the lack of training the participants had. There was no time to get them used to using the device.

Appendix A

Circuit Diagram


JP3
JP4
U2
U3
ULN2803ADWR
ULN2803ADWR
PCA9685
IC1
LED1



I2C Address =
1 + A5 + A4 + A3 + A2 + A1 +A1 + RW
Open = 0 / Closed = 1
U1
PCA9685
16 Channel 12-Bit PWM
I2C Address: 1[A5..A0][R/W]
VDD: 2.3-5.5V IO: 5V Safe
Output: 25mA Each/400mA Total
VDD
SDA
SCL
#OE
EXTCLK
A0
A1
A2
A3
A4
A5
GND
GND EXTCLK when not in use!
PCA9685
PWM0
PWM1
PWM2
PWM3
PWM4
PWM5
PWM6
PWM7
PWM8
PWM9
PWM10
PWM11
PWM12
PWM13
PWM14
PWM15
C_MC
10µ
R_RST
10k
OE
SJ1
SJ2
SJ3
SJ4
SJ5
SJ6
+3V3
GND
U2
ULN2803ADWR
U3
ULN2803ADWR
1B 2B 3B 4B 5B 6B 7B 8B
1C 2C 3C 4C 5C 6C 7C 8C
COM
VIN
IN OUT
ADJ
IC1
LM317MDTRKG
R_VU
121?
R_VD
5k?
C_U3
100µ
C_V1
100µ
R_SCL
10k
R_SDA
10k
LED1
VCC
R_LED
220
JP3
JP4

Appendix B

Arduino and Processing

B.1 Arduino

At first the Arduino PWM Servo library needs to be downloaded PWM Servo Driver.h[1].Keep the .zip file in the same folder as your Arduino IDE

Include it along with the Wire library to your code. Upload your code to the microcontroller.

```
#include <Wire.h>
#include <Adafruit_PWMServoDriver.h>
```

Figure B.1: Include libraries

B.2 Processing

After that import the serial communication library into Processing.

[1]https://github.com/adafruit/Adafruit-PWM-Servo-Driver-Library

```
import processing.serial.*;
```

Figure B.2: Include serial communication library to processing

Choose the study you want to perform and set it to true.

```
boolean executeLeftOrRightStudy = false;
boolean executeMemoryStudy = false;
boolean executeTopOrDownStudy = false;
boolean executeIntensityStudy = false;
boolean executeIdentificationStudy = false;
```

Figure B.3: Choose your study in Processing

Start processing and the study can start.

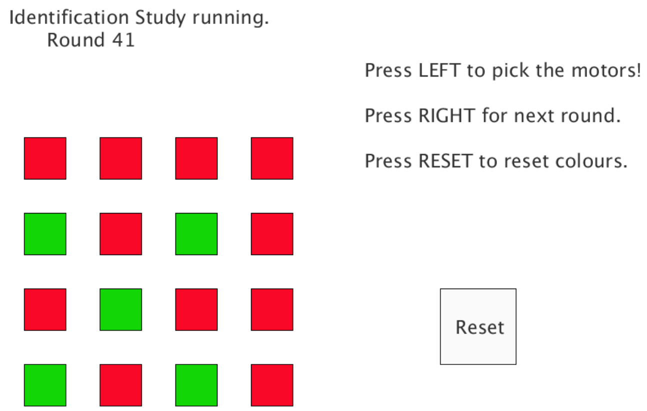


Figure B.4: Example Identification study Interface

The logfiles will be saved in the processing sketch folder. For the Identification study, the pictures of each turn are saved.

The Code for the studies is uploaded to the given CD and to Oliver[2].

[2] afp://oliver/Public/ResearchProjects/PersonalPhotonics(BMBF)/user studies/HapticSense-thesis-userStudies.zip

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