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Acknowledgements

Thank you!

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]

[a]http://hci.rwth-aachen.de/public/folder/file_number.file

Chapter 1

Introduction

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Chapter 2

Related work

In this chapter we first describe the basic differences between the two most popular touch input technologies and which is best suited for wearable scenarios. Then we give an overview of the latest related research in wearable touch input devices. We will focus on hardware prototypes and their underlying techniques. Wearable computation is a current field of research over the past years. Therefore a lot of different approaches were made to make textiles touch sensitive hence we only present some of them. An overview of the presented touch pad prototypes is shown in table2.1.

2.1 Resistive vs. Capacitive Touch

The two most popular touch input technologies are resistive and capacitive. Both serve the same purpose but the underlying principle differs making them more or less suited for wearable computing.

Characteristics of Capacitive Touch

Capacitve touch uses a non-conducting material with conductive material underneath. The capacitance of the human body changes the electrical field of the sensor which is measurable. The advantages of capacitive touch is the easy support for multi-touch input and today's touch screens only need a slight touch without force. The main disadvantage is the human body itself, since it generates its own capacitive field which makes it hard to detect the intentional touch. This flaw is intensified by the body movement continuously changing the proximity between the sensor and the human body. Therefore complex isolation technique is required to isolate the sensor and the human body which is unfeasible for fast prototyping.

Characteristics of Resistive Touch

Resistive touch technology uses two separated layers of striped electrodes such that it is arranged to a matrix. The spacing material in ordinary resistive touch screens is either an air filled chamber or a non-conductive material which separates both layers while no external force is applied. Therefore one can operate it with a stylus or with gloves since no conductivity is required. On the one hand this solves the main disadvantage of the capacitive method regarding wearable computing, on the other hand it is still prone to deformation and thus to unintentional contacts.

2.2 General Overview

Holleis et al. [2008] presented several prototypes based on capacitive sensing. They embroidered conductive wires to a phone case, a glove, and an apron resulting in small conductive buttons. Beside that they used conductive foil for buttons on an helmet as well. Their user study however only evaluated the apron with three different button layouts with different visibility. Based on the results they present guidelines for wearable controls.

Speir et al. [2014] built two prototypes, a wristband and a glove. The wristband prototype uses a circular conductive fabric surrounded by resistive linqstat. A conductive finger cap connects both of them an generates a value which is used to determine the location and the movement of the touch. The glove works on the same principle. They evaluated their prototypes as remote controls using one- and two-handed interaction and have found that the users have no clear preference.

Prototype	Touch technology	Gesture detection
Pinstripe	capacitive	detects size of pinch and movement of pinch in 1D
GesturePad	capacitive	not tested (theoretically able to detect 2D gestures)
Pocket touch	capacitive	multistroke gestures using N$ by Anthony and Wobbrock [2012]
FabriTouch	capacitive	swipes in 2D
Grabrics	resistive	detects axis of fold and movement of pinch in 2D

Table 2.1: Current textile touch pad technologies.

Ubiquitous drums

A different application is presented by Smus and Gross [2010]. They used force-sensitive resistors and pull-down resistor circuits to sense percussive touch. They taped the sensor into the inside of a pair of jeans and to the sole of a shoe. They created a program that translates the sensor values to different parts of a drum.

Time Domain Reflectometry

[Wimmer and Baudisch, 2011] created 13 prototypes based on time domain reflectometry (TDR). For this approach only one pair of wires is needed. The change in capacitance caused by conductive objects close to the pair of wire is measured and the location determined. Distance between the wires and their shape have significant influence on reliability. Their prototypes include stretchable, curved, and arbitrary shaped surfaces. They can sense touch at a distance up to 20m but TDR is prone to radio interference of mobile phones.

2.3 Textile Touch Pads

Pinstripe

Pinstripe is a continous textile input prototype created by Karrer et al. [2010]. It detects pinching and rolling of clothing by connecting conductive thread sewn on it. However, it is an unidimensional input device and not a touch pad. Nevertheless, when they introduced the users to the sensor they intuitively expected a touch pad.

GesturePad

Rekimoto [2001] presented GesturePad which is a capacitive touch pad integrated in clothing. They propose slightly different architectures consisting of the upper fabric, receiver, transmitter, and a shield layer to reduce the influence of the human body. However, their work was not further evaluated.

PocketTouch

Another capacitive approach was developed by Saponas et al. [2011]. PocketTouch is an eyes-free, calibrateable capacitive touch pad which can sense the proximity of a finger through a wide range of fabrics. They used a touch sensor of a touch screen and attached it to a base which makes it not bendable. The reliability of PocketTouch was not further evaluated.

FabriTouch

FabriTouch is a flexible, capacitive textile touch pad presented by Heller et al. [2014]. It consists of lining, piezoresistive foil, spacing mesh, conductive fabric, and outer garment together integrated into a pair of trousers. FabriTouch is able to reliably detect simple swipe gestures on rigid surfaces rather than on the human thigh. Also movement has a negative impact on the performance of the sensor.

Grabrics

Grabrics by Nur Al huda Hamdan [2016] is a resistive textile sensor based on similar interaction principles as Pinstripe. However, Grabrics is able to detect 2D strokes and is made by separated conductive circular pads. Therefore scaling is the major problem when it comes to production-scale manufacturing since the embroidered conductive threats, for each pad one, need appropriate distance.

Going for Resistive Touch

After taking all characteristics into account we decided to go for the resistive touch technology, because we can drop all considerations of capacitive noise caused by the human body.

Chapter 3

Hardware Prototype and Software Development

Then we proceed with showing several iterations of the hardware prototypes using pinstripe material. Furthermore we describe the disadvantages and improvements of each iteration leading to the final prototype. The software implementation is described afterwards.

3.1 System Design

All prototypes presented here are using pinstripe, a fabric with separated conductive lines. For the first prototype we were using the Texas Instruments MSP430G2452 micro-controller. Each row and column of the pinstripe has to be connected to a *digitalRead* pin of the micro-controller. The MSP430 controller has 16 of these pins but only 14 can be used since two pins are used for serial communication. This results in a matrix resolution of 7 by 7 at maximum.

MSP430 for first prototype

ToDo: exact specification of pinstripe and micro-controller und den gripper probe Klemmkabeln!!

Definition:
Resolution in pinstripe context

RESOLUTION IN PINSTRIPE CONTEXT:
When speaking of a certain resolution of our prototype, we talk about the number of connected rows and columns. Since the pinstripe fabric is of a fixed size (3mm conductive material and 3mm spacing). Therefore the higher the resolution the larger the prototype gets.

We are using the TI EK-TM4C1294XL for the advanced prototypes. This board has the ability to connect more than 40 pins for *digitalRead* to operate a 20 by 20 pinstripe matrix. The board is connected to a Computer via USB for serial communication.

Programming Environment: Energia IDE and Processing to gather, send and process input data

For programming the micro-controller we are using the Energia IDE[1]. It is an easy to use IDE to upload programs to the TI micro-controller. The micro-controller itself is solely responsible for sending the data of the sensor to the computer via serial communication. Meaning that it tests a pin against ground for each other line and column. A *1* is written to the serial-port when it is connected to another line or column and *0* otherwise. This is done for each pin where *numberOfPintripes* is the number of all lines and columns. For each prototype an integer array is declared and can easily be commented and uncommented depending on the prototype. The where the pin numbers are sorted such that the first pins correspond to the x-axis and the last pins to the negative y-axis. After all pins were tested we send a line-break to determine the end of the current input.

We are using Processing[2], a Java based IDE, to structure the input stream from the micro-controller for further analyses. This includes several programs which either displays the raw touch points for debugging purpose or filters and interprets the sensor data. The changes of software are described along with each hardware iteration.

[1]http://energia.nu
[2]http://processing.org

3.2 Early Testing

After deciding to go for the resistive approach, the essential challenge is to find a spacing material with certain characteristics. The material should

better note something here

- be flexible by means of being wearable.
- reliably separate the pinstripe fabric while no touch is intended.
- concede rather easily when intended force is applied.

We glued both layers of the pinstripe fabric to sheets of paper to eliminate stretching and curling of the fabric. We cut equidistant circular holes to provide space for the pinstripe layers to connect. For displaying where a touch is present, we created a simple program with Processing. Therefore we are using foam for the latest prototype.

ToDo: insert pictures of materials here. Say "we tried the following materials....

3.3 The Prototype

The prototype uses a 3 mm thick layer of foam which is coated with thin layer of cotton. Foam has the properties we need to separate the pinstripe layer while no force is applied and yield rather easily when the user presses on it. Another positive feature is the increased resistance to unintended pressure caused by bending or accidental contact with the sensor.
We use a laser cutter to cut equidistant holes out of the foam to allow the pinstripe layers to connect. This procedure leaves enough foam between the holes to retain the properties we need.

ToDo: model of lasercutter?

Another problem we have to address is the stretchability and the translatory movement of the fabrics. Each time the user performs a gesture the upper layer moves in

Issues with flexibility and translatory movement the respective direction due to the friction between the operating finger and the surface. This causes the the pinstripe fabric to shift such that the conductive stripes are not aligned to the holes properly, resulting in the prototype to stop working. When we started testing we used needles, clips, and nails to fix the materials to each other. Not only that these methods are not well suited for wearablity, also fixing the materials exclusively at the edges is not sufficient. Nonetheless the flexibility of the pinstripe fabric can cause the shift we want to eliminate.

ToDo: Add a picture of each material and step.

Vliesofix for fixating the components of the prototype

ToDo: find exact product description

To deal with the issues described above we use Vliesofix. Vliesofix is an adhesive on paper which can be ironed on textile. The paper can be removed afterwards and another fabric can be ironed to the corresponding textile. This results in an extensive adhesive area between two fabrics. The application of Vliesofix not only resolves the translatory movement but also the curling of the pinstripe fabric.

We decide two to prototypes with different dimensions. The first prototype has a resolution of 14 by 14 pinstripes and the second prototype has a resolution of 20 by 20. Since the procedure of making the prototypes is similar we only describe its building procedure for the smaller one.

ToDo: determine exact size of all used materials

We start by cutting out a x by x cm piece of the 3 mm foam using the laser cutter. Then we cut out two sheet of Vliesofix with the corresponding dimensions and proceed by ironing them on both sides of the foam. This has to be done carefully since the applying heat for two long can cause the foam to melt. After cooling down the foam looses the desired properties to a certain degree. When removing the iron too soon the Vliesofix might not be adhesive enough.

Once the material is cooled off we can remove the paper of the Vliesofix. We proceed with cutting the holes in the foam with the Vliesofix. Making the laser cutter cut more rows and columns of holes ensures that the resistance of the foam is the same throughout the touch sensitive area. Otherwise more force is needed at the edges than the center.

To prepare the two pinstripe layer to adhere it to the foam we again use Vliesofix first for preventing the fabric from curling and easy stretching. We do so before cutting out the pinstripe to make handling the fabric easier. Note that, while using Vliesofix with the pinstripe fabric, it is even more important to apply heat for too long. When the Vliesofix becomes liquid it gets soaked into the fabric. In some cases we ascertained that for this reason the conductivity of the pinstripes gets lost in some places. This immediately renders the sensor useless. Apart from that we do not remove the paper of the Vliesofix at this point.

We proceed with attaching the pinstripe layers to the foam. The stripes of each layer must be perpendicular to one another. Then we iron the untreated side of the one pinstripe fabric to the foam and after cooling off the other pinstripe to the other side. We have to make sure that the conductive stripes and the holes in the foam are aligned properly. Now we can remove the paper from the pinstripe fabric.
After that we iron a corresponding piece of polyester on the upper side of the sensor to reduce the friction between the finger and treated pinstripe layer. The last step is to connect the sensor to the micro controller. Furthermore we connect a Bluetooth module for wireless data stream. The power source can either be a computer or an battery pack which are connected by a micro USB cable.

ToDo: bluetooth module?

3.4 The Software

The software is divided into two parts, the code running on the micro controller and the application running on the computer. The code for the micro controller is straight forward. We define an one dimensional array for each prototype in which the pin numbers are stored such that the first half of the array denote the horizontal x-axis starting from left to right and the second half the vertical y-axis starting from top to bottom. Now we can check each pin of the array respectively if it is connected to ground. This means that the conductive stripe connected to that pin has a connection to another stripe and a *1* is sent via the serial communication and a *0* otherwise. The line break after the *for*

Code for TI EK-TM4C1294XL

loop lets us determine if a complete input set is received.

Receiving the data via serial communication in Processing

In Processing we read the data from the serial communication and store it in a buffer including the time stamp. If at least one *1* per data set is read, we consider it to be a touch. Sometimes the contact of the pinstripe layer is lost while performing a gesture due to insufficient pressure or a undersized locating surface of the operating finger. Therefore we implemented a threshold in which we can read only *0* without the touch phase to end. This threshold is reset anytime if a *1* is read. The raw data is logged for potential analyses as shown in figureYou either map these numbers to the wires of the prototype or remove this image 3.1.

Use a filter algorithm to reduce the data

Since more than one vertical and horizontal pinstripe can be connected at the same time we apply a filter algorithm. This filter algorithm takes all x-coordinates and calculates the average and the same for the y-coordinates. The resulting triple composed of the coordinate and the time stamp is added to an *Arraylist* buffer. This is done for all input sets except for all those, who only consists of *0's*. There are two reasons for filtering the input data. The first is the resilience to noise caused by unintended connections or slow separation of the pinstripe layers. The second reason is fact that it is easier for implementing gesture recognition. Apart from this the user intends to press only one point at the sensor.
When a gesture starts we take the coordinates and subtract them from all filtered coordinates of this gesture. Therefore every gesture starts at $(0, 0)$ regardless where it is performed on the sensor. This is done for the graphical representation of the strokes and will be useful later on.

Implementing mark-based gesture recognition

The next step is to actual recognize easy strokes performed on the prototype. Since our prototypes have a rather low resolution compared to typical touch input devices we focus on rather simple unistroke gestures. These mark-based gestures are shown in figure 3.2. We extend this gestures

```
0000100000000000000110000000;4.0
0000010000000000000110000000;5.0
0000001100000000000110000000;5.0
0000000010000000000110000000;5.0
0000000001000000000100000000;70.0
0000000001110000000100000000;340.0
0000000000010000001000000000;340.0
0000000000010000010000000000;340.0
0000000000000000100000000000;340.0
0000000000000000000000000000;358.0
0000000001100000100000000000;433.0
0000000001000000100000000000;720.0
0000000110000000100000000000;720.0
0000000100000000010000000000;720.0
0000000100000000001000000000;721.0
0000000100000000000100000000;721.0
0000000110000000000010000000;789.0
0000000110000000000001100000;1071.0
0000000010000000000000010000;1071.0
0000000010000000000000001000;1071.0
0000000100000000000000000100;1072.0
0000000000000000000000000010;1090.0
0000010000000000000000000010;1141.0
0000100000000000000000000100;1403.0
0001000000000000000000001000;1404.0
0001000000000000000000010000;1404.0
0000100000000000000000110000;1404.0
0000010000000000000000100000;1438.0
0000001100000000000000100000;1489.0
0000000010000000000000110000;1754.0
0000000000100000000000010000;1754.0
0000000000001000000000010000;1754.0
0000000000001000000000010000;1754.0
0000000000001000000000010000;1805.0
0000000000001000000000000000;1856.0
0000000000000000000000000000;2094.0
```

Figure 3.1: Example of the raw data of one gesture. On the left-hand side the sensor input and on the right the time stamps in milliseconds.

set by adding 5 gestures. These gestures are a tab and for each swipe gesture we expand it with a swipe in the opposite direction. This leads to a gesture set with 17 simple gestures.

Our gesture recognition works as follows. First of all we do not recognize in real-time. We analyze all filtered points, stored in the buffer, after a gesture is considered finished. Then the algorithm works as follows.

- `check for tab`
  - `return` *true* `if the size of the buffer is 1`

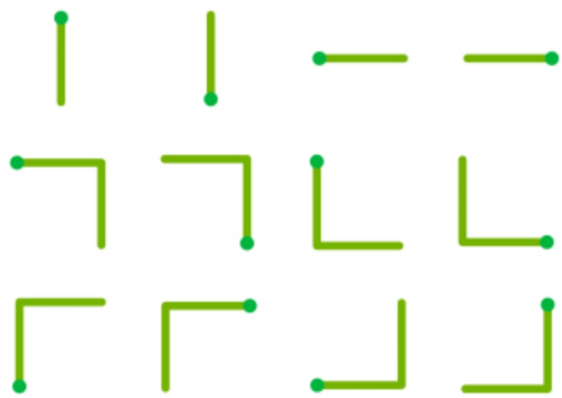

Figure 3.2: Mark-based gestures. Gestures start at the dots. Bragdon et al. [2011]

  - return $true$ if the all coordinates have a $distance$ smaller or equal to 1 respectively and the time elapsed is smaller than 200 milliseconds
  - else check for other gestures

- check for swipe
  - assume there is a swipe with the first and the last item of the buffer as terminal points
  - calculate the $distance$ of the line
  - return $false$ if the $distance$ is smaller than 3
  - for all other points calculate the $distanceToLine$
  - return $false$ if at some index the $distanceToLine$ is greater than 1
  - else determine the direction of the swipe and return $true$

- check for angle
  - check if there is a line between the point at $index - 1$ and last point in the buffer under the exact same conditions applied for swipe

  - `return` $false$ `if at some index the` $distanceToLine$ `is greater than 1`
  - `calculate the directions of both lines and return` $true$
- `end of checking`

This algorithm classifies each gesture as a tab, swipe, angle, or no gesture. In combination with the directions we calculate for each swipe we can distinguish between all 16 mark-based gestures. The orientation of a line is mapped to one of the four directions up, left, right, or down. Therefore our prototype is resilient to a certain degree of input error. With less effort we can further extend the gesture set by distinguish more directions.

Using 1$ Unistroke Recognizer for complex gestures

When testing our gesture recognizer with our current prototypes we observe an almost 100% recognition rate. Based on this finding we decide to go beyond simple mark-based gestures and continue with recognizing more complex gestures. Therefore we make use of the 1$ Unistroke Recognizer by Wobbrock et al. [2007]. This is an easy to implement recognizer which does not require any training data. Providing a template for each gesture is sufficient. A template is an array of consecutive pairs of coordinates. We can pass the coordinates in the filtered buffer straight to the 1$ recognizer.
This recognizer is orientation independent. Meaning for the marked-based gestures that, without further analysis of orientation, we can only distinguish between a swipe, an angle to the right, and an angle to the left. However, we can recognize a set of free-form gestures shown in figure 3.3.

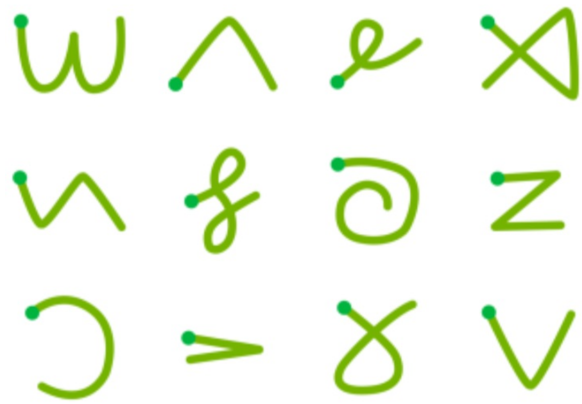

Figure 3.3: Free-form gestures Bragdon et al. [2011]

Chapter 4

System Evaluation

In this chapter we will evaluate the robustness of our prototype in different extreme conditions. We will take a closer look at the performance of the 14 by 14 prototype. Since the prototype is designed as a wearable, we are interested in its behavior under certain changing conditions. We conducted an informal user study to test the physical limitations.

Testing the 14 by 14 prototype

4.1 Physical Limitation Study

The human body is in motion almost all the time and the clothes we are wearing are not fixed to the skin. This *looseness* and the changing subsurface are variables that may influence the performance of our prototype. Another variable is the *friction* of the overlaying material. Depending on the fabric and method of fashioning, it can, more or less likely, happen that the user slips of the touch-sensing area, or experiences an unpleasant feeling in the operating finger. Furthermore the *softness* of the underlying surface may influence the performance of our prototype. The amount of muscles, adipose tissue, and so forth also differs from human to human. This, in the first place, affects the pressure needed by the user. Then there are the different levels of curvature. Our prototype has flexible spacing-material to separate the pinstripe layer. After a certain amount of

Independent variables: friction, softness, looseness, and curvature bend the material starts creasing, causing some permanent contacts. In this study we will test our prototype in conditions which aim to simulate the in field scenarios. To test to which degree of bend the prototype breaks we used different foams with fixed thickness and different density.

4.2 Study Design

The participants had to perform 8 different gestures in different conditions. The set of gestures is shown in figure 4.1. To control the curvature, we used aerosol cans with 53mm diameter and 66mm diameter. As a baseline we also used the table with a flat surface. When we tried to perform gestures on a curvature below 53 mm we got permanent contacts immediately. To fixate the aerosol cans we build stands using a laser cutter. The prototype was fixed with duct tape to the surface of the cans. To achieve the curvature with the foam, we used a book and wrapped the foam around the cover and clipped it in a vise. The fabrics (jeans, cotton, rib knit cotton) were pinned to the prototype with needles. Nevertheless, there is still a certain amount of movement due to the flexibility of the fabrics. The user cannot see the output on the screen.

ToDo: insert pictures

The conditions, at least curvature and softness, were chosen at random. In order to shorten the time of the study, we tested all fabrics consecutively changing the order. Some prior testing has shown that the foam with a density of todofind that paper with the numbers xxxxxx and xxxxxxx perform alike. Thus we dropped the foam with higher density after the first participant tested both foams in one condition without differences in terms of input error.

We asked two right-handed participants, one male (24) and one female (22). One had no experience with wearable where the other was working with wearable computing.

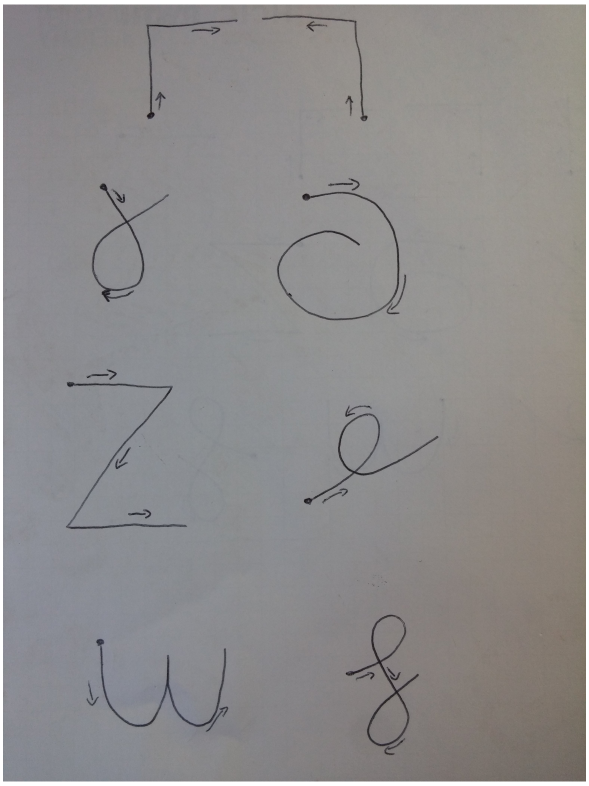

Figure 4.1: Gesture set: right angle, left angle, slope, spiral, z, pigtail, w, doubleslope

The participants were filmed while interacting with the prototype. Furthermore the screen with the application was captured to determine by eye, whether the gesture was recognized correctly or, if not, should have been recognized correctly. Additionally, our program created two log-files for each condition. One logged the filtered data and one the raw sensor data. Both files logged the time stamps of each data point.

4.3 Study Procedure

After the user arrived we introduced her to our prototype. We explained the basic functionality and demonstrated how the output looks like. Then we let the user test the eight gestures and some freestyle strokes. This was done without foam or any additional fabric. We pointed out that a certain amount of pressure is essential for our prototype to recognize the touch. When they felt familiar enough, about 2 minutes of testing, we prepared the first condition.

For each condition we setup a GoPro Hero 3 to capture the prototype and the acting hand of the user. When we were ready to start recording the screen and setup, we told the user to continue. Since the user cannot see the output during the study, we told the user when insufficient pressure was applied or when the touch-sensing area was left. In both cases we most likely recognized one or two wrong gestures. We represent the number of wrong gestures with an x in the respective chart.

When one condition is completed we asked the user about their impressions of the fabric, softness, and curvature.

4.4 Observation

The results proof the general applicability of our prototype. The overall success rate of performed gesture is shown in figure 4.3. We distinguish between the hardware results by eye, with recognition, and with repetition if the user left the touch sensing area. There is a consistent difference between the two participants due to the varying level of experience. This indicates a significant learning effect which also was the subjective impression of both participants. Primarily the required pressure to generate a contact is remembered over time. 84,5% of all gestures generated recognizable data. Meaning that by eye the output of the data matches the current gesture. However only 75,5% of these gestures were recognized correctly using the 1$ recognizer. One example of a false negative is shown in figure **??**. Therefore we made this separation, since we are interested in the capabilities of our hardware prototype. Therefore we let the participants repeat those trials, where they left the touch sensing area. This leads to an average success rate of 87.5% and the second user even achieved 91%.
The difference of hardware success rate and recognizer

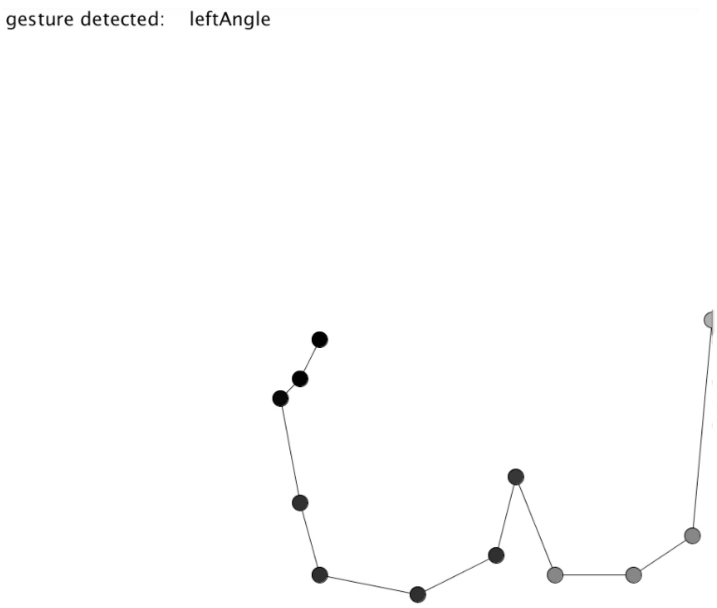

Figure 4.2: The characteristics of w are there, but nonetheless *leftAngle* was detected.

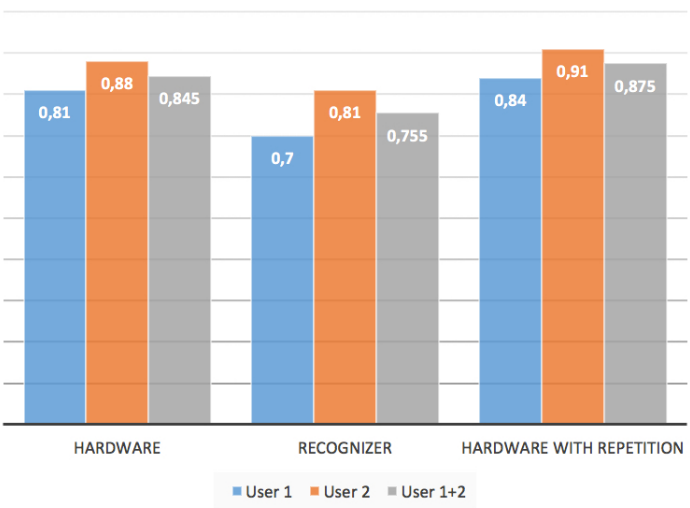

Figure 4.3: Success rate of all performed gestures with different criteria.

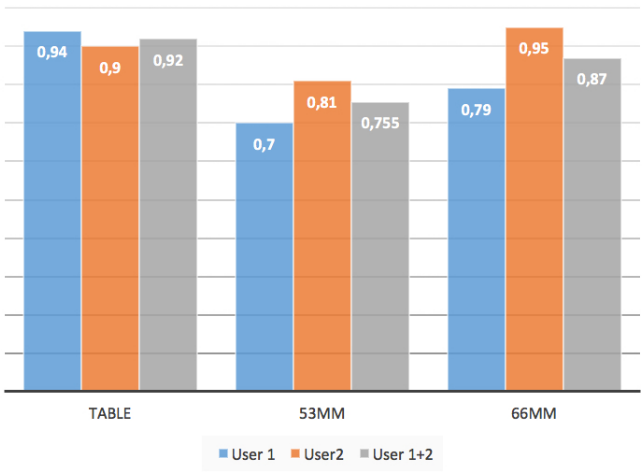

Figure 4.4: Success rates on surface curvatures

success rate is almost the same for all conditions. Since we are interested in the performance of the hardware we only consider the success rate of the hardware from now on.

flat surface is best, 53mm worst

When it comes to surface curvature we got the results we expected shown in figure 4.4. The curvature with a 53mm diameter performs worst but still with a success rate of 75,5%. The best curvature is no curvature at all. On the table both users achieved a success rate above 90% with an average of 92%. It is notable that the user with experience obtained a rate of 95% with 66mm curvature where the other user got 79%. Nevertheless, the inexperienced user outperformed the other user on the flat surface.

When we asked the participants which curvature they prefer they agree that the flat surface it most pleasant for touch input and the more curvature, the more likely it happens that they slip off the surface. This leads to unintentional input and thus to more input error.

The success rates with different softness is shown in figure 4.5. Our hypothesis that softness has a bad influence on the performance of our prototype was falsified. One user obtained 81% in both cases and the more experienced user performed better on the foam (92%). The participants reported that is was much more pleasant to perform the gestures on the foam due to the distribution of the pressure.

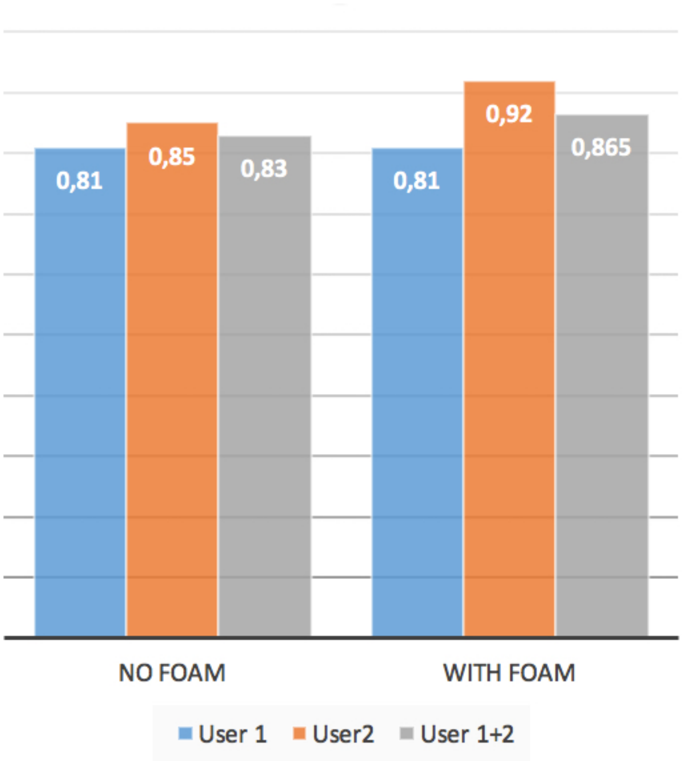

Figure 4.5: Success rates with and without foam

The different materials seem to have no influence on the performance of our prototype as shown in figure 4.6. The average success rate is between 84% and 86%. However, the participants reported that the rib knit fabric is extremely annoying due to the immense flexibility. One user said he likes jeans for getting good results but after a while the abrasive surface of the jeans leads to tingle and makes it unpleasant. Both participant prefer cotton and jeans because of their stiffness resulting in less folds. Although the participants reported occasional wrinkles of the rib knit fabric and therefore perceived lose of contact, the sensor still recognized the input as fine as the other fabrics.

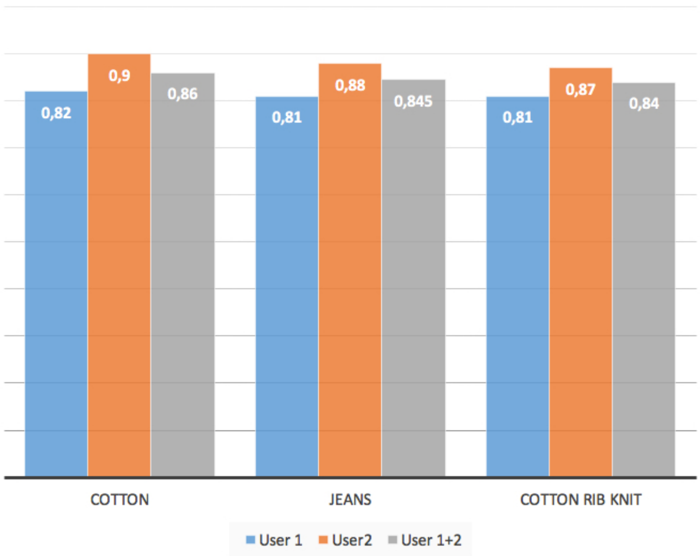

Figure 4.6: Success rates with different materials

The success rates of each gesture is shown in figure 4.7. The most complex gesture was *doubleslope* and was the hardest gesture to perform with an average success rate of 66,5%. However the difference between the users is huge (81% and 52%). Applying the required amount of pressure steadily is more difficult when the gesture key characteristics are complex. The *doubleslope* gesture requires more changes of direction than *pigtail* (average 85%).
There is notable difference between *left angle* (89%) and *right angle*, which has the best average success rate of 95,5%. It remains to test if this is ascribed to the dominant hand. Except for the *w* gesture (75%), the rest of the gesture are within 85% and 93,5%.

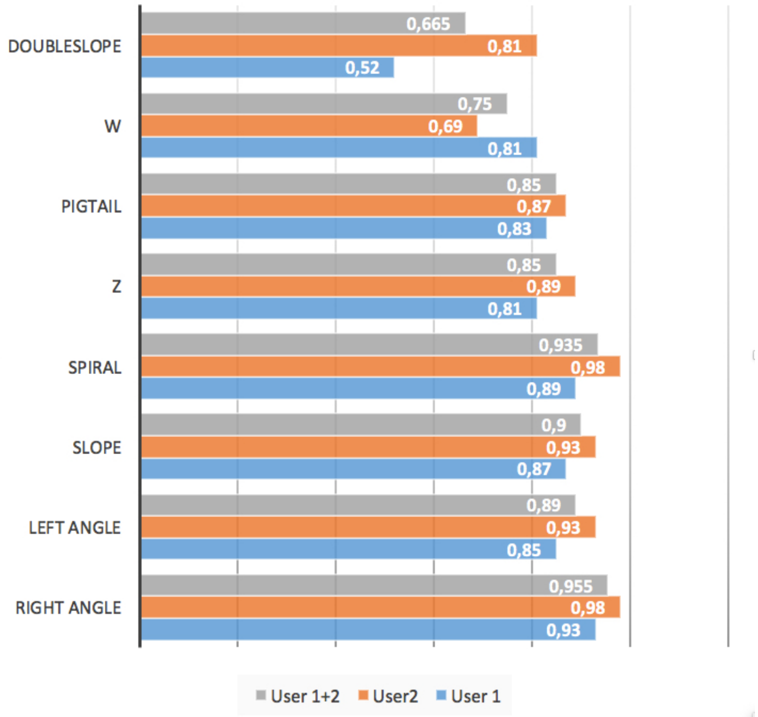

Figure 4.7: Success rates for each gesture

Chapter 5

Summary and future work

In this chapter we will give a summary of our contribution to the field of human computer interaction. Reviewing the hardware and its capabilities will point us to constitutive ideas for future work.

5.1 Summary and contributions

We presented a 2D textile touchpad for eyes free interaction with novel properties compared to the latest prototypes in this field. It is based on the simple principles of resistive touch technology which has some advantages over capacitive technology when it comes to wearable touch sensing. We presented several related touch pad prototypes in chapter 2. Most of them use capacitive touch and the gestures they are able to detect are rather limited due to the noise generated by the human body. Our prototype only yields a touch if the layers are physically connected. *Grabrics* uses resistive touch as well but the interaction design differs from simple 2D touch.

In chapter 3 we described how we built our prototype with low cost materials. The touch pad itself is made out of textiles only making it bendable and breathable, but limit the stretchability of the sensor at the same time. We explained step by step how to attach the pinstripe fabric layers to the spacing material, such that everyone is able to rebuild it in short time. The necessary code is linked in the Appendix. Our prototype is easy scalable and is only limited in the number of pins of the used microcontroller. Although we made our prototypes equilateral, it is simply possible to give it any rectangular size. We want to note that a lot of testing of the 14 by 14 was done prior to the user study.

Furthermore we explained the software for our sensor to detect simple unistroke mark-based gestures using our own recognizer. Then we went one step further and even recognized more complex unistroke free-form gestures. This is the first full textile touch pad being able to do that consistently. An informal user study, presented in chapter 4, has shown that. We let two participants test the prototype under multiple conditions to evaluate the physical limitations of the sensor. We found that there is a learning effect since we observed better results from the more experienced user.

Beside that we found that the 1$ recognizer is not optimal for sensors with a rather low resolution of 14 by 14. Curvature seems to have only significant impact on the overall performance which makes the thigh best suited additional to the fact that both participants prefer jeans fabric for interacting with the sensor. Although both participants liked operating the sensor, both agree that it gets unpleasant over time it it would be best suited for occasional use.

5.2 Future work

The most immediate step would be making the sensor actually wearable by integrating it into everyday clothing. This yields new challenges beside recognizing 2D touch. The wiring of sensor and micrcontroller and the power supply should be imperceptible. Furthermore the data processing and gesture recognition should be ported to the microcontroller.

A number of embedded prototypes could be built with more different fabrics used in today's clothing. Then series of user studies could be conducted to test the performance of the sensor in daily use.

Appendix A

APPENDIX

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Appendix B

TITLE OF THE SECOND APPENDIX

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